RUBBER TO METAL BOND FAILURE DURING THE MANUFACTURE OF CONCENTRIC BUSHES

A Thesis Submitted for the Degree of
Doctor of Philosophy
by
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Interdisciplinary Higher Degrees Scheme

University of Aston in Birmingham

April 1981

The University of Aston in Birmingham

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Summary

The research is concerned with bond failures found during the manufacture of rubber-to-metal bonded bushes, the bond being formed using a polymeric adhesive intermedium and completed concurrently with the vulcanisation of the bulk rubber. Failure occurs when stresses developed as the composite parts cool after moulding act on the comparatively weak 'hot'bond.

Three techniques are utilized for measuring the shrinkage stress i) a finite element method which shows the distribution of the direct stresses, ii) an empirical calculation which indicates the average direct stress acting on the bond, iii) an experimental method serving as a confirmation of the theoretical approach.

The main factors influencing the hot bond strength immediately after moulding are identified and include:-

Rubber hardness
Rubber moisture content
Adhesive type (reactivity)
Heat input during vulcanisation

These are quantified using a specifically developed test-piece.

Bush cooling characteristics are studied to allow a direct comparison of shrinkage stress with bond strength and to predict the theoretical likelihood of bond failure.

The research shows that, under ideal conditions, only in a few products is the shrinkage stress sufficient to cause bond rupture.

Bond failure rates are greater than the theory suggests and the main causes are identified as being due to lack of process and management control on the shop-floor. Recommendations are made as to methods required to obtain better control.

A new adhesive was evaluated and introduced into the company giving potential for a 40% reduction in bond failure levels with a cost saving of £50,000 p.a.

Key Words: Rubber-to-metal; Bush; Bonding; Cooling; Stresses.

ACKNOWLEDGEMENTS

My special thanks to Dr. G. Beaumont for his guidance and moral support as my main supervisor, and to Mr. G. Hopkins my industrial supervisor for his help, especially early in the research when I was a complete stranger to the technology of rubber-to-metal bonding. My thanks also to the other members of the supervisory team, Dr. A. Amass and Mr. D. Hickson, for their sound counselling.

I am grateful for the help received during the past 3 years from the I.H.D.office staff and from my colleagues at Dunlop (PED), in particular Mr. D. Stevenson (Bonding Development Superintendent) and Mr. J.Thorpe (Senior Development Engineer).

May I also express my gratitude for the financial support given by the Science Research Council and Dunlop Holdings Ltd.

Finally my thanks to Mrs. R.Aldwinckle for typing my thesis and for putting up with a multitude of corrections, arrows and asterisks on the manuscript.

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CHAPTER ONE

INTRODUCTION

Concentric bushes are a family of products manufactured by bonding rubber to metal. This chapter explains the nature of rubber-to-metal bonding, reviews the history and present operations of the industry and examines the major U.K. markets for all bonded goods.

The attention is then focused on concentric bushes, their configuration, properties and applications. Finally chapter one concludes with an introduction to the bond failure problem, found in many of these products.

1.1 General

Any type of movement creates some form of disturbance and throughout the ages man has sought means for damping out vibrations.

Solid members of frameworks or mechanical systems transmit vibrations or forces and therefore designers have had to develop parts to absorb these vibrations.

For instance, early attempts involving coaches used leather straps to support the body of the coach but these were not suitable for the industrial application of vehicular transport that became needed with the industrial revolution.

Mechanical springs were developed and improved upon until the present day.

Rubber has been known to have properties which could absorb shock and vibrations since the early Nineteenth Century but it was only during the Second World War that engineers started to use it on a large scale for this purpose as a need arose for machines to be transported to and maintained at the battlefront while withstanding rigorous shocks of mechanical warfare.

Initially a rubber pad was clamped or bolted into position but later it was bonded to metal to form a rubber/metal unit. These units were incorporated into a whole host of military equipment and could be replaced in service with comparative ease.

1.2 Rubber to Metal Bonding

Bonding in the context of this thesis is a process whereby rubber is united with metal by a bond formed through a suitable interlayer such as brass or polymeric adhesive. When producing the bond, heat and pressure are required to initiate the reaction between layers of rubber, adhesive and metal thus forming a chemical link. These aspects are not normally present in the basic glueing process where physical bonds predominate.

Bonding as a technique has been known since 1862 when Sanderson[1] submitted his patent. This involved the bonding of rubber to iron or steel using brass as an intermediary. Little development seems to have been done with the process until 1911 when Hood[2] adopted the brass plating method for obtaining adhesion between rubber and metal in the production of rubber rollers.

After the 1939-45 War, industry started developing the applications of rubber-to-metal parts and improvements in the technology of bonding were required.

In the early Sixties the brass plating method, i.e. an intermediate layer of brass, was replaced by using an intermediate layer of polymeric based proprietary adhesives, commercially termed 'Bonding Agents' which enabled the bonding technique to be exploited for the large volume production industry when markets grew with the increase in domestic automobiles. To meet the demand for new products, units of higher performance and complexity were designed, often to the customers strict specifications.

Bonding agents have reached a new degree of sophistication and are now employed exclusively. Rubber compounds are also very advanced today enabling engineers to use rubber in many varied situations. The metal base for the components is still mainly mild steel which is relatively cheap.

The manufacturing techniques of rubber-to-metal bonding are improving, especially with the use of micro-processors for machine control and computers for aiding production planning and factory management. Although these techniques have yet to be fully intergrated into U.K. companies, in the U.S.A. they are already providing substantial benefits in terms of increased efficiency.

1.3 The Industry

Worldwide many companies are engaged in manufacturing rubber to metal products. To a certain extent the level of activity in each country is reflected by the scale of the major market, the automotive industry. Thus the U.S.A. is the major producer, followed by the major European motor manufacturing countries and finally Japan. Russia produces a large number of these products although mainly for military and public transport uses.

The four main producers in the U.K. are Dunlop Ltd., Long and Hambly Ltd., Avon Industrial Polymers Ltd., and the B.T.R. Group. In all 12 U.K. companies (with over 100 employees) are engaged in this industry, their names appear in Appendix No. 1.

Most of these companies have stemmed from or are part of general rubber manufacturers as the technology is predominantly rubber based. Therefore most outside research and support comes from the rubber and plastic research organisations, such as the Malaysian Rubber Producers Research Association (M.R.P.R.A.) and the Rubber and Plastics Research Association (R.A.P.R.A.) and commercial guidance from manufacturing associations, e.g. the British Rubber Manufacturers Association (B.R.M.A.).

1.4 Markets for Rubber-to-Metal Bonded Products

The U.K. markets can be classified according to the main areas of product application.

a) The Automotive Market

The domestic section of this market spans the major motor car manufacturers and products include engine mountings, bushes and prop-shaft bearings. These are generally high volume, low cost products.

The commercial automotive market includes lorries and other heavy vehicles requiring similar but larger and better quality components than for domestic automobiles.

b) The Industrial Market

A diverse range of products exists for this market, from instrument and machine mountings to anti-vibration panels.

c) The Railway Market

Products destined for the rail market are normally manufactured for specific contracts and mainly consist of rail carriage springs and bolsters.

d) The Marine Market

Until recently products for the marine industry tended to be large and complex, e.g. engine mountings and dock fenders. Now companies are moving into the small boat market by manufacturing small engine mountings and propeller couplings.

e) The Construction Market

Products for this market range from bridge bearings to recording studio floors.

f) The Aerospace Market

Although comparatively small in the U.K., a market exists for high precision(and cost)products for aircraft and defence systems, e.g. helicopter rotor blade mountings.

About half of the products (by volume) manufactured by Dunlop (PED) Ltd are for the Automotive Market, about a third for the Industrial Market, and the remainder are divided mainly between the Rail and Marine Markets.

1.5 Concentric Bushes

In this context the basic shape of a bush could be described as 'Two concentric metal cylinders separated by a layer of rubber'. Plate 1 shows a selection of typical bushes.

A typical bush would have dimensions of 6 cm in length, 4 cm diameter with a rubber cross-section of 1 cm. Appearance of the finished article varies from completely black to black rubber and grey metals. A typical value for this size of bush in large scale productions is £2 per unit.

The rubber/metal bush is an extremely important type of mounting unit. Main features of the bush are:-

a) a basically simple design, but remarkably effective

b) the rubber is mostly protected from mud, dirt or water, hence a long service life

c) it can absorb shock in all directions

d) the possibility of break or failure in a good part is remote

e) it is completely silent

f) it requires no lubrication

Three major types of bush have been identified although none of these is rigorously met in practice.

They are:-

a) Constant rubber length.

Constant rubber length bushes are the commonest type and are made in a large variety of shapes and sizes. Radial loading can be several times greater than the loading applied axially.

b) Rubber length decreasing linearly with radius.

These bushes are used for applications involving radial and torsional loads/deflections. Taken to the extreme there is the constant torsional stress bush with a thick rubber section and short length.

c) Thin rubber, high radial stiffness.

This type of mounting is designed for applications requiring high radial stiffness - for instance in articulating joints. The rubber is precompressed to give optimum fatigue life combined with more control of service performance. The inner metal sleeve is usually longer than the outer sleeve to avoid contact of the fixing bolt with the rubber. Cross-sectional diagrams for all three types of bush are contained in Figure 1.1.

Sometimes to increase maximum angles of oscillation and flexibility double bush mountings which use three metal sleeves are used. They can be regarded as two separate type C bushes for the purposes of this study.

Although they can be used on their own, normally bush type rubber mountings are intended for use in assemblies where there might be rotational movement supporting radial, axial and torsional loads. Oscillatory movements are permitted without the need for lubrication by deflecting the rubber in shear.

Bushes can be easily slotted into spring assemblies with the minimum of fixing or clamping and can be replaced when worn-out or damaged with similar ease.

1.6 Bond Failure in Concentric Bushes

A concentric bush experiences a fall in temperature during manufacture and the rubber, which has a much greater coefficient of thermal contraction than the metal, is restrained from shrinking by the part configuration and the rubber-to-metal bond, giving rise to a tensile stress acting against the bond. If, at the same time, the bond is 'weak' due to the thermoplastic nature or lack of reactivity of the polymer adhesive then bond failure is likely to occur.

It is thought that most bond failures are prevalent in high stiffness (type C) bushes where the shrinkage stresses are high, but the overall picture is clouded by the variation in processing conditions which effect the bond strength.

Although the bond failure problem occurs during the manufacture of bushes and the high cost of scrapped parts is borne by the manufacturer, eventually the product price must reflect levels of bond failure. In 1977 the cost to Dunlop (PED) Ltd of bond failure in bushes was in the region of £100,000 per annum (excluding testing, rework and disposal costs).

The main intention of this research project is to limit high production costs associated with bush bond failure which are unacceptable to Dunlop (PED) Ltd in its present situation.

CHAPTER TWO

THE COMPANY

Dunlop today is a conglomerate of diversified companies united by the common use of polymeric raw materials. These companies are organised into several groups, with Dunlop Holdings controlling the overall financial and strategic situation. In turn the groups are sub-divided in divisions which are largely self-contained and autonomous companies operating within a specific field. Certain functions, e.g. Corporate Planning and Research are centralised.

Polymer Engineering Division (PED), a member of the Industrial Group was formed in 1968 to develop and expand the business of the John Bull Rubber Co.Ltd., and its subsidiary Metalastik Ltd. John Bull, founded in 1906 and Metalastik, established in 1937, became part of the Dunlop organisation in 1952.

The division now comprises two product groups, one manufacturing Metalastik products and the other automotive hose. Each product group has its own technical, production, marketing and purchasing facilities on the 14 acre site at Evington Valley Road, Leicester. A smaller factory in the west of the city produces large parts for heavy engineering applications.

P.E.D. employs about 1600 people of which a fifth are salaried staff. Sales turnover for 1978 was £16.8 m and a gross profit of £672,000 was achieved. About 60% of goods produced are exported.

The Division has suffered a decline in recent years due to i) the simpler processing techniques required to manufacture basic products, thus enabling small companies to take more of the market share and ii) the unplanned evolvement of the factory which in certain respects exhibits characteristicsof Nineteenth Century manufacturing industry. However, a change in attitudes and conditions is now taking place brought about by new senior management and a substantial capital investment programme, over £2 m in 1978.

Metalastik components have been manufactured from 1937 onwards when the company began to develop the technique of bonding rubber to metal. In the early years specialisation was in components for the motor industry, specifically Chrysler torsional vibration dampers and engine mountings. Subsequently further products were developed to combat the effects of noise, vibration and wear in many branches of engineering.

The company is now seeking to diversify from reliance upon the automotive industry and is developing in markets both home and overseas in the rail and marine industries.

CHAPTER THREE

METALASTIK PROCESSES

This chapter describes the factory, its layout and operations. All processes involved in producing bushes are reviewed.

The final part of the chapter describes alternative processes, i.e. those not used at Metalastik, which may be employed in manufacturing concentric bushes.

3.1 The General Factory Environment

A factory has been on the site for over 57 years. Originally the main products were rubber vehicle tyres but in the late thirties rubber-to-metal bonded goods were introduced and from 1958 work has been wholly concerned with Metalastik products. Although based still on rubber technology the main purposes of the factory has dramatically changed from that intended in its conception which has resulted in compromises in layout, machines and services.

Since the change to Metalastik processes a slow evolution has taken place, dictated by immediate needs rather than rational forecasting and planning. Major changes, for instance from brass plating to polymeric adhesives, have also caused further compromises to be made.

Typical of much British industry, there exists an atmosphere of muddling through the day, or week, with old equipment written off years ago, doing a different job from that originally intended. Meanwhile savings are sought wherever possible to cut production costs of products sold in very competitive markets.

3.2 The Factory Layout

A large corridor runs the length of the main factory building and opening off this are areas, each dealing with a specific process or groups of similar processes. This process layout configuration is suitable for the large number of small batches of products.

However, certain products can be grouped into product families. Bushes form a group of similar products and the company is in the act of setting up a Group Technology (G.T.) cell[3] whereby the operations required to manufacture bushes are brought together in one area,or cell, within the factory. The cell will be incorporated into a 5 year plan for reorganising the whole shop-floor layout due for completion by 1983.

3.3 Metalastik Processes

This section describes the various operations carried out at Metalastik. The flow of materials through the factory can be represented by a flow diagram (see Figure 3.1).

3.3.1 Raw Material Preparation

The raw rubber, normally a natural grade (Standard Malaysian Rubber Grade 5), is received in 50 kg bales. Other rubbers are used for special jobs although not usually for bushes.

Carbon black, the main filler, is now handled in large bulk containers which form part of the automatic handling and weighing plant.

Other raw materials which are incorporated into the rubber compound include oils, anti-oxidants, curing agents and solvents.

In the factory 'Drug room' the compounding ingredients are weighed and mixed according to the recipe for a specific rubber compound. These ingredients are then added to the raw rubber (or base polymer) in the Banbury Mills[4] and the rubber is compounded or mixed.

Compounding the rubber incorporates the ingredients and ancillary substances ready for vulcanisation while the fillers are mixed in to increase the bulk, to impart a uniform strength to the compound and to modify the rubber hardness or modulus.

The table in figure 3.2 lists the composition of three typical compounds.

The unvulcanised rubber is rolled into long sheets approximately 1 cm thick and 60 cm wide. These sheets are stored up to 6 months before vulcanisation.

3.3.2 Metal Preparation

Mild steel is employed almost exclusively as the metal component for concentric bushes. Several grades of steel are used, the choice depending upon the customers specification and quality of the part. Some metal parts are bought preformed, but for high volume bushes metal tubing is bought. These tubes are cut and the pieces finished on site resulting in lower raw material costs and a simplified stock control system.

Whatever method of bonding is employed it is necessary to ensure that the metals to be bonded are free from oil, grease, scale and other contaminants[5].

Oil and grease are removed with an organic solvent (trichlorethylene) or with hot aqueous alkali mixtures containing wetting agents.

Removal of metal oxides and scale is achieved by either mechanical treatments, normally grit blasting with chilled iron grit or by dipping in hot dilute acid followed by water rinses and chromic acid passivation.

In practice the solvent degrease is used in conjunction with the mechanical cleaning and the alkaline degrease with the acid pickling and chromic passivation. The latter combination is incorporated into the main automatic metal preparation plant ('C Plant').

The metal having been cleaned free of contaminants, the next stage concerns the application of the bonding agents which are applied soon after the metal is cleaned, usually within 6 hours, to avoid further contamination. Adhesives used in the factory are complex proprietary mixtures of an undisclosed composition as are most commercially available adhesives. They are designed for specific uses, in this case bonding natural rubber compounds to mild steel. These materials are normally received, dispersed in an organic solvent, in 200 litre drums.

One to three coats are applied, according to the bonding system used.

The preferred methods of bonding agent application are i) by spraying a diluted mixture onto the metal or ii) by dipping the metals in vats of diluted mixtures. The dipping process forms the second stage of the automatic metal preparation plant. The method chosen depends upon the metal shape, batch size and type of metal cleaning process used. Each coat of bonding agent is dried before the next is applied and sometimes the metals are pre-heated to speed up the drying operation.

The adhesive film is non-tacky and coated metals are stored for several weeks in bins,covered to prevent contamination,prior to moulding.

3.3.3 Moulding

The moulding of rubber to metal bonded parts introduces complications over and above those experienced in the manufacture of all rubber items.

Basically the operation consists of bringing the prepared metal together with the rubber compound and enclosing both in a prewarmed mould. When the mould is closed further heat and pressure is applied to both vulcanise the rubber compound and to cure the rubber-to-metal bond. This is achieved by placing the mould in a hydraulic press which is heated to about 160°C.

The moulds, which are designed to accommodate the rubber and metals correctly while allowing the moulded part to be released, are made to a close tolerance. Out of necessity for large scale production multi-cavity moulds are often used and each mould needs to be completely dismantled to load the metals and to remove the finished parts.

Several types of mould are used, they fall into three categories:-

a) Compression Moulds.

Here the rubber blank is placed in direct contact with the metal surface, the mould is then closed and pressure applied. The rubber softens and spreads through the mould to take the shape of the cavity. The rubber hardens during the curing process and after the required time has passed the mould is opened and the part prised out.

In common use with bushes is a variation of this process whereby the part is prefilled with softened rubber under pressure by use of a bush filling machine and then further heat and pressure is applied in the usual way.

b) Transfer Moulds

This is the commonest type of mould used at Dunlop(PED) and differs from a compression mould in that the rubber is placed in a separate chamber under a piston as shown in Figure 3.3.

On closing the press the rubber is 'liquified' and transferred through holes into the cavities where curing and bonding takes place.

Advantages of this process include i) presentation of a fresh rubber face to the bonding agent surface and ii) the need for only one rubber blank in a multi-cavity mould.

c) Injection Moulds

Injection moulds form an integral part of the presses around them. Rubber is fed through a screw-thread or ram injector, which in turn 'injects' the 'liquified' rubber into the mould under high pressure. Injection moulding machines can easily be automated and operate at a faster throughput and are better controlled than conventional moulds and presses.

Several moulding areas exist on the shopfloor, each with a particular make of machine or type of operation. They are:-

i) Conventional or Standard - These are transfer or compression moulds in conventional presses.

ii) Off Press Curing (O.P.C.) - Are large moulds initially in standard presses then placed in ovens.

iii) Rep - Automated injection machines.

(iv) Meterjet - Semi-automated injection machines.

v) Hydramoulds - Semi-automated compression moulding machines requiring prefilled parts.

The standard presses and moulds are being replaced gradually by the newer concept of the moulding machine, e.g. Rep and Hydramould.

By keeping the press platens, mould and part at a specified temperature and adjusting the cure time according to the rubber cure rate and mass of the part, the optimum vulcanisation properties are achieved.

3.3.4 Post-Moulding Operations

Parts removed from the mould are covered in excess rubber, termed flash, which is caused by mould leakage, transfer holes and channels linking parts in multicavity moulds. Flash is removed with hand trimming, buffing with wire brushes and in certain cases cryongenic tumbling with solid carbon dioxide.

Testing follows set procedures and batches of parts are only 100% tested if a sample has had more than the allowed number of failures. Bushes are tested for dimensional errors, rubber stiffness, bond failure and general finish. Bond failures are detected by simple visual inspection while the part is stressed under a specified load.

Some products, including bushes, require manipulation of the metal for as the rubber shrinks it experiences a tensile stress whereas in service it is beneficial for the rubber to be in compression. In the case of some bushes the metals are dimensionally adjusted by expanding the inner metal or contracting the outer metal by cold drawing or hammering respectively.

Depending on customer requirements various finishes are applied. These range from temporary protective oil finishes to phosphating and painting or, for critical applications, zinc plating.

3.4 Variation in existing processes

In an on-going organisation deviations from the norm, however minor, are always happening. So the processes described above may in practice consist of several variations, according to the number, size and shape of parts in each batch.

There are preferred routes through the factory but often these are impossible as other factors such as machine loading, breakdowns and operator availability dictate the most efficient and economical path.

Continual up-dating of processes to meet the increasing demands for better productivity and to satisfy ever more stringent customer requirements mean that specification changes occur frequently.

3.5 Alternative Processes

Although most other manufacturers use the same general operations as Metalastik, certain major alternatives exist.

Three such alternatives which have a direct bearing on this research are detailed below.

a) Post-Cure Bonding

In conventional bonding the rubber is vulcanised and the rubber to metal bond is formed at the same time. With post-cure bonding the rubber is moulded and vulcanised separately then attached to the prepared metal and the bond is then cured by further heating.

For bushes, the rubber section is made larger than the space between the two metal tubes and, when forced in, is precompressed ensuring a good bond and optimum 'in service' properties.

This method has been widely adopted in the U.S.A. and has several advantages including the elimination of shrinkage stresses.

b) Direct Bonding

Direct bonding is the same as conventional bonding except that no bonding intermediary is employed. Instead adhesion promoters are incorporated into the rubber compound, which will bond directly to the metal surface.

As one process is eliminated and no bonding agents are used substantial cost reductions are possible. However, as these modified rubber compounds can bond indiscriminately to other metal surfaces, mould fouling is a problem.

c) Cold Bonding

The rubber section is moulded and vulcanised. Then both rubber and metal surfaces are roughened and a contact adhesive is applied. The part is assembled and clamped together. No heating is required at this stage as anaerobic adhesives of the cyanacrolyate type are used.

This method is suited best to producing low volume, complex parts which are really hand built.

CHAPTER FOUR

THE BOND FAILURE PROBLEM

Sections 4.1 and 4.2 describe the bush bond failure problem and indicate how it occurred, while sections 4.3 and 4.4 review how the research project was structured by showing the major areas of investigation and how they are interlinked.

4.1 The background to the problem

Prior to the introduction of polymeric adhesives, the major method of bonding rubber to metals was based on brass plating where a chemical bond is developed between the sulphur in the rubber and the copper in the intermediate brass layer.

At Dunlop (PED) Ltd the brass plating technique was superceded by the use of bonding agents during the 1960's and was completely phased out by 1965.

Bonding agents were introduced for the following reasons:-

a) a simpler and cheaper plant was feasible which required less operator skill.

b) an overall cost reduction was possible.

c) operations were more flexible.

Several proprietary bonding agents were originally introduced, although one system (Chemlok 205/Chemlok 220) predominated and soon became the accepted standard.

For several years the new bonding technique gave acceptable bond failure levels and associated low scrap costs. However, during 1972 high bond failure scrap rates were noticed on certain products[6]. Due to the complex operations and tremendous variability of parts, batch sizes and processes, the causes of the problem were not identified until late in 1974. An internal report[7] summed up the findings of a preliminary technical investigation and concluded that the failures were caused by the inability of the bond to resist thermal shrinkage stresses. By this time failures were isolated to bushes and closely related products (e.g. shackle pins). The type and manner of bond failure in these products is specific to their shape configuration.

Through the normal media of reports, memos and meetings, management discussed the alternative solutions open to them and, because of the urgency to return to 'normal' conditions (underlined by catastrophic failures on products for an important overseas customer) a stop-gap measure was introduced. This entailed altering the specification on some products to provide for a third coat of adhesive, applied over the standard Chemlok 205/Chemlok 220 two coat system. In some cases the Chemlok 220 was substituted with Chemosil X 2311, a more reactive bonding agent. Scrap levels decreased dramatically although they never reached a wholly satisfactory level.

Nevertheless the change had the effect of diminishing the urgency so efforts to fully solve the problem, to quantify it and to investigate the root causes were allowed to subside.

Except for a few minor changes, this situation has remained ever since with bond failure rates for bushes always being higher than the average for the factory,but now only very occasionally exhibiting the catastrophic failure levels of earlier years.

A shop-floor working party studied the causes and magnitude of general reject levels in the factory for the period 1/1/77 - 30/6/77. Their report[8] demonstrated that concentric bushes still accounted for over half the total bond failures, even though by then a 3 coat bonding system was specified for most products.

Among their conclusions they listed; better quality control procedures, better adhesives and improved operator training and supervision as ways in which general scrap costs may be reduced. It was generally thought that an in-depth study was needed to resolve the real causes of bond failure, to quantify all the major factors involved and to predict the behaviour of materials and processes. Moreover with increasing product liability legislation it was crucial that the probability of failed parts reaching the customer remained low.

In response to the above needs the research project reported here was instigated.

4.1.1 The extent of Bush Bond Failures

The extent of the problem is evident from the factory scrap information, and bond failure levels experienced since the problem was first recognised fall into 3 phases:-

a) Very early on, catastrophic failures (50+% by volume) were common on many products.

b) On application of emergency preventative measures in 1977 the scrap rates were reduced and most catastrophic failures brought under control. The overall effect was a halving of total bush failure levels from 12% to 6% (although at this time the level for all Metalastik products was 2.7%).

c) By 1979 the bond failure levels for bushes were increasing, due mainly to a poor performance in producing a few high volume products.

Appendix No. 2 shows the situation in 1979 prior to the corrective action being taken as part of this research project.

4.2 The Underlying Causes of Bush Bond Failure

Buchan[9] has shown that the bond strength of a brass to rubber bond decreases when its temperature is raised. At 150°C a typical bond strength of 4.000 MN/m² is achieved. As this is greater than the hot tear strength of the rubber compound (2.750 MN/m² at 150°C) an applied stress would first cause rupture of the rubber rather than bond interface failure.

In contrast to the above, the rubber to metal bond obtained using bonding agents is apparently more thermoplastic and for most bonding agents at elevated temperatures the bond is weaker than the rubber compound. For instance, experiment has shown that the bond strength of Chemlok 205/Chemlok 220, the system in use when the bush bonding problem was first noticed, is approximately 1.950 MN/m² at 150°C.

Salomon and Schonlau[10] have determined the temperature sensitivity of bonds formed by a number of processes and also conclude that polymeric adhesive bonds are generally more thermoplastic in nature than bonds formed by the brass plating method.

Therefore even though rubber/metal bonds greater than the rubber strength can be achieved at room temperature the hot bond is much weaker when using some bonding agents and under certain conditions the bond will fail.

When a bush is removed from the mould it is set aside to cool. The drop in temperature, normally 130°C, results in the rubber shrinking by about 5% by volume (about 20 times the metal shrinkage). A problem normally associated with rubber shrinkage is that parts must be moulded to dimensions about 2½% greater than required in the finished part specification. Unfortunately some products, including concentric bushes, cannot dimensionally shrink as the metals are unable to move in relation to each other. Thus the tubular cross-section of a bush hinders free movement and a stress is developed in a normal direction to the bond interface due to the differential shrinkage of rubber and metal.

The combination of a high shrinkage stress and low hot bond strength is enough to initiate parting of the rubber and metal at the bond.

Marsh[6] reports that a distinct pattern of failure is evident at the bonding agent/rubber interface which is typical of this problem. He describes this as, characterised by a leafy pattern of minute bonded fragments of rubber adhering to substantially unbonded areas, with a small nucleus often occurring in the centre of each area where failure is at the metal/bonding agent face.

This effect he termed 'foliation', a name generally used by the company to describe the failure. Other manufacturers have noticed the same effect but refer to it by other terms such as 'starburst' failure.

Shrinkage stress failure is most noticeable in long bushes where the rubber section is relatively thin. Ultra-Duty and other high stiffness bushes fall into this category. The sub-standard bond is normally revealed at the testing stage by either simple visual examination where the metals are eccentric rather than concentric combined with bulging rubber at the bush ends; or if the failure is internal and not large, by showing high deflection for a constant radial load. This load/deformation test is applied to bushes on a statistical basis with only reject batches receiving 100% testing.

The high scrap levels associated with the bush bond failure problem are over and above the base scrap levels experienced by all products at Dunlop (PED). The other problems result in a base scrap level of around 1% and are solely derived from incorrect specifications of materials and processes or poor shop-floor control.

4.2.1 Literature References - Bond Failure in Bushes

Shrinkage of the rubber in bushes has been a concern of rubber-to-metal manufacturers, not only in terms of bond failure but because the in-service properties are inferior when the rubber is in tension, as happens when a bush cools. Freakley and Payne[11] mention that shrinkage stresses can be relieved by using an outer metal consisting of 2 segments which are free to move together as the part shrinks. Mernagh[12] also mentions the problem and suggests slitting the metals or the use of post-cure bonding.

The British Rubber Manufacturers Association in an investigation on general bonding difficulties considered the bush failure question, and attributed high failure rates to shrinkage stresses. Their report[13] also highlighted the general factory inadequacies rather than technical modifications and innovations.

With the exception of these brief reviews of the bush bonding situation there is little recognition in the literature to the subject. However, the problem of differential shrinkage in composites is a subject of much scientific literature, e.g. the problem of shrinkage stresses in a nylon heat shield bonded to a cylindrical aluminium case[14] could be allied to bush shrinkage.

4.3 The Original Research Objectives

Ever since the problem arose explanations and solutions have been tendered, many of which are of a subjective nature. Factors influencing the bond behaviour were supposedly identified and although some improvements helped they were mainly arrived at through trial and error methods.

Therefore the main purpose of the experimental work described in this thesis has been to positively identify and quantify the parameters involved.

A bond fails because the applied stress is sufficient to separate the bond and/or the inherent bond strength is inadequate. It is necessary to examine separately these two main areas which influence bond failure.

4.3.1 Shrinkage Stress

This area is primary dependent on the relative shrinkage of rubber to metal, the bush profile and the change in temperature of the component on cooling. Although rubber shrinkage has been quantified and well documented for reasons of mould design, no information existed on the amount of shrinkage stresses in bushes.

Three methods, two theoretical and one experimental, are employed in this research leading to a classification of concentric bushes in order of magnitude of bond stress. A means of measuring shrinkage stresses utilising a suitable test-piece formed the basis of the experimental work.

4.3.2 Hot Bond Strength

The bond failure problem revolves around the strength of the bond at relatively high temperatures.

Behaviour of the bond at ambient or in service temperatures is well known; in contrast little scientific information has been divulged on the hot bond strength.

Therefore a test designed to measure the bond strength of a rubber/metal bond immediately after moulding has been developed especially to study the situation as a part slowly cools. This is also different from other high temperature tests whereby the bond is reheated from room temperature before testing its strength.

With the test it has been possible to monitor the increase in bond strength as a newly formed bond experiences a temperature change and to demonstrate how materials and processes effect the result.

Figure 4.1 encompasses all the identified parameters of bush bond failure indicating where interdependence occurs and where measurement is possible.

4.4 Modifications of and additions to the original research

The two aspects described above both depend, to some degree, on change in temperature. Unfortunately shrinkage stress increases in proportion to the change in the average temperature of the rubber section while bond strength depends on the bond temperature.

Thus to equate stress with bond strength one must either assume that the part cools uniformly or must determine the respective temperatures of the bond and the rubber section throughout the cooling process. The original research programme was based on the uniformity of temperature assumption but it became clear that a knowledge of heat distribution in the part is required.

The heat transfer characteristics of bushes are examined to give general guidelines for estimation of temperature throughout these parts, serving as a link between shrinkage stress and bond strength.

Although most experimental work contained in this thesis has been carried out under laboratory conditions the results should mirror the 'real-life' production environment situation. Research early on in the project indicated that a difference existed between ideal and real bond failure levels. Therefore a study of shop-floor conditions was necessary to explain these differences and to act as a link between the experimental work and actual bush productions. This study included a review of general and specific problems, an in-depth analysis of bond failure data and a confirmation of some laboratory experiments.

Finally,part of the project has been to investigate the suitability of bonding agents for bonding bushes with the most promising bonding agent being then evaluated under full production conditions.

CHAPTER FIVE

SHRINKAGE STRESSES IN CONCENTRIC BUSHES

5.1 Introduction

The bond failure problem in concentric bushes has long been associated with internal stresses developed when the part cools from moulding temperatures. It is generally appreciated that these stresses are due to the differential thermal contraction of rubber and metal.

The main object of the research described in this chapter is to identify and quantify shrinkage stresses in most of the concentric bushes manufactured by the company. Two aspects are involved

i) the thermal contraction/expansion properties of rubber and metal,

and ii) the subsequent rubber strain and stress on the bond.

Although rubber shrinkage and stress/strain properties have been studied by other researchers[15,16,17] no previous work has been carried out whereby these two aspects are linked together.

The theoretical backgrounds of the above aspects are reviewed,followed by a study utilising three techniques of the stresses involved.

5.2 Thermal Contraction

5.2.1 Rubber

The linear coefficient of thermal contraction of a pure gum rubber is about 0.0002 $^{o}C^{-1}$. Even with the addition of a considerable amount of filler, e.g. carbon black, the value drops only to about 0.0001$^{o}C^{-1}$ which is still much higher than for metallic materials.

The high coefficient of expansion is an affect of rubber's unusual molecular structure. Unlike most materials where the molecules are closely packed in a rigid form and inter-atomic forces predominate, rubber is composed of large chain molecules loosely entwined in a disordered state (i.e. highly entropic). These chains become more ordered as the substance cools and eventually takes on a crystalline structure at around -70°C.

As well as the molecular structure of the rubber base polymer, thermal contraction of a rubber compound is influenced by the amount and type of other ingredients in particular the carbon black. Figure 5.1 shows the effect of increasing carbon black levels on the shrinkage coefficient (see section 5.4.2).

5.2.2 Mild Steel

A typical value of the thermal contraction coefficient for mild steel is $0.00001\,^{\circ}C^{-1}$, which is approximately 10-20 x smaller than for a rubber vulcanisate.

For a metal tube the change in diameter is mainly dependent on the thermal contraction in the circumferential direction and therefore would be pi(π) times smaller than the linear contraction coefficient of the material. For thick walled metals the tube wall radial contraction would be significant. Nevertheless in view of the disparity between the thermal contraction of steel and rubber, the change in the bush metal dimensions will be ignored in the subsequent evaluation of shrinkage stresses.

5.3 The Stress/Strain Relationships of Rubber

5.3.1 Rubber Physical Properties

a) The Young's Modulus (Eo), i.e. the relationship between lengthwise stress and strain for an unrestricted material, is difficult to measure for rubber due to non-linear and shape effects, and most practical research is based on shear modulus measurements.

b) The Shear Modulus (G) is the ratio of the shear stress over the shear strain where the strain is the ratio of linear deformation to the thickness of rubber and the shear stress is the load in the XY direction divided by the area on which it applies. The relationship between Eo and G theoretically should be Eo = 3G (given a Poissons ratio value of 0.5). However for rubbers containing a large amount of non-rubber constituents Eo increases to 4G.

c) For rubber, the hardness is essentially a measurement of the reversible, elastic deformation produced by a specially shaped indentor under a specified load. Results obtained by this apparatus are expressed in International Rubber Hardness Degrees (I.R.H.D.). These units are directly related to the Young's Modulus so are generally used to characterise the stress/strain behaviour of vulcanised rubber. Lindley[18] gives a table comparing hardness with various rubber properties including the Young's Modulus. The table is reproduced in Figure 5.2.

d) The Poissons ratio (ρ) is defined for simple uniaxial extension or compression as the ratio of lateral contraction or expansion (i.e. the fractional change in cross-sectional dimensions) to longitudinal extension or compression (i.e. the fractional change in length). The bulk modulus of rubber is high and therefore Poissons ratio is theoretically close to 0.5 as no change in volume is possible. In fact for filled rubber compounds Poissons ratio lies in the range of 0.4993 to 0.4997[19] and these values hold for most applications.

5.3.2 Rubber Elasticity

The elastic behaviour of rubber differs fundamentally from that of metals, in that deformation of rubber does not involve any straining of inter-atomic bonds and hence the forces required are much less.

Three theories of elasticity are outlined below:-

a) The Statistical (or Kinetic) Theory

A molecular explanation for the behaviour of rubber is given in the Statistical Theory based on a statistical treatment of the probable end-to-end distance of a single molecule. The original work by Treloar[20] derived expressions for bulk rubber properties using the behaviour of molecular chains together with the effect of entropy changes on the retractive forces of deformed rubber. He developed the following equation and attempted to predict the shape of the stress/strain curve for rubber in either elongation or compression.

$$f = G(\lambda - \lambda^{-2})$$

where f = stress

G = shear modulus

λ = ratio of strained to unstrained length.

Figure 5.3 shows the curve predicted by this equation.

It must be noted that the compression part of the curve assumes unconstrained rubber surfaces such that a rubber block would take the same shape on deformation.

b) The Phenomenological Theory

In parallel with the development of the Statistical Theory there has arisen a formal mathematical theory, based on more general concepts of bulk elasticity, which provides a mathematical framework for the treatment of all materials that are capable of large elastic deformation.

Work along the above lines was first pursued by Mooney[21] and enlarged by Rivlin[22].

The Phenomenological theory has hitherto found little application in the analysis of rubber elasticity and in engineering design, owing to the reasonable agreement of the more simple Statistical theory with experimental results. However, since the introduction of computers to handle the large number of complex calculations required, the Phenomenological theory has seen more use in practical applications.

NB. At present Mooney/Rivlin equations can only be applied to 2 Dimensional analyses.

c) The Classical Theory

The above two theories are employed to explain the large strain behaviour of rubber, i.e. where Treloar's curve deviates from linearity. In contrast the Classical Hooke's Law theory may only be accurately applied to 'low' strains (less than 10%), and then the rubber elasticity is simply defined by Young's Modulus, (as Hooke's law is a relation between stresses and strains given by

$$e = \frac{1}{E_o} f \quad ; e = \text{strain} \qquad)$$

The Finite Element technique and the Empirical Calculation (both described later in this chapter) are based on the Classical theory as the strains involved are small(e.g. 4%)and unpublished work at Dunlop (PED) has demonstrated that for high stiffness bonded units the elasticity characteristic lies somewhere between those characteristics of the two components, namely rubber and metal.

5.3.3 The Shape Factor

The theories of elasticity derive expressions for load/ deformation of unconstrained rubber units which retain their general shape during compression or elongation.

Unfortunately when rubber is bonded to metal, constraints are introduced which alter the stress/strain properties making it necessary to take into account the ratio of the bonded rubber area under load to the free rubber area. This ratio is referred to as the shape factor (S).

For rubber blocks bonded on 2 sides, e.g. 'Sandwich' mountings

$$S = \frac{\text{Bonded Area}}{2 \times \text{Free Area}} \text{ or } \frac{dw}{2t(d+w)}$$

as shown in Figure 5.4.

A bush rubber section can be considered for some approximation purposes, as an infinitely long rubber block, thus

$$d \longrightarrow \infty \quad \text{and } S = \frac{w}{2t}$$

where w = bush rubber length

t = rubber thickness

Other equations can be derived for other shapes of unit.

5.4 Shrinkage Stress Identification and Quantification

5.4.1 The Finite Element Method (F.E.M.)

The objective of the finite element method is to make a complete analysis of shrinkage stresses and associated strains, etc. thus providing a picture of the forces acting on the rubber-to-metal bond as the bush cools.

Although this technique is based on classical thermal contraction and elasticity theories they are not applied to the rubber section as a whole. Instead this method embodies the concept of representing the physical structure by a model consisting of a finite number of idealized elements that are interconnected at a finite number of points or nodes. Known loads are applied to this model, a system of equations is solved and the desired results (e.g. stresses at each node) are obtained. The behaviour of the model closely approximates the behaviour of the real structure, becoming closer as the number of elements utilised increases.

Details of the theoretical considerations of Finite element analysis appear in Appendix No. 3.1.

A computer is used to perform the series of complex mathematical reiterations involved in the analysis. Considerable experience has been gained in use of computer aided finite element analysis at Dunlop (PED)[23].

5.4.1.1 Procedure

The S.U.P.E.R.b. finite element program, owned by the Structural Dynamics Research Corporation (S.D.R.C.) Cincinnati, Ohio, USA, was used for this research. SUPERb forms the nucleus of a package of programs available to the design or structural engineer on a time-sharing basis. In the U.K. these programs are accessed through the G.E.I.S.C.O. (General Electric Information Services Co.) time-sharing system, using an I.C.L. 7075 termiprinter at Dunlop (PED).

The method of performing the analysis is briefly outlined below. For information on actual data inputs, etc., see Appendix No. 3.2.

i) As the cross-section of a bush is symmetrical about the X-axis and can be rotated about the Y-axis, as demonstrated in Figure 5.5, for the purposes of this analysis the area 'A' need only be considered. The area 'A' is divided into a grid containing a number of axisymmetric-ring elements each bounded at the corners and mid point of each side by a node.

ii) The X,Y coordinates of each node forms the main data input to enable the computer to draw up a 2-dimensional matrix with 3rd dimension achieved by theoretically rotating the element grid through 360° about the Y axis. Elements and nodes are readily identified by a numbering system. The metal/rubber boundary is fixed, ignoring any metal shrinkage (as mentioned in 5.2.2) and therefore nodes lying on the bond interface are constrained as are the nodes along the X axis centre of symmetry. The former in both X and Y directions and the later only in the Y direction.

iii) When the structural model is defined the next stage is to specify the material properties,e.g. Youngs Modulus,and also to state the temperature change which the rubber section will experience.

iv) The final set of input data are required to act as program commands which will specify the program options required in terms of analysis type, output type and time-sharing priority.

The above data need only be input in the right order and appropriately spaced as a pre-program (SUPER) will format the data and create the 'formatted job file' which can be checked before submitting to the main finite element program. After the main program is run results are saved on files which may be accessed at a later date or used as the data for post-plotting routines.

The results include:-

a) Nodal displacements - nodal movement in relation to the axis

b) Strains - at each node in all directions

c) Stresses - at each node in X, Y and XY (shear) directions

d) Forces - at each node

e) Von Mises stress factor - at each node.

It is convenient to plot the results on the diagramatic representation of a bush (section 'A').

5.4.1.2 The Choice of Parts for Analysis

A problem arose due to the large number of bush products available for analysis which made it difficult to choose a meaningful sample. This was further compounded by the high cost of each run on SUPERb and resulted in only 2 bushes being examined. These are actual production parts, not hypothetical bushes, as the results of the analyses can be matched with other aspects of this research.

The F.E.M. technique has also been used to study the stress/strain properties of the modified test-piece (see Section 5.4.3.1).

5.4.1.3 Results

i) Bush No. 13/1914

Rubber Hardness = 60 IRHD

Shape Factor = 6.25

Temperature Change = 130°C

The elemental grid, stresses, nodal displacements and Von Mises factors for the area'A' are shown in Figure 5.6.

More detailed results are given in Appendix No. 3.2.

Stress in the X direction (i.e. normal to the bond)

The average stress acting on the inner metal/rubber bond

= 8.792 MN/m^2

" " " " " the outer metal/rubber bond

= 9.040 MN/m^2

The maximum stress (occurring at node 7) excluding localised end stresses = 13.843 MN/m^2

The distribution of the normal(referred to as the shrinkage stress elsewhere in this thesis) stress along the bond interface is shown in Figure 5.7.

The end maxima are normally reduced by contouring the rubber ends of this bush.

ii) Bush No. 13/665

Rubber Hardness = 75 IRHD

Shape Factor = 3.97

Temperature change= 130°C

The elemental grid, nodal displacements, stresses and Von Mises stress factors are shown in Figure 5.8.

Again more detailed results are given in Appendix No. 3.2.

The stress in the X direction (i.e. normal to the bond)

Average stress acting on the inner metal/rubber bond
= 8.398 MN/m^2

" " " " the outer metal/rubber bond

= 8.130 MN/m^2

Maximum stress (occurring at node 3) (excluding localised end stresses)

$= 12.640 \text{ MN/m}^2$

The stress distribution curve is similar to 13/1914 shown in Figure 5.7.

iii) The modified Test-Piece (see section 5.4.3.1)

Rubber Hardness = 60 IRHD

Shape Factor = 2.11

Temperature Change = 130°C

For the model area, half the rubber cross section was deemed sufficient due to the symmetry of the test-piece (refer to Figure 5.14). The stresses and nodal displacements are shown for the half cross-section in figure 5.9.

NB. Both bonds experience the same stresses and only one was included in the model.

Average stress in Y direction = 2.246 MN/m^2

Maximum " " " " = 3.355 MN/m^2

5.4.2 The Empirical Method

The finite element method can be used to demonstrate the type, quantity and distribution of stresses on the rubber-to-metal bond, produced when a bush cools. However, the method is longwinded and expensive to operate. Therefore an alternative method is needed to assess shrinkage stress in a large number of products.

The empirical method meets this objective in that it provides a means of readily obtaining an estimate of the shrinkage stress in most bushes manufactured by Dunlop (PED), but at the expense of accuracy and resolution.

The average stress along the bond length (rather than the maximum stress) is found by these calculations and this is sufficient to classify bushes in shrinkage stress order. By use of a factor one can also employ the results to arrive at the probability of a bush exhibiting bond failure by comparing the maximum stress with the bond strength.

The calculations are based on the concept of the rubber shrinking freely, as if the metal could move radially, and then requiring a force (equivalent to the shrinkage force) to return it to its original dimensions. Of course in practice the steel remains relatively fixed throughout cooling.

Unfortunately the shrinkage of rubber in bonded products cannot be represented by simple application of the thermal expansion coefficient, due to the shape of these products and moulding interference such as rubber precompression and vulcanisation. Instead equations have been developed at Dunlop (PED) to determine the amount of shrinkage in parts that are bonded and can dimensionally change shape[24] e.g. sandwich mountings and buffers. These equations can be applied to bushes to evaluate the rubber contraction when assuming that the rubber section is an infinitely long rubber block (see section 5.3.3.). This block is free to move in the direction normal to the rubber/metal bond plane but is constricted by molecular bonds in the direction tangential to the bond.

Thorpe (ibid) claims that these formulae are based on the fundamental definition of coefficient of expansion but applied to an unchanging volume material and that they generally yield results close to the actual measured values. In fact the difference between experimental and theoretical values of dimensional change are smaller than the metal and mould tolerances.

Rubber flow during moulding, mould pressure, vulcanisation characteristics and the thermal conductivity of rubber are all taken into account by this approach and a value of unrestricted rubber shrinkage (shrinkage coefficient α) obtained by application of Thorpe's equation. The shrinkage value must then be combined with a knowledge of the restricted rubber area fraction, i.e. shape factor and a rubber profile correction factor (determined empirically).

Thorpe's equation of rubber shrinkage in bonded units is given below:

$$P = 100 \left[(1 + \alpha \Delta T) \left\{ 1 + \frac{(2 U S \alpha \Delta T)}{(1 + U S)} \right\} - 1 \right] \% \qquad (1)$$

Where P = % rubber shrinkage

α = coefficient of shrinkage, $^{\circ}C^{-1}$

ΔT = change in temperature, $^{\circ}C$

U = correction factor for rubber profile

S = bush shape factor.

U is effectively a constant (0.75).

The change in the rubber section thickness (Δt) is equal to $\frac{P \times t}{100}$

Treloars curve (see Figure No. 5.3) predicts that in the region of small compressive and tensile strains the stress/strain relationship is linear with the curve passing through zero. For convenience the bond stress is calculated using formulae derived for the study of uniaxial compression of rubber blocks even though in this context a rubber 'block' would be in tension.

Although the expressions, derived earlier in this chapter, describe the deformation of ideal units under simple loading conditions and provide the basis for the consideration of deformation characteristics in practical rubber units, they assume perfect lubrication of the load surfaces when under uniaxial compression. With bonded units this is not the case and the loaded area is normally restrained by the rubber/metal bond and on compression the free surface bulges outward while in tension the free surface takes a concave profile. At the free surface or edges of the rubber compressive stresses are combined with shear stresses and the shape factor must be incorporated into any equation to compensate for this combined stress affect.

Gent et al[25] has based a series of formulae, for determining the deformation of bonded blocks, on classical Hooke's Law theory.

Allen et al[26] describe these equations using the compression modulus in place of Youngs Modulus thus f = Ec x ec

Where Ec = compression modulus

ec = compressive strain

f = stress

The compression modulus relates to the Youngs modulus of the material and shape of the rubber - a block or strip

a) For a rubber block

$$Ec = Eo\ (1 + 2kS^2) \qquad -(2)$$

(where k = carbon black constant)

Thus the stress is given by

$$f = Eo(1 + 2kS^2) \times \left(\frac{\Delta t}{t}\right); \text{ as } ec = \frac{\Delta t}{t} \qquad -(3)$$

Although for most applications rubber may be considered incompressible in bulk, for applications involving a very high shape factor, the bulk compression modulus (E_∞) is significant and Ec is then derived as:

$$\frac{1}{Ec} = \frac{1}{Eo(1 + 2kS^2)} + \frac{1}{E_\infty} \qquad -(4)$$

Substituting in equation (3) we have

$$\frac{1}{f} = (Eo(1 + 2kS^2) + E_\infty)\left(\frac{t}{\Delta t}\right) \qquad -(5)$$

b) For rubber strips

(In this context the transfer of a block to a strip takes place at a ratio, length to breadth of about 3:1).

Here $$Ec = \frac{4\ Eo\ (1 + kS^2)}{3} \qquad -(6)$$

Therefore the shrinkage stress is given by:-

$$f = \frac{4\ Eo\ (1 + kS^2)\ \Delta t}{3\ t} \qquad -(7)$$

and if needed the bulk compression modulus can be incorporated thus:

$$\frac{1}{f} = \left(\frac{4\ Eo\ (1 + kS^2)}{3} + E_\infty\right)\left(\frac{t}{\Delta t}\right) \qquad -(8)$$

For the context of this shrinkage stress evaluation f is considered to be the direct stress acting in the normal direction to the bond.

The equation(3) is applicable to the modified test-piece while equation (7) applies to the bush situation, when the bush rubber is deemed to be an infinitely long strip. The bulk compression modulus has little influence for all but the highest shape factor parts and can be disregarded.

Therefore the average direct stress (shrinkage stress) in bushes is determined by

$$fx = \frac{4 \times Eo \times \Delta t \times (1 + kS^2)}{3 \times t}$$

fx is equivalent to the product of the average stress along each bond, divided by 2. In practice the inner bond stress is marginally higher than for the outer bond due to the smaller inner metal/rubber interfacial area.

5.4.2.1 The influence of Rubber Hardness, Shape Factor and Temperature Change on the Shrinkage Stress

The empirical calculation may be used to evaluate the influence of the main factors which effect the shrinkage stress.

The shape factor(S) has the major weighting, with the bond stress rising dramatically as this factor increases as demonstrated in Figure 5.10.

The hardness indirectly influences the shrinkage stress through the Youngs modulus value, the coefficient of shrinkage and the carbon black correction factor. For a series of rubber compounds with hardness ranging from 45 IRHD to 75 IRHD the variation in bond stress is plotted in Figure 5.11 where an increase in hardness develops greater stress.

Finally the effect of temperature change is noted in Figure 5.12 which shows that shrinkage stress is directly proportional to a change in temperature (ΔT) with the line obviously passing through the origin.

5.4.2.2 Application of the calculation to Metalastik bushes

The main objective of this method lies in the examination of bushes manufactured by the company. The bush-like products on current specification files number about 1,700. However, only 525 of these bushes come within the bounds of this research, i.e. concentric bushes. (It is difficult to draw the line between these 525 bushes and some of the others). Nevertheless the number is still too large for manual calculation and a computer program has been developed to handle the exercise.

The program, BUSHSTR, carries out a number of functions, including the application of equations 1 and 7 on the 525 bushes and is written in advanced BASIC on a Hewlett-Packard 9845 B computer. Details of the program and a table of results appear in Appendix No. 3.3.

The results show a wide range of shrinkage stresses from 0.146 MN/m^2 (for 13/1895) to 29.165 MN/m^2 (for 13/2004 Dual). A histogram showing the distribution of stress values among the 525 bushes is given in figure 5.13.

Most bushes lie within the 0.0 MN/m^2 to 2.75 MN/m^2 range.

NB. The above values refer to the shrinkage stress for 130°C temperature change.

5.4.3 The Experimental Method

The experimental method acts as a confirmation of the results obtained using the two theoretical techniques and is not designed for directly determining shrinkage stress values in bushes.

To evaluate practically stresses in a bush would need a complex test arrangement and require expensive equipment. Then the problem would also arise of 'what is a representative or typical bush' as only a limited sample of the 525 Metalastik bushes could be studied.

In the light of these points a bobbin-like test-piece has been developed with the following advantages:-

i) The stress distribution is not as complex as for a bush and can easier be equated to direct forces or loads.

ii) An existing mould can be utilised thus saving the cost of an expensive capital item.

iii) The general principles were already developed and tried, needing only modification and therefore saving limited resources of time and money.

5.4.3.1 The Shrinkage Stress Test-Piece

The test-piece and associated equipment is basically a development of the Dunlop bond test bobbin which measures bond failure in a similar manner to the ASTM direct pull test D429-56T Method A.

The significant difference between the old Dunlop test and the new shrinkage test-piece is that the former had no direct measurement of the force involved while the latter incorporates a load cell measuring device. The cross-section of the new test-piece is drawn in figure 5.14.

The modification consists mainly of introducing the load cell (in the form of a threaded stud) and redesigning the metal discs to take both the load cell and the larger cap-head bolt. The metal discs are of mild steel while the cap-head bolt is hardened steel.

The load-cell, manufactured by the Strainsert Company, Bryn Mawr, Pennsylvannia, U.S.A., was obtained from A.J.B. Associates Ltd., 54 High Street, Wells, Somerset, and is part of their range of internally gauged studs. The part consists of a hollow bolt containing a number of strain gauges and has been altered for this particular application by removing one threaded end.

During moulding the test-piece arrangement is such that the cap-head bolt and load cell ends are just touching. When the part is removed from the mould the rubber tries to shrink thus drawing the metal discs together but is prevented from doing so by the bolt abutting onto the load cell. This results in a force on the load cell which combined with a knowledge of the bond area enables the tensile bond stress to be measured. When the bolt is unscrewed, after the part has cooled, the change in the load reading can also be related to the bond stress. In practice the results are based on this second observation.

Appendix No. 3.4 gives more details of the test-piece and associated equipment.

By changing the shape factor, rubber hardness and temperature range while noting the bond stress for each situation the theoretical calculations may be verified.

NB The shape factor of the test-piece is found by

$$S = \frac{R-r}{2t}$$

where R = radius of metal disc

r = radius of hole

t = rubber thickness

The finite element analysis of this test-piece is described in section 5.4.1.3.

5.4.3.2 Procedure

A description of the experimental procedure is given below.

i) The metals are cleaned and the bonding area coated with adhesive e.g. a 3 coat system,Chemlok 205/Chemlok 220/Thixon AP1559. A cap-head bolt is inserted into metal A, the load cell into metal B and the connections completed with the Wheatstone bridge, amplifier and digital readout module. A suitable rubber blank is prepared.

Plate 2 shows the test-piece metals inserted into the mould which is then assembled and placed into the press.

ii) Prior to the press closing the cap-head bolt is tightened until a force is registered on the readout indicating that bolt and load cell are in contact. Moulding is performed in the conventional manner using the two cavity transfer mould (the spare cavity contains a dummy test-piece). During this operation some load/force fluctuations are noticed due to mould movement and rubber pressure on the load cell, however these can be ignored in the stress determination.

iii) Immediately on removal from the mould the test-piece load reading is recorded (reading 1) and the part then allowed to cool. The temperature difference between the moulding and room temperatures is measured by placing a thermocouple through a hole in the cap-head bolt. After cooling the force reading is noted (reading 2) and theoretically should represent the maximum compressive force on the load cell due to the rubber shrinkage. When the cap-head bolt is unscrewed a further reading (reading 3) is taken which gives the no shrinkage stress situation.

The bond stress can be found by taking either the difference between readings 1 and 2 or between readings 2 and 3 (the latter being the most accurate as reading 1 is recorded during a period of rapidly changing temperature conditions) and dividing the value by the area of one bond interface.

5.4.3.3 Results

To corroborate the results obtained theoretically a number of variables e.g. shape and rubber hardness were altered and bond stress measurements taken. However the variables were first held constant for a number of separate determinations and the reproducibility of the technique checked. The average stress value for these conditions was 0.893 MN/m² with a variance of 0.0137 MN/m².

The evaluation of these variables is summarised below and the results appear in Appendix No. 3.5.

a) Shape Factor

The test-piece shape factor in normal operation is 2.0. To achieve a higher shape factor value a metal ring was placed behind one of the metal discs during moulding thus decreasing the rubber thickness.

b) Rubber Hardness

Compounds of 3 different rubber hardnesses were employed for the comparison. The compound curing system remained unchanged.

c) Temperature Change

By recording the load cell values as the test-piece was cooling the effect of temperature change (ΔT) was monitored but due to the rapidly change temperature situation and distribution of heat in the part the results are not reliable.

The results of these 3 techniques for evaluating the shrinkage stress are discussed and compared in Chapter 8.

CHAPTER SIX

THE STRENGTH OF THE RUBBER-TO-METAL BOND

6.1 Introduction

To enable a full appraisal of the problem in manufacturing concentric bushes a study of shrinkage stresses must be complemented by a knowledge of the bond strength. The research described in this chapter is concerned in particular with the strength of the bond at moulding temperatures.

An analytical technique has been developed to examine the hot bond strength (the test-piece and test method are described in section 6.4).

The aim of the hot bond test is to investigate the effect of material and process variables on bush bonding and to evaluate the suitability of adhesive systems for bush manufacture.

6.2 Background to the Bond Strength Investigation

A number of general text books on rubber technology are available and these serve as an introduction to rubber/metal bonding[27,28]. Blow's book contains a section on rubber-to-metal bonding, written by Hopkins and Powell of Dunlop (PED) Ltd., which describes the methods of bonding already reviewed in this thesis.

Only one book written specifically for rubber-to-metal bonding is known to the author[29]. Buchan wrote this text in 1959 and therefore most of the information is based on the old brass plating method and he only briefly reviews polymeric adhesives.

Most publications on the technology of rubber-to-metal bonding originate from the bonding agent manufacturers and consequently relate to the use of their adhesives and not to reaction mechanics nor to bonding agent constituents.

Perhaps the first major contribution to knowledge on polymeric adhesive reactions was by D.M.Alstadt[30] in 1955. Although previous information had been published regarding the applicability of specific materials for bonding, little information was available regarding the general concepts and Alstadt strived to fill this gap. In particular he emphasised the need for a polarity gradient between the highly polar metal and the non-polar rubber. De Crease[31] concentrated on the effect of elastomer variables on bonding, giving different rubbers a 'Bondability Index' wherein Natural Rubber = 4 on a scale 1 to 10. F.H. Sexsmith[32,33] has revealed some 'secrets' on the mechanism of bonding in several papers based on Alstadt's original paper.

A more recent paper by De Crease[34] extolled the importance of understanding the bonding theory in assessing everyday bonding problems and he coined the term 'Interfacial Dynamics' to define the extremely dynamic states created when the rubber to metal bond is formed. His paper also reviewed the types of bond failure that can occur and postulated reasons for the separation of the rubber and metal.

By the early seventies the technology of adhesive bonding was no longer new and general guidelines had been published by various research organisations, industrial associations and the adhesive manufacturers. However the emphasis was on the material and process factors rather than extrapolation of theoretical concepts into practical ideas. To date most publications have concentrated on these factors, often on specific problems and developments. For instance, Meier and Findley[35] reported on new developments which included, curing methods, precoating of metals and post-vulcanisation bonding.

Often papers emerging from the adhesive manufacturers just restate the 'obvious' in terms of better bonding resulting from use of their particular brand of bonding agents; although one paper, by J.D.Hutchinson, does include a fine 'Process Flow Chart' for elastomer bonding setting out some of the main areas where control is needed[36].

Most researchers consider that the bond strength (or comparative bond failure levels) to be the prime factor in gauging the influence of the many variables on bond performance.

6.2.1 Bond Strength and Bond Failure

The term 'bond strength' is somewhat a misnomer in that the load required to break a rubber-to-metal assembly is determined not just by the strength of adhesion between the various materials but also by the cohesive strength of the rubber and of the bonding agent system.

Any attempt to measure the strength of adhesion requires measurement of the strength of a joint. Application of a breaking force produces non-uniform stresses within the joint and failure occurs when the stress at any point exceeds the strength at that point.

In this thesis, bond strength measurements are of the whole assembly strength and the ellucidation of results is helped by comparing bond strength values with the type of failure, wherever possible, to indicate why failure occurred (a weakness in the bond or in the rubber).

In fact, ever since the introduction of polymeric adhesives it has been necessary to classify failure types to account for the above ambiguity. Peterson[37] describes the types of failure generally encountered and figure 6.1 shows diagramatically the categories under A.S.T.M. procedures. In practice, classification of a failed part into one of these groups is difficult as probably a composite failure will have arisen and it is then hard to judge exactly in which layer failure has occurred.

The mode of stressing influences the degree and character of the reject bond, Schultz and Westbrook[38] have suggested ways in which results could be obtained by limiting the multiplicity of forces present when the bond is tested. Their work recommended the use of a conical test-piece similar to that detailed in the next section.

6.2.2 The measurement of bond strength

The American Society for Testing Materials list three methods for testing the adhesion of vulcanised rubber to metal. These are used by most organisations connected with rubber-to-metal bonding although modifications of the laid down tests are common, especially for specific applications and for internal research programmes.

The 3 A.S.T.M. methods are:

a) D429-73 Method A

A rubber part is assembled between two parallel circular metal plates. The plates are then pulled apart using a standard tensiometer and the load on failure is recorded, together with the type of failure. Results are expressed in KN/m^2 or P.S.I. and in the case of all rubber tear the bond adhesion shall be higher than recorded. This test is commonly known as the round bobbin or butt joint test.

b) D429-73 Method B

A 90° stripping test where the rubber part is bonded to one metal plate. This is the most widely used test for determining the adhesion strength of elastomer to metal bonding agents. The results are obtained by measuring the pull necessary to separate a rubber strip from the metal surface at a 90° degree angle. The adhesion value is expressed in N/mm or Pounds/inch of rubber width.

c) D429-73 Method C

Measurement of rubber to metal adhesion with a conical test specimen. A development of Method A, this method produces failure at the bond interface by use of the correctly shaped conical test metals. Method C is often referred to as the Painter Bicone Test after G.W. Painter who published the original paper[39] showing that interfacial separation is a more meaningful measurement of adhesion than partial fracture within the elastomer body. The adhesion values are given in Newtons or Pounds force required to break the bond and it has been shown that the pattern of failure is closely related to these values. Figure 6.2 shows the type of test-piece employed for each method.

Methods A and B are in use at Dunlop P.E.D. for bonding development work. However, more emphasis is placed on detecting or assessing bond failure than on the bond strength evaluation. For bond testing production parts either a simple visual check (under load) or load to destruction tests are employed.

Non-destructive rubber-to-metal bond tests are still in their infancy. The use of ultrasonics[40] and infrared[41] (to detect head flow through bonded parts) can reveal voids between rubber and metal but as yet cannot differentiate between a weak and strong bond, and therefore these tests are ignored in this research.

6.3 The Hot Bond Strength

The bond tests mentioned in the last section all refer to the bond strength at, or around, room temperature, i.e. the moulded assemblies are allowed to cool before the test is applied. From work pursued at Dunlop (PED) during the period of catastrophic bush bond failures it is clear that the bond separates soon after leaving the mould when the part is 'hot' (120°C - 160°C).

It is therefore essential that a knowledge of the bond performance at high temperatures is sought. As the cure time may effect the ultimate bond strength the loading of the bond to failure must take place immediately following the moulding operation.

Although several researchers have evaluated the performance of rubber-to-metal bonds at high temperatures, e.g. Buchan[42] and Stahr[43] it is apparent that their results were obtained by allowing the bond to cool then reheating the part to moulding temperatures to test the bond. This does not reproduce the bush bonding situation. Calkins[44] outlines results obtained within 20 seconds of moulding but he only is concerned with percentage bond failure and not bond strength.

No other reference to hot bond testing immediately on demoulding, has been found. Unpublished work carried out at Dunlop (PED) to study the hot bond strength of different adhesives failed to recognise the time lag effect between moulding and testing although the temperature was maintained. Furthermore the test used (D429-73 Method A) was slow to tension the bond with over a minute from initial loading to failure. Results from this experiment were generally inconclusive.

Another 'in house' test employed by Dunlop (PED) consists of a test-bobbin similar to that used in D429-73 Method A except one metal is drilled and a bolt inserted which abutts onto the second metal. On removal from the mould the bolt is turned to produce a 12-20% strain on the rubber and hence stress the bond. When the part cools it is hand stripped and the type of failure recorded[45]. This test does not measure bond strength, it can only show whether a bond is good or failed and this limitation hampers the application to serious research work.

To reproduce the bush bond failure phenomenon, a means of obtaining the strength of adhesion (or cohesion) is required and the load must be,

a) Applied at the same temperature range as bushes
b) Applied immediately or within seconds from removal from the mould
c) Applied quickly to breaking point.

6.4 Development of a test-piece to measure the hot bond strength

This section describes a test method developed specifically for this research project. For convenience this will be referred to as the 'hot bond test' and the test bobbin, a version of the D429-73 Method A, 'the modified test-piece'.

A load cell has been incorporated which indirectly measures the stress on the bond prior to and during failure.

Due to the limited time and financial resources available a fundamental redesign of the test methods to closely represent the bush was not possible, although some conceptual ideas of suitable test assemblies are given in Appendix No. 4.1.

6.4.1 The modified test-piece

Figure 5.14 shows the 'modified' test-piece. This arrangement is similar to the experimental test-piece depicted in Chapter 5 and a full description appears in Appendix No. 3.4.

The metals are mild steel of a similar grade to that used in bushes. One metal has a hole through its centre threaded to $\frac{1}{2}$'' U.N.C., the other has a hole threaded to $\frac{1}{2}$'' U.N.F. The U.N.C. hole receives the load cell, the U.N.F. hole the tensioning bolt.

6.4.2 Description of the Test-Method

The two metal bobbins are cleaned using one of the standard techniques and adhesive applied to the bonding surfaces (normally by brushing). A suitable rubber blank in the region of 30 gms is cut from a standard 1 cm rubber sheet. The double cavity transfer mould used to produce the modified test-piece is contained between the platens of an electrically heated laboratory press.

Both the tension bolt and the load cell are placed in their respective metals, the load cell can be now connected to the amplifier unit, and the chart-recorder zeroed.

When the mould temperature stabilizes the mould is removed from the press, opened and the individual metals placed inside, together with a dummy test-bobbin in the spare cavity.

Plate 2 is a picture of the opened mould containing the test metals.

The rubber blank sits in the feeder cup and when the mould is assembled lies under the transfer piston. Finally the mould is returned to the press and the platens closed to initiate the moulding cycle. As the press closes adjustments are made to the tension bolt so that the load cell is just within contact with it. During the above operations the load cell is momentarily disconnected from the amplifier unit.

Plate 3 shows the test-piece, amplifier unit and chart recorder.

Throughout the vulcanisation cycle the readings from the load cell are recorded although these only indicate the interference from the high pressures or forces within the mould (the load cell will register high radial loads). Nevertheless the pattern drawn on the chart should be similar for every moulding charge and an unusual pattern will indicate a deviation from the norm, such as insufficient press load or incorrect seating of the metals and mould inserts.

At the specified time the mould is opened and the test-piece removed, immediately to be placed in a pre-heated clamp. The tension bolt is quickly turned by hand, using a conventional Allen key, until bond or rubber failure occurs, indicated by either the visual separation of the test-piece or by the sudden fall off in the load reading. Figure 6.3 shows two typical test curves. Curve (a) is an example of the chart when failure occurs in the rubber. Curve (b) represents the typical curve caused by substantial failure at the bond.

The results are calculated as follows:-

The difference between the load reading prior to application of the stress and the maximum load reading obtained before failure occurs (on the diagram in figure 6.3 load min and load max) gives the load acting on the load cell. This force is divided by the area of the bond interface and the results expressed in MN/m^2.

A thermocouple placed inside the tensioning bolt measures the temperature of the bond during moulding and when the stress to failure is applied.

For some experiments the bond strength at lower temperatures was studied by allowing the assembly to cool before placing in the clamp and turning the bolt. The temperature of the test was recorded with all the subsequent results.

6.4.3 Reproducibility and Accuracy of the Test

The reproducibility of the hot bond test is difficult to establish due to the numerous variables or factors involved in producing the bond. Nevertheless analysis of the results for near constant conditions indicate an experimental deviation of ± 5% of the actual result.

The accuracy of the values obtained using this test cannot be absolutely judged as no comparable results exist, but linear extrapolation of bond strength/temperature plots to the ambient temperature region give typical bond strength values obtained using conventional methods. Also comparisons with other aspects of this research, e.g. bond failure in laboratory produced bushes, are encouraging and the hot bond test can be taken as a meaningful technique to study the effect of some variables on rubber to metal bonding.

6.5 Bonding Agents

At Dunlop (PED) both the metal parts and rubber compounds are chosen at the design stage to satisfy the specific requirements of the customer. Thus any change in the metal or rubber of a bush in order to increase bonding performance would be at the very least inconvenient and in general unacceptable to other functions within the company. However, the bonding agent is open to substitution without undue repercussions elsewhere.

This section describes the available preparations, reviews their general 'chemistry' and reports on a study of their ability to resist shrinkage stress. The results are obtained using the modified test-piece under near ideal laboratory conditions. NB. Further work on bonding agents in the production environment is recounted in Chapter 10 of this thesis.

Although manufacturers of rubber-to-metal goods have been known to make their own bonding agents, the normal procedure encompasses the use of proprietary adhesives.

The major suppliers of rubber to metal bonding agents are listed in Appendix No. 4.2 together with the relevant adhesive brand names.

Hughson Chemicals and their U.K. licencies, Durham Raw Materials Ltd., have by far the greatest experience, expertise and facilities for producing bonding agents and are the world market leaders with their 'Chemlok' adhesives.

6.5.1 Bonding Agents - Ingredients and Reactions

Little has been revealed regarding the composition of the adhesives examined in this research, except for general indications given in patents and by employees of the manufacturers[46,47,48]. Buchan[49] reviews the formulations of bonding agents but his work includes only the early commercial bonding systems. Medvedeva[50] has published a more recent survey although his conclusions are subjective and based on assumptions rather than hard facts.

What is commonly known are the main groups of ingredients, these include halogenated polymers of an elastomeric nature, halogenated thermosetting resins, carbon black, specific vulcanising agents, organic solvents and small amounts of other materials such as accelerators and reactive salts.

The mechanism of adhesion can be classified into two types, physical adhesion involving secondary valence forces (Van Der Waals forces) and chemical adhesion where primary valence forces (chemical bonds) are involved.

In terms of the physical forces the object of the adhesive is to bridge the polarity gap between the highly polar metal and low or non-polar rubber. Some halogenated polymers (e.g. chlorinated N.R., Neoprene, brominated 2,3-dichlorobutadience-1,3,Polymer) fall in the middle of this range and therefore form the basis of adhesive formulations. Obviously a compromise exists and the 'art' in preparing the adhesive lies in formation of the optimum adhesion to both metal and rubber.

Nevertheless the possibility of these adhesive mixtures adhering to both elastomer and metal by polar forces alone is remote and some form of chemical bridging must be introduced.

At the elastomer end there are two capabilities of chemical activity.

a) The adhesive contains a mobile vulcanising or crosslinking agent capable of reacting across the interface(e.g. sulphur, peroxide or free-radial type crosslinkers). These reactions are fast due to fast reaction rates of the crosslinking agents.

b) The adhesive contains polymers that are themselves attachable through a migrating moiety from the main elastomer compound. These are generally unsaturated polymers or monomers capable of generating double bonds. The reaction rates are very slow compared to those in (a) due to the slow diffusion of the active compounds and intermixing of bonding agent and rubber.

The reaction rate is also dependent on the type of polymer and curing system in the rubber compound.

Adhesion to the metal can also be achieved by chemical bonds, i.e. chemisorption. Here certain molecular groups are thought to react with hydrated oxides on the metal surface. Groups known to react include: polyisocyanates, organo-functional silanes and phenol-formaldehyde resins. The actual mechanism of chemisorption is complex and may involve the production of unknown intermediary compounds when the bond is heated.

Figure 6.4 (after Sexsmith) attempts to delineate these various adhesion routes that take place in rubber to metal bond formation.

The order in which these occur can vary, an example is given below for a conventional two coat adhesive system.

i) Adsorption (physical with some chemisorption) of the primer ingredients onto the metal surface.

ii) Adsorption and interdiffusion of the adhesive cover coat with the primer polymers.

iii) Interdiffusion of polymers and crosslinking agents across the rubber interface.

iv) Internal vulcanisation of the adhesive

v) Cross-bridging at the elastomer/bonding agent interface

vi) Internal vulcanisation of the elastomer.

This is the most common order of events, obviously with a single coat adhesive some stages are omitted and conversely a three coat system requires interdiffusion and crosslinking between the second and third coats. There is also evidence of crosslinking between the intermediate coat and the rubber. The order can be interchanged if other properties are changed, e.g. stages v and vi can be reversed if a fast curing rubber is bonded with a slow reacting bonding agent.

So far the general ingredients and reaction mechanisms have been described. Specific ingredients or groups of ingredients of the bonding agents studied here are contained in Appendix No. 4.2 together with their probable patent reference numbers.

The bonding agent systems studied in this research are listed in figure 6.5.

Some of the above systems include two bonding agents of different brand names and from different suppliers. These 'hybrid' systems have evolved through the trial and error emergency development projects instigated by the adhesive users to overcome specific problems.

6.5.2 The comparative hot bond strength of commercial bonding agents

The hot bond test method is described in section 6.4.2.

The adhesive systems mentioned in figure 6.5 have all been evaluated, using the hot bond test, for their suitability to resist stress at or near demoulding temperatures.

The experimental conditions are given below and the results compared in figure 6.6

Metal Preparation : Degrease, alumina blast, degrease

Adhesive Thickness : for primer coats ≃ 7 g/m^2

'' cover coats '' 18 ''

'' third coats '' 18 ''

'' single coats '' 25 ''

Rubber Compound : Semi E.V. Type; Hardness = 60 IRHD

Cure Conditions : Cure time = 15 minutes; Cure temperature = 150°C

With reference to figure 6.6. the following points should be noted.

a) The rubber tear strength ranges from approximately 2.750 MN/m^2 at 150°C to approximately 5.500 MN/m^2 at 100°C and above the dotted line represents the area of 100% rubber tear.

b) Graphical points are left out to clarify the diagram (only Thixon OSN-1 and OSN-2 show a large scatter of values) and the graphical lines are merged into bands.

c) Shrinkage stress developed prior to manual tensioning of the bond is included in the values plotted.

Most failure occurs between the rubber and cover coat (R.C. failure). However each adhesive system exhibits a characteristic pattern of R.C. failure and the 'foliation' effect mentioned by Marsh during the period of catastrophic bush failures is characteristic of the Chemlok 205/Chemlok 220 and related adhesive systems.

In figure 6.6 the results are shown as four bands. Adhesive systems in band 'A' give 100% rubber tear at 150°C and therefore are not evaluated at lower temperatures. The band A adhesives are the most suitable for manufacturing concentric bushes with the suitability diminishing in the order A B C D. Furthermore, from these results it can be concluded that some systems are definitely not able to withstand the rigors of the high temperature/high stress environment and these along with the experimental adhesives are not considered further in this research.

6.6 The Effect of Variables on the Hot Bond Strength

It has been recognised for many years that certain rubbers and compounding ingredients along with process extremes all affect the quality of the rubber to metal bond. Hopkins and Powell[51] mention these main variables and state how they must be 'controlled' to ensure good bonding. This research quantifies the influence of variables on the hot bond strength.

The main variables not under investigation are held constant as each test is prepared and moulded.

6.6.1 Metal Variables

The different types of mild steel used for bush metal components only differ in quality of fabrication and hence are assumed to have no effect on the bond interface.

The method of metal preparation prior to bonding has a relation on the cold bond performance due to the change in surface condition. The results in figure 6.7 indicate that, although different cleaning methods produce various amounts of bond failure, the hot bond strength remains the same irrespective of surface cleaning.

Most failure occurs either in the rubber or at the rubber/cement interface therefore it appears that no problem exists with the metal/primer interface as the adhesion here is greater than for other levels in the bond.

6.6.2 Rubber Variables

Natural rubber (N.R.), Polyisoprene and Styrene Butadiene rubber (S.B.R.) are the elastomers studied. Over 90% of bush production can be represented by two natural rubber compound series,(i) conventional sulphur cured compounds (named 01X series - e.g. 1160) and(ii) semi E.V. cured compounds (named the 16X series - e.g. 19060) (See figure 3.2 for details of these compounds.)

Mixtures of 50:50;N.R:Polyisoprene are occasionally used in the above compounds in place of the normal 100% N.R.

A third major series of compounds used in bushes is based on mixtures of 50:50;N.R: S.B.R. rubbers and these are named the 43X series.

The above variations have been studied, using the hot bond test, and the results are given in figure 6.8.

A number of bonding agent systems are used in this exercise to demonstrate the interdependence of adhesive and rubber properties on the bond performance.

The individual influences of compound constituents on bond performance have not been determined owing to the large number of permutations (each requiring analysis) to enable a fruitful study to be fulfilled. In any case most bushes manufactured at Dunlop (PED) contain either 01X or 16X rubber with similar constituents.

However the influence of the carbon black is indirectly studied as it is partially responsible for governing the hardness of the rubber compound.

The true influence of the rubber hardness is difficult to judge when using the modified test-piece as the rubber tear strength is directly dependent on the hardness. Hence hard compounds have a relatively high tear strength and any failure will occur at the bond interface while a soft compound will readily tear and may leave the bond intact.

Therefore in figure 6.9 the bond strength values for soft rubbers are based more on the rubber tear strength than the bond interface strength while the opposite is true for hard rubbers. For medium hardness rubber (around 60 IRHD) failure occurs in either the rubber or at the bond depending on the conditions of the test.

Bond failure types range from patchy R.C. with soft rubber compounds to thin rubber/smooth R.C. with harder rubbers.

Having considered the effect of controlled or intentional variables in the rubber this research now explores the influence of the rubber moisture content on the bond strength. Water is used in both the processing of raw rubber and the preparation of the rubber compound. It is also present, in small amounts, in some compounding additives. Water diffusion through a rubber compound is slow, a matter of weeks for a compound to reach equilibrium, so varying amounts of water can be retained in the rubber during moulding.

Unpublished work at Dunlop (PED) Ltd has shown that water molecules in the rubber compound will alter the ability of a rubber to bond. This phenomenon was confirmed by the author using a number of bonding agents and 3 rubber compounds, 'wet', 'normal' and 'dry'. (see figure 6.10).

The results of a more in depth and quantitative study using the least and most affected bonding agent systems are shown in figure 6.11 which reveals that a near linear relationship exists between the hot bond strength and the moisture content of the rubber.

Research carried out by Dunlop (PED), Dunlop Central Research and the Malaysian Rubber Producers Research Association revealed a natural constituent of N.R. which is thought to influence the bond performance in the bush situation. This substance gives rise to a peak at 1704 cm^{-1} in the infrared trace of the N.R. acetone extract.

Concerted efforts by these organisations to analyse the substance failed to ascertain the exact chemical structure, but it is believed to be a phthalate ester or protein. Samples of rubber with high and low contents of this substance were tested at Dunlop (PED) and the high content sample produced inferior bonding. One hypothesis was, that as this substance is produced in the rubber tree the concentration may have a seasonal variation.

During the course of the present project samples of raw rubber have been taken at regular intervals and their acetone extracts examined. The infrared results when compared to the date each raw rubber batch was produced show no seasonal variation in concentration, rather a batch to batch variation is evident.

Samples with a high content of this substance were mixed together and compounded as were samples with a low content. Both compounds were then tested for their relative hot bond performance and no difference between them was recorded. (see fig. 6.12).

Other rubber variables have been briefly examined and within reasonable bounds these do not have any effect on the hot bond strength. They include:-

a) The age of the rubber compound

b) Rubber scorch properties

6.6.3 Bonding Agent Variables

Bonding agents have already been examined in section 6.5. In this section the adhesive application variables are considered.

Within normal limits the type of application (brushing, spraying or dipping) should, theoretically, have no influence on the hot bond strength. This is borne out by the results shown in figure 6.13.

Rubber-to-metal bonding organisations place great emphasis on the thickness of the adhesive layer in terms of the general bonding requirements. Too thin coats cause bond failure or in the extreme no bond formation, thick coats can result in cohesive failure within the bonding agent or in rubber lamination. The situation can be further complicated by use of hybrid 3 coat adhesive systems where the relative thickness of each coat is critical in ensuring optimum bond strength.

In the hot bond context it is only extremely thin coats that give rise for concern by showing a reduced bond strength (see figure 6.14).

The following variables were briefly tested and no direct correlation found with the hot bond strength (under reasonable conditions).

a) Age of bonding agent

b) Length of time between bonding agent application and moulding

c) Moisture content of bonding agent

6.6.4 Moulding Variables

Creation of a rubber-to-metal bond involves fundamental chemical reactions and hence relies to some degree for completion on an input of energy into the system, i.e. heat is required to form a satisfactory bond with the rate of reaction being linked to the temperature (rate of heat input).

During the moulding operation the heat is required to primarily vulcanise the elastomer, and moulding temperatures or times are normally calculated on this basis. Sexsmith's diagram (figure 6.4) indicates that the bond cures before the bulk elastomer but if the heat input required for the bond and elastomer are similar or more heat is required for the bond, then bond failure may occur. Most bonding agent manufacturers claim that the adhesive and rubber optimum cure conditions are the same.

The two elements of heat input, cure time and cure temperature are 'infinitely' variable. In practice the cure temperature is constant for a range of products or type of moulding machine and the time altered to achieve optimum cure. Figure 6.15 gives the hot bond strength for a range of cure times and for a number of bonding agent systems. Also included is an indication of the rubber cure condition.

This graph shows that not only is the hot bond strength very dependent on the cure time but also the curve shape reflects the type of bonding agent used. The newer single coat adhesives are more reactive than the conventional two coat system and require substantially less heat input to reach a strength comparable to the rubber tear strength.

If the rubber compound is changed to that of a slower curing compound then the rate of bond formation falls (although so does the rate of bulk rubber cross-linking) but the relative positions of the curves are unchanged.

The influence of varying cure temperature (const. cure time) on the hot bond strength is difficult to determine as the temperature at which the part is removed from the mould, and hence the test temperature, will fluctuate. The experimental points in figure 6.16 correspond to the hot bond strength at a number of demoulding temperatures.

A paper by Gervaise et al[52] mentions that a high moulding pressure (around 172 MN/m^2) can offset the rubber shrinkage but only pressures in the region of 1.0 MN/m^2 are needed to ensure adequate bond quality.

The paper prompted an investigation into the influence of the mould pressure on the hot bond strength. A range of moulding pressures has been studied and the results, shown in figure 6.17, indicate that once sufficient pressure is applied to give good rubber/bonding agent contact then no further significant improvement in the hot bond occurs. At the lowest value (3.5 MN/m^2) the part exhibits the characteristics of a 'not-made' component, i.e. insufficient rubber flow has occurred to completely fill the mould cavity.

Excessive pre-heating of adhesive coated metals can cause 'pre-bake' of the adhesive film where either internal cross-linking reactions are initiated or reactive ingredients are lost due to volatilization. Figure 6.18 demonstrates the way in which different bonding agents resist pre-bake.

6.7 Major Factors which Influence the Hot Bond Strength

Only four of the factors studied here have a major influence on the hot bond strength.

i) The heat input during curing

ii) The rubber moisture content

iii) The type of bonding agent

iv) The rubber hardness

The first two factors are both known to influence the rate of bond formation. The bonding agent determines the rate of bond reaction together with the optimum hot bond strength both relying on the type and degree of chemical cross-linking between the adhesive and the rubber compound.

Change in rubber hardness produces various types of bond failure and differing bond strength values.

Although this is not a comprehensive study, an attempt has been made to identify and quantify the variables which in theory may influence the hot bond strength. Other factors probably have a marginal effect but these are of little importance in assessing the overall probability of a bond to fail and the subsequent investigation into the real world of the factory shop-floor.

CHAPTER SEVEN

BUSH COOLING CHARACTERISTICS

7.1 Introduction

When a bush cools both the hot bond strength and the shrinkage stress increase. However the hot bond strength is related to the bond temperature while the shrinkage stress depends on the average temperature of the rubber. So for a comparison of bond strength and stress a knowledge of the temperature distribution throughout the part (on cooling) is required.

The moulding operation takes place at $\simeq 160^{\circ}C$ giving rise to a temperature difference of $\simeq 130^{\circ}C$ between the newly moulded bush and the surrounding air. As the air density near the hot surface is less than that of the main bulk of air, buoyant forces cause an upward flow of air which carries away heat through the gas layers by bulk motion. This phenomenon is natural convection and can be quantified by the heat transfer coefficient (thermal emmisivity) for the particular surface and bulk medium. Forced convection, whereby the air is forced past the hot surface can also occur.

Soon the heat loss is such that a temperature gradient builds up between the centre of the rubber and the surface of the part. This is related to the heat conduction through the rubber and metal. The temperature at any given point changes with time so this process is referred to as transient heat conduction.

In bushes these two aspects of heat transfer are further complicated by the use of materials whose heat properties differ considerably. The rate of heat flow through steel is high (thermal conductivity is around $5 \times 10^{-2} Jmm^{-1}s^{-1}{}^{o}C^{-1}$) while rubber is a poor conductor of heat (thermal conductivity $2.5\times10^{-4} Jmm^{-1}s^{-1}{}^{o}C^{-1}$). On the other hand heat convection from the rubber surface is faster than from the surface of the metal.

Therefore it can be appreciated that the use of classical calculations to express the complete heat transfer position in a cooling bush necessitates an in depth knowledge of the subject together with a convenient method of solving complex algebraic equations. An alternative is to apply the theory of Finite Elements to the problem and to use a computer to solve the necessary equations. For the purposes of the research this technique was deemed sufficient and a readily available software package was used. The work is described in the following section.

A practical approach for determining the cooling curves of bushes is also feasible and is included in this part of the research, primarily to serve as a check on the computational analysis but also to substantiate the temperature measurements of the hot bond test.

7.2 The Finite Element Analysis of Heat Transfer

The principle of finite elements is shown to be applicable to many types of problem; already in Chapter 5 this technique has been used to calculate shrinkage stresses. For the application concerned here, temperature changes for given material and environmental conditions are investigated with one major feature, that of a reliance on time.

The main program used for this exercise (named ANSYS) is part of the S.D.R.C. software package.

The experimental procedure described below is similar to that given in Chapter 5 except for the different inputs and outputs coupled with a need to take the metals into account when designing the model.

The procedure is:-

1) Draw-up model and elemental grid (include metal cross-sections)
2) Number nodes, place value of initial temperature at each node
3) Input constraints (e.g. convection faces, axisymmetric axes etc)
4) Input bulk air temperature, material constants (e.g. thermal conductivity and emissivity).
5) Run a checking program
6) If data is correct then submit to main program (ANSYS)
7) Analyse results, draw heat contour graphs etc.

If necessary alter input data and repeat stages 5-7.
Examples of the program details (inputs and outputs) along with a short theoretical appraisal of the method are given in Appendix No. 5.

As the main object of this experiment is to examine the fall in average rubber and bond temperatures, the thickness of the rubber is important. Two bushes have been examined, one of thin rubber section (13/1914) and the other with a thick rubber section (13/1983).

The above technique has also been used to examine the modified test-piece.

7.2.1 Assumptions and Simplifications

a) The model represents a bush in isolation, completely surrounded by air. In practice the bush is in contact with a container and other warm bushes whose heat properties would influence the rate of cooling of the part under study. It is also assumed that the convection is natural, not forced as sometimes is the case.

b) It is now thought that the rubber thermal conductivity depends on the molecular structure and particle shape of the fillers in the compound and hence may differ in each direction if the filler particles are 'laid down' in a uniform manner[53]. However, these differences in thermal conductivity would not be large enough to effect the results of this experiment and the conductivity value for rubber used in the program was the same for heat flow in all directions.

c) The accuracy of input data and the effect of errors or inaccuracies on the results are difficult to check since the constitution of the program is unknown.

7.2.2 Results

Material Properties

The following analyses are on parts containing the same materials i.e. mild steel and natural rubber (60 IRHD). The relevant properties are given below:-

Thermal conductivity (Rubber) = $2.34\text{x}10^{-4}\,\text{Jmm}^{-1}\text{s}^{-1}\,{}^{o}\text{C}^{-1}$

'' '' (metal) = $4.6\text{x}10^{-2}$ '' '' ''

Thermal emissivity (Rubber) = $2.5\text{x}10^{-5}\,\text{Js}^{-1}\text{mm}^{-2}\,{}^{o}\text{C}^{-1}$ *

'' '' (metal) = $1.6\text{x}10^{-5}$ '' '' '' *

Specific heat (Rubber) = 2.01 $\text{Jg}^{-1}\,{}^{o}\text{C}^{-1}$

'' ''(metal) = 4.87 '' ''

Density (Rubber) = $1.2\text{x}10^{-3}\ \text{g mm}^{-3}$

'' (metal) = $7.8\text{x}10^{-3}$ ''

* calculated on natural convection.

a) 13/1914 Bush

Dimensions:-

Rubber length = 38.06 mm

Rubber thickness = 3.53 mm

Inner metal length = 50. 8 mm

Outer '' '' = 44.15 mm

Inner metal thickness = 2.64 mm

Outer metal thickness = 2.03 mm

Initial temperature:- Air temperature = 30°C; 20°C
Uniform bush " = 150°C; 160°C
(i) (ii)

Figures 7.2 and 7.3 summarise the temperature changes as the bush cools and should be consulted in conjunction with figure 7.1, the model grid.

The temperatures are averaged out to give cooling curves for the rubber section and the rubber-to-metal bonds.

b) 13/1914 (Thick inner metal)

The model (see fig 7.1) was altered to indicate an inner metal of double the normal thickness.

Other data inputs are the same as those in analysis (a) (Air temperature = 20°C; Uniform initial temperature = 160°C).

The resulting cooling curves are drawn, and compared to cooling curves obtained using the normal metals, in figure 7.4.

c) 13/1983 Bush

Dimensions:
Rubber length = 58.73 mm
Rubber thickness = 14.72 mm
Inner metal length = 74.00 mm
Outer metal length = 58.70 mm
Inner metal thickness = 2.50 mm
Outer metal thickness = 1.63 mm

Initial temperatures: Air = 160°C
Uniform bush = 20°C

The graph in figure 7.5 indicates the average cooling curves for the rubber and the bonds.

d) The Modified Test-piece

The test-piece is incorporated here to indicate the temperature of the bond interface during the hot bond test and to compare it with the area of temperature measurement in the cap-head bolt.
(The dimensions are irregular).
Initial temperature: Bulk or Air temp = 30°C
Uniform nodal temp = 150°C

A cross-sectional model of the test-piece including the node positions is drawn in figure 7.6.

The thermocouple is placed near node 22 during the hot bond test and the table, figure 7.7, compares the temperature at this node with the bond temperature, (nodes 16-21).

The table shows that the area of temperature measurement cools in a similar way to the bond.

7.3 A Practical Method for assessing Bush Cooling Characteristics

An attempt has been made to verify the finite element method by practical experiment.

Thermocouples were inserted into holes drilled into the 13/1983 bush and in the modified test-piece. The positions of the holes are given in figure 7.8.

The parts were then placed in a laboratory oven and the temperature recorded on a Foster Cambridge CLEARSPAN P120L,6 channel recorder. When the part(s) reached a uniform 150°C they were withdrawn from the oven and allowed to cool to room temperature while the temperature was recorded for each point. During this period both parts were surrounded by air and were not resting on any surface.

From the temperature readings, the cooling curves shown in figure 7.9 are deduced.

7.4 Interpretation of the Results

a) For thin rubber sections(of 10 mm or less) the average rubber and bond temperatures are similar. However, as the thickness increases the difference between the average rubber and bond temperatures becomes significant with the bonds cooling faster than the rubber.

By definition, the 'problem' high shape factor bushes have thin rubber sections and hence the fall in temperature can be considered uniform throughout these parts. Very long (greater than 100 mm) bushes are an exception and may be high stress bushes yet still be thick sectioned.

b) Where the inner metal is comparatively thick and the bore small, cooling will be considerably slowed as most heat in the inner metal must be lost by conduction through the rubber and the outer metal (the convection surface of the inner metal is limited). Therefore the inner bond is comparatively hotter than the outer bond and the bulk rubber.

c) A lower air temperature serves to increase the rate of cooling and 'separates' the cooling curves of the bond and the rubber.

d) Most heat is lost through the side walls of the bush and only a minimal amount is dissipated through the bush ends. Except for a slight lowering of the relative temperature at the ends (which is ignored in the stress and bond strength calculations) the temperature along the bush is uniform.

e) The values obtained using the two techniques compare favourably and the finite element results are accurate enough for the aims of this research.

In the remaining chapters of this thesis any comparisons of shrinkage stress and bond strength are based on a uniform temperature throughout the part. The only exceptions to this rule are

i) bushes with thick rubber sections, and

ii) bushes with thick inner metals.

Products in these two categories are identified as special cases and calculations acknowledge the different temperatures of the bond and the bulk rubber.

CHAPTER EIGHT

THEORETICAL DISCUSSION

8.1 Introduction

Although the shrinkage induced stresses exist in a large number of products manufactured at Dunlop (PED) the problem is most serious in bonded bushes where the rubber shrinkage is restricted by virtue of the part design.

The rubber-to-metal bond formed by brass-plating is sufficient to withstand bush shrinkage stresses developed after moulding whereas the hot bond strength of polymeric adhesives is generally lower and bond failure often occurs.

The following discussion examines the experimental work in determining shrinkage stress and bond strength and links these two areas so that, for a given situation, the probability of bond failure occurring can be assessed. To predict whether or not a particular bush (manufactured under specific conditions) will fail, the cooling characteristics of the part must also be considered.

8.1.1 Permutations and Combinations of Rubber to Metal Bonding

The main purpose of the experimental work has been to identify and quantify the parameters which determine bonding performance. However, a detailed study of all the factors which may influence the shrinkage stress and strength of the bond would require considerable resources. On the other hand to investigate a specific product under a unique set of conditions would yield results not strictly applicable to other bushes.

Therefore a compromise is reached where the author has been aware of many of the variables but only considered in detail those which seem the most important.

A further cause for concern is the interdependence of variables, as the main technique in this research has been to hold all major variables at a constant value except for the one under investigation. The complete study of all conditional sets using just the major variables would require well over 500,000 experiments and therefore some assumptions are made, e.g. by graphical extrapolation, to cover the possible combinations and to estimate the theoretical bond condition.

8.2 Bush Shrinkage Stresses

Physical properties of rubber compounds can vary enormously depending on the type and amount of some compounding ingredients, e.g. fillers and oils. Although these properties are strictly controlled at Dunlop (PED), the table (figure 5.2) used for converting hardness values to modulii etc. is open to criticism as it is based on just one polymer type and compound. Nevertheless the table has proved a valuable aid in this research and the inaccuracies, if any, are probably less than other sources of error.

The elastic behaviour of rubber is considered in section 5.3.2. Both the Statistical and Phenomenological theories are included to illustrate the specialised treatment needed to explain the unusual stress/strain relationships of rubber, especially in the large strain region.

Treloar's Statistical theory is used to derive the curve shown in figure No. 5.3 supporting the assumption that for small strains rubber compression and tension relationships are linear.

Although the Phenomenological theory has been used in finite element computer work on rubber[54], for bonded units of high stiffness, Hookes Law based finite element methods are more appropriate as the unit behaves more like a conventional material. Unpublished work by J.Thorpe at Dunlop (PED) in collaboration with Dr. Lindley at M.R.P.R.A. substantiates the use of Hookes Law for bonded units when only small strains are involved.

8.2.1 Use of the Finite Element Program

Finite element analysis is an excellent technique to study the whole stress picture and is widely used in engineering design applications. Here the use of the 'SUPERb' computer program greatly simplified the work while allowing for better resolution than would be possible with manual calculations. Unfortunately the way basic concepts are applied to the problem remains a secret of the programmers and the effect of using this general, Hookes Law based, program to analyse rubber shrinkage and elasticity is unknown.

Reliability of physical constants, application of the model and the number of reiterations all contribute to the end results. Most physical constants for rubber are well proven and the nodal grid (or model) needed for a bush is relatively simple thus results should portray a meaningful image of the shrinkage situation.

The results given in section 5.4.1.3. demonstrate how the forces are distributed throughout the rubber section, but more importantly show the stress at each point along the bond.

8.2.2 Use of the Empirical Calculation

The main objective of this technique lies in classification of bushes in order of shrinkage stress and to equate the results with the hot bond strength. The accuracy of the empirical method is deemed sufficient if the following assumptions are made:-

a) Thorpe's shrinkage equation is applicable to every case.

b) Rubber in the bush is represented by an infinitely long block or strip.

c) Compression and tensile stress/strain relationships are linear.

d) Little metal expansion/contraction or other dimensional movement takes place.

Application of the shrinkage equation has been common place at Dunlop (PED) for designing moulds with good results.

Use of the Gent rubber strip load/deflection equation presents more uncertainty as the application is unusual.

The main advantage of the empirical method lies in its simple application to any concentric bush, yielding adequate results well within practical errors or deviations such as metal dimensional errors.

8.2.3 Use of the Experimental Method

The experimental method was developed to confirm the stress values obtained using the empirical calculation, not to absolutely represent the forces produced in concentric bushes.

Experimental errors are considerable if the method is performed incorrectly and some practice was required before consistent results were obtained. Most errors are associated with the moulding operation and are due to operator inconsistencies or poor mould design allowing movement of the mould inserts as the press closes. Providing the correct temperature during moulding also proved to be a problem (even under laboratory conditions).

Unfortunately the range of shape factors that could be studied was limited by the size of the test-piece. A high shape factor would require a very thin rubber section and normal metal tolerance and mould movement errors would then become critical.

The results described in the next section show that, although a limited experiment, the experimental technique has served as a useful confirmation of the theoretical methods. However, as a means of examining the fundamental nature of shrinkage stresses in bushes the method used here is crude and slow.

8.2.4. A Comparison of the Three Techniques

Before comparing the results of the 3 techniques the practical considerations of transfer moulding are reviewed.

During moulding, rubber is initially forced between the metal parts and then the rubber pressure will rapidly increase as soon as the rubber ceases to flow. At the same time the temperature throughout both the rubber and metal is striving to reach equilibrium. The rubber to metal bond is formed at this stage and once this has happened the part is complete. Any further temperature increase causes the rubber to expand, thus increasing its precompression.

When a part is removed from the mould and begins to cool a transient heat flow state is evident until the whole part reaches room temperature. During this temperature transition stresses build-up in the rubber but as some molecular bonds then break some stress is relieved, a phenomenon known as stress relaxation.

A comparison of the results from all 3 techniques is shown in figure 8.1.

Following from these results some observations are made below:

a) Values obtained from all 3 methods are in the same order of magnitude and are in close agreement for the Empirical and Experimental techniques.

b) The reason why the finite element method gives higher stress values than the other two methods is because the F.E.M. takes no account of:-

i) Metal shrinkage

ii) Moulding pressures and temperature gradients

iii) Rubber flow at the start of moulding

Furthermore the Young's Modulus was considered to be 4 x the Shear Modulus when the F.E.M. work was carried out. Latterly unpublished research at Dunlop (PED) has indicated that for most rubber compounds $E_o = 3G$.

However, even if the average bond stress is higher than actual values, the results given by this method do give a clear picture of the stress distribution.

c) Although the empirical calculations do not allow for metal contraction, the moulding vagaries are partially compensated for by Thorpe's treatment of rubber shrinkage. In bushes, metal contraction would reduce the shrinkage stress by about 5%. Any remaining discrepancies between the experimental and empirical methods, are probably due to the rubber stress relaxation as the part cools.

8.2.5 Shrinkage Stresses in Concentric Bushes

Various stresses are developed when a bush cools but only the tensile stress in a normal direction to the bond is fully analysed here.

The finite element analysis revealed that shear stresses are 5 times smaller than the tensile stress and probably have no significant effect on bond failure levels.

Hoop stresses have not been evaluated in this exercise and although important, they follow a similar relative distribution to the tensile stress.

High tensile stresses at the ends of the bush are normally overcome by contouring the rubber end and this practice is described by Freakley and Payne[55]. With the exception of these end stresses, the tensile stress maximum occurs at the centre of the bush as demonstrated in figure 5.7. Bond failure is often found only in this centre region which would substantiate these theoretical observations as an area of maximum stress would be most prone to bond separation.

Unfortunately the empirical calculation gives only the average tensile stress and short of applying the F.E.M. program to every bush or undertaking a detailed research project into the stress distribution there is no way of determining the true stress at failure. However, the F.E.M. analysis of two bushes indicates that the maximum is approx. 1.5 times the average shrinkage stress. This value will alter slightly depending on the bush length. However, for section 8.6 of the following discussion the maximum stress is estimated to be 1.5 times the average value calculated by empirical means.

8.3 Bond Criteria

In Chapter 6 general bonding principles have been reviewed, test procedures outlined and the modified hot bond test described. The hot bond strength of various bonding agent systems together with the influence of variables on bond failure have also been examined.

8.3.1 Use of the Hot Bond Test

The aim of the hot bond test is to measure the strength of the bond while it cools from moulding temperature. Although the modified test-piece has a different geometry than for bushes,analysis shows that the stress concentrations are similar (see figures 5.6, 5.8 and 5.9).

However questions do arise, for instance:-

a) What is the exact temperature of bond and rubber ?

b) Does the speed of stressing affect the result ?

c) What is the influence of rubber precompression ?

d) Does the method of moulding alter the bond strength ?

Although these topics need further investigation before the test could find widespread use, for the present research they had not significantly influenced the hot bond strength results, which have in the main been of a comparative nature. Therefore the test has proved adequate for the research presented in this thesis.

With an improved test-piece and a more sophisticated test method other areas of research are possible including reaction kinetics studies and evaluation of the in-service hot bond performance.

It must be again emphasised that here the hot bond test measures bond strength immediately following moulding. The results do not relate to the true thermoplasticity of the bond, i.e. the bond strength once cooling and reheating has taken place.

8.3.2 Bond Formation - A Theoretical View

Section 6.5.1 outlines the two main methods of adhesion (physical and chemical adhesion) and the reaction steps proceeding throughout bond formation.

Physical bonds, which depend on the rubber polarity and surface contact, form relatively quickly compared to chemical bonds. As physical bonds are much weaker than their chemical counterpart a situation arises whereby a weak bond develops when the rubber and metal make contact followed by a gradual formation of stronger cross-linking chemical bonds to raise the bond strength. After moulding the cross-linking reaction may still continue, together with bond hardening, while the part cools and both contribute to the increase in bond strength. (see figure 6.6).

In the bush bonding problem the chemical bonds are the most important, with the critical reactions occurring between the adhesive cross-linking reactant and the bulk rubber polymer chain.

Two typical reactions are postulated in figure 8.2.

When a bush is removed from the mould and the shrinkage stress develops, the proportion of cross-linking molecular bonds already formed will determine the strength of the total rubber-to-metal bond and the likelihood of bond failure initiation. Therefore the rate at which the above reactions proceed will affect the bond strength on demoulding.

The following criteria influence the reaction rate:

i) Type of reaction, i.e. free radical or covalent

ii) Concentration of reactants

iii) Energy input

The first two are laid down by the adhesive type (and to a certain extent the rubber type) while the energy input depends on the moulding conditions.

The situation is further complicated by other reactions in the adhesive and rubber, i.e. internal vulcanisation, as portrayed in Sexsmith's diagram (see figure 6.4).

Steps 3-6 of this diagram hold the key to the bush bonding problem with respect to the hot bond strength. For good bonding the principal step (cross-bridging at the elastomer/bonding agent interface) must be completed before internal vulcanisation of the rubber, if the heat input is determined on the basis of optimum rubber cure. Ideally complete cross-linking should be achieved concurrently with optimum rubber cure - a fact claimed by most bonding agent manufacturers !

The more conventional bonding agent systems, relying on sulphur migration and interdiffusion to form the cross-linking, do not complete the cross-linking stage until after optimum rubber cure has occurred. In practice the moulding times and temperatures are calculated on the basis of optimum rubber cure leaving the cross-linking to carry on during cooling and in some cases not even completing.

With newer bonding agents reaction rates are quicker due to more and better cross-linking ingredients giving a well developed bond prior to optimum rubber cure. Again, in practice the actual moulding conditions will determine the heat input and subsequent reaction.

8.3.3. Bonding Agents

No attempt has been made to develop an 'in house' adhesive system for the following reasons:-

a) A high probability of infringing existing patents

b) Development must start at an early stage, as at present, one can only speculate on the chemistry of bonding.

c) Even if the chemical recipes were known, a new technology must be learnt prior to any large scale production.

In fact some people claim that adhesive formulation is more of an art than a science.

The list of bonding agents, their possible ingredients and patent references (see Appendix No. 4.2) is included to help the reader understand (i) the number of alternatives available and (ii) the general differences or similarities between them. It also acts as a general guide to explain some of the experimental results.

The hot bond strength evaluation of most bonding agent systems (see figure 6.6) has resolved the suitability of each system for manufacturing bushes. Some of these results compare favourably with results obtained at Dunlop (PED) and with experience in actual production throughout the industry.

The main differences between the adhesives examined are due to the criteria mentioned in the previous section, in general the newer Hypalon based, high cross-linking reactant concentration and single coat bonding agents react the fastest and ensure good hot bond strengths. Most bonding agent systems were eliminated at this point due to their unsuitability for manufacturing bushes.

The commercial aspects of the most suitable bonding agents are discussed in Chapter 10.

8.3.4 Factors Influencing the Hot Bond Strength

Within normal acceptable limits, metal cleaning and bonding agent application variables have little effect. Outside these limits more general bonding problems may arise. However, with very thin adhesive layers ($< 5g/m^2$) and very rough metal surfaces (4μ trough to peak) the metal peaks may influence the primer/covercoat interface bond and premature failure will then occur due to high, localised stress concentrations. Figure 8.3 demonstrates this point.

Differences in the hot bond strength when changing from one rubber compound to the next are not great, but only the common rubber compounds have been examined and lower bond strengths may be obtained when using the specialised rubbers. In this respect the newer bonding agents are more versatile than the original bonding systems.

Rubber hardness is important in two ways. Firstly, as the hardness increases so does the true hot bond strength. Secondly, for hard rubber compounds the hot bond strength is high but unfortunately so is the rubber tear strength and normally the bond will fail first. For soft rubbers the converse is true and considerable rubber failure is experienced when the bonded unit is stressed to breaking point. For medium hardness compounds where the rubber and bond strengths are roughly equal the relative amounts of failure will vary; a good bond producing rubber failure, a poor bond producing bond failure. By far the majority of Metalastik bushes are produced in the medium hardness range (45-65 IRHD) and other aspects of this research are based on these compounds.

It is generally recognised that moisture in the rubber compound retards the rate of cure, probably by poisoning the reactive sites along the rubber molecular chain.

These reaction sites are also needed for bonding agent/rubber bonds and therefore the bond strength is reduced. The conventional two coat system, Chemlok 205/Chemlok 220, (see figure 6.11) is not affected as much as the new Chemlok 252 bonding agent, probably due to the interdiffusion required for the former to bond thus presenting more active sites to the interface (i.e. the interface is a diffuse band not a sudden molecular change).

The figure also predicts the true bond strength of Chemlok 252 by extrapolating the graph to the area where 100% R failure normally occurs.

Fortunately, experiments have indicated that the moisture content of rubber compounds produced at Dunlop (PED) is low, in the region of 0.1%, and therefore moisture does not pose a serious problem when using Chemlok 252.

The most significant factor contributing to the hot bond strength is undoubtedly the heat input or cure time/cure temperature relationship.

For constant temperature conditions a dramatic fall in hot bond strength is noticed when the cure time decreases (see figure 6.15). The shape and position of the curve depends on the bonding agent employed or ultimately on the types of chemical reaction and concentration of reactants. The new single coat adhesives achieve adequate hot bond strengths on demoulding for shorter cure times than the optimum rubber cure. Older bonding agent systems require more cure time than the rubber to achieve high initial hot bond strengths, and the Chemlok 205/Chemlok 220 system tends not to improve with further cure time, after a bond strength plateau has been reached - an explanation why early catastrophic failures, found at Dunlop (PED) when Chemlok 205/220 was in general use, were not improved by increasing the cure times.

Constant time conditions yield a fascinating situation (see figure 6.16) where, for the higher temperatures, advantages gained by greater heat input are outweighed by the increased plasticity of the bond. In fact one rubber-to-metal manufacturer had tried to overcome the bush bonding problem by increasing the temperature to 180°C while keeping the time constant and experienced catastrophic bond failure levels.

8.3.5 The Bond Strength of Bushes

Experiments described in Chapter 6 are based on the laboratory test-piece. There is little evidence that the hot bond strength, or the influence of varying conditions and bonding agents are any different when considering the bond in concentric bushes. The main difference is the speed of stress build-up, in bushes this is slow compared with the laboratory test.

In section 8.5 the bond strength is considered to be equivalent in all bushes under the same conditions and when using the same bonding agent system.

8.4 Bush Cooling Characteristics

Application of the finite element method to problem solving using a computer software package has again been achieved with meaningful results.

3 main categories of concentric bush have been identified.

1) Thin rubber and thin inner metal (uniform cooling)
2) Thick rubber cross-section (greater than 10mm)
3) Thick inner metal cross-section (greater than 5 mm)

Other categories exist but do not have specific cooling characteristics:-

e.g. 1. Thick inner metal and thick rubber (is similar to (3)).

e.g. 2. Thick outer metal (classed depending on inner metal and rubber thickness as the cooling characteristics are largely independent of outer metal thickness).

Of the 525 bushes studied:-

373 fall into category (1)
117 fall into category (2)
35 fall into category (3)

The latter category is the worst from the bonding aspect as heat held in the heavier inner metal must pass through the poor-conducting rubber section giving rise to a relatively hot inner bond and increasing the probability of bond failure on the inner metal.

Of course in the above investigation the bush is studied in isolation. On the factory floor, bushes are dropped into tote bins probably containing a number of other parts of various temperatures. Heat would dissipate slower than calculated leaving more time for the cross-linking reaction to complete.

8.5 Links between bond strength and shrinkage stress

Under what conditions will bond failure occur ?

Here values of shrinkage stress and bond strength are brought together in an attempt to show when and why bond failure arises as a bush cools.

Graphical comparisons of shrinkage stress and bond strength against temperature change, for each cooling category, describe the situation:-

Category 1 (Uniform Cooling)

In figure 8.4 increase in stress vs. fall in temperature is plotted for 3 bushes.

i) Low stress bush :- 1.000 MN/m² for 130°C
ii) Med " " :- 5.000 " " "
iii) High " " :-10.000 " " "

The dashed line indicates 1.5 x the average stress (i.e. the approximate maximum stress).

These values are compared with the increase in bond strength for 3 bonding agent systems. All variables are assumed to be at normal values. The cure time/temperature are at the optimum rubber cure conditions and based on 60 IRHD rubber.

Only the high stress line comes anywhere near to the bond strength and even with a margin of error would only pose a threat to the bond formed by Chemlok 205/Chemlok 220.

Category 2 (Thick rubber)

Figure 8.5 shows how the shrinkage stress line for the high stress bush has moved away from the bond strength line because of the slower rate of bond cooling relative to the rubber. Therefore the thicker the rubber, the less chance of bond failure occurring (on cooling characteristics alone).

Category 3 (Thick inner metal)

The opposite situation is evident in figure 8.6 where the probability of bond failure increases as the bond is relatively hotter than the rubber.

For all bush categories only those having average shrinkage stresses in excess of $\simeq$10.000 MN/m^2 should in theory exhibit bond failure and only then if the bonding agent is weak.

In exceptional circumstances, when very high stresses are present the stress/bond strength curves may intersect above the rubber tear strength and split rubber combined with bond failure is possible. For this reason the estimated rubber tear strength is included in the above diagrams.

As cure heat input plays such an important role in determining the hot bond strength, influences of this variable must be considered.

Figure 8.7 (based on figure 8.4) includes a number of bond strength lines representing different states of bond cure. The broken lines are extrapolated from a single point and take the same slope as the unbroken line which represents optimum rubber cure conditions.

Changes in rubber hardness will alter the bond strength and the rubber tear strength. For extremely soft rubbers these will be much lower than previously shown while for hard rubbers both will be higher, see figure 8.8.

Fortunately soft rubbers are unusual in high shape factor, and hence high stress, bushes.

8.6 Bond Failure in Laboratory Moulded Bushes

A number of bushes were moulded in the laboratory to test the theoretical links postulated in the last section.

Non-critical variables were kept at values assumed in the theoretical approach.

Results:-

a) 13/1914 Bush (A small category 1 bush-uniform cooling)

i) Bonding Agent Comparison

Rubber hardness = 60 IRHD; Cure = 15' @ 150°C

Maximum shrinkage stress (1.5 x average) = 21.814 MN/m^2

(N.B. C = Chemlok)

Bonding Agents	Theoretical	Experimental	
C.205/C.252	Good bond	-	100% R
C.205/C.220	Bond failure	10% RC	90% R
C.205/C.220/Thixon A.P.1559	Good bond	Trace RC	100% R

ii) Rubber Hardness Comparison

Bonding System = C.205/C.220/Thixon A.P. 1559; Cure = 15' @ 150°C

Hardness IRHD	Theoretical	Experimental	
45	Good Bond	-	100% R
60	Good Bond	Trace T R	100% R
79	Bond failure	5% RC/TR	95% R

iii) Heat Input Comparison

Rubber hardness = 60 IRHD; Bonding system = C.205/C.252

Cure time temp	Theoretical	Experimental	
15' @ 150°C	Good bond	-	100% R
12' @ 150°C	Good bond	-	100% R
9' @ 150°C	Good bond	1% RC,	99% R
6' @ 150°C	Bond failure	5% RC,	95% R

b) 13/1944 Bush (Category 3 - thick inner metal)

i) Heat Input Comparison

Rubber hardness = 60 IRHD; Bonding system = C205/C252

Maximum shrinkage stress(1.5 x average) = 10.364 MN/m^2

Cure(time,temperature)	Theoretical	Experimental	
15' @ 150°C	Good bond	-	100% R
12' @ 150°C	Good bond	-	100% R
9' @ 150°C	Good bond	25% RC	75% R

Good agreement is achieved between the theoretical study and the experimental results if presented in the above manner. However, due to (i) assumptions made in the stress calculations (ii) unknown factors which influence bonding, (iii) the extrapolation of experimental hot bond strength data, the theoretical links and conclusions cannot be used to account for:-

a) the bond failure levels in each batch of products

b) the percentage area of bond failure (or type of failure) for each part.

8.7 The Prediction of Bond Failure in Concentric Bushes

Which Metalastik bushes shall, in theory, evince signs of bond failure ?

To predict the occurrence of bond failure; the shrinkage stress, hot bond strength and cooling characteristics for each concentric bush are linked together.

Appendix No. 6 contains the results which are shown in the following manner.

For each part and bonding agent system, three grades of failure are given:

FAIL - when the shrinkage stress is greater than the bond strength, i.e. the graphical lines intersect.

PROB FAIL (Probable fail) - when the shrinkage stress is greater than 75% of the bond strength.

POSS FAIL (Possible fail) - when the shrinkage stress is greater than 50% of the bond strength.

Values of shrinkage stress are taken from the results in Appendix No. 3.3. (those computed using the empirical calculation).

Values of bond strengths were obtained from laboratory experiments, reviewed in Chapter 6 and were, in some cases, extrapolated over a range of temperatures.

Adjustments are made to the relative temperatures of bushes falling into categories 2 and 3.

In order to treat most concentric bushes in this way and to keep the amount of computation to a minimum, the moulding temperature is assumed to be 160°C and the cure time equal to optimum rubber cure.

The results given in Appendix No. 6 demonstrate that very few of the 525 bushes examined should, in theory, exhibit bond failure. The number will depend on the bonding agent system employed as shown below:-

Adhesive System	FAIL	PROB FAIL	POSS FAIL
C.205/C.220	15	13	39
C.205/C.220/T.1559	4	4	1
C.205/C.252	1	1	3

(C = Chemlok; T = Thixon)

When the conventional C.205/C.220 bonding agent system is used only about 20 of the concentric bushes are, in theory, liable to bond failure. This contrasts with the catastrophic failure levels experienced when the above bonding agent was used in full production.

For the 3 coat adhesive system employed on the shop-floor until June 1980, the theoretical predictions of only 8 problem bush products bear no relation to the 50-100 products which gave high bond failure levels (10+%) in practice.

Of course the predictions are based on ideal conditions and assume no shop-floor problems exist.

The remainder of this thesis explains the reasons why there are discrepancies between the theoretical and actual situations and attempts to account for the serious bond failure problem still experienced at Dunlop (PED).

CHAPTER NINE

SHOP-FLOOR PROBLEMS

9.1 Introduction

Although the theoretical approach predicts that less than 20 of the concentric bush products manufactured at Dunlop (PED) should give bond failures, in practice nearly all bush products exhibit failed bonds from time to time and for many bushes, a significant number of failed parts are found in every batch manufactured. Bond failures are also found in non bush-like products where no shrinkage stresses are present.

Problems which cause bond failure fall into two categories, subjective (or indirect) and objective (or direct) problems.

Subjective problems are those associated with fundamental manufacturing concepts and are common to any industrial organisation, i.e. the deviation of the real world from the ideal world. Subjective problems are briefly described in section 9.2.

Section 9.3 reviews the objective problems, mainly the technical or engineering troubles which are known to exist on the factory shop-floor. Objective problems most prevalent in concentric bushes are further detailed in section 9.4.

The final section reports bond failure found in a sample of bushes representing a 3 month production period.

9.2 Subjective Problems

a) Evolutionary Changes

The manufacturing organisation can be represented as a 'Productive System'[56] where resource inputs are transformed to create useful goods and services. The inputs are raw materials, energy, labour, machines or facilities, information and technology, all of which must be efficiently managed.

The productive system at Dunlop (PED) Ltd has gradually changed over the years due to short term changes in managerial policies and decisions. This evolutionary process is difficult to quantify but the effect, a finely balanced shop-floor situation, results in minor technical inadequacies leading to major production problems. Studies involving comparisons between operations, processes and machines are made more difficult by the need to account for daily changes. Finally the task of comparing the past with the present,(e.g. why did the bush bond failure condition arise in the early 1970's ?) to explain why an indeterminate change has occurred, also may be hindered.

b) Large Scale Changes

With a very large number of varied products and operations, a 'Jobbing' or batch production system is employed. Thus it could be argued that the manufacture of every product is unique.

Process changes at Dunlop (PED) beneficial to one product or group of products, if introduced on a large scale, are often detrimental to other products. Similarly a material change can lead to benefits in one process area and initiate problems elsewhere on the shop-floor.

c) Shop-floor layout changes

The layout of the shop-floor has evolved to keep in line with process and product changes (remember that the factory originally manufactured tyres).

The large number of varied products means that the process layout is further split for operations particular to specific groups of products. This is manifest in the case of some bushes where a pseudo (some operations are still carried out elsewhere in the factory) Group Technology cell has been established.

However most problems concerned with layout are in the conventional moulding areas where presses are grouped together according to type, make or size of machine. Transfer moulds in the main moulding shop may be distributed to any press and the operator, working moulds of equal cure times, must travel between different press lines during his work cycle. NB. Each operator works a group of moulds, not a line of presses.

d) Job Loading Problems

Associated with the layout difficulties in the main moulding shop is the rather ad hoc method of loading jobs between presses which is solely the responsibility of the senior foreman. To increase output, specifications may not be followed and a particular product may be moulded on one press line one day and another on the next. Variation of this nature makes it difficult to 'tie down' a specific machine or operator to a particular batch of parts.

e) Financial Constraints

Unit production costs are kept to a minimum due to the general industrial recession, high interest rates and low profit margins coupled with a declining automotive market for rubber-to-metal bonded goods.

The outcome, is a policy by the Company of a very tight control on costs, leaving little room for production errors and redundancy in manufacturing methods. Problems must also be solved with the minimum use of resources, often leading to an incomplete solution.

Other subjective problems which may influence general shop-floor conditions are listed below:-

f) Poor communication

g) A tall management hierarchy

h) A low calibre of staff and operatives receiving little job training.

i) Tight specifications leading to dilution of shop-floor tasks

j) Division of the Company into functions with associated cost centre accounting procedures resulting in some rivalry at function manager level.

The remainder of this chapter considers the more tangible objective problems.

9.3 Objective Problems

9.3.1 Causes of Objective Problems

The reasons why specific bond failure problems arise on the shop-floor can be loosely classified into 4 categories:-

a) Inadequate or poor facilities

The total productive system may be adequate but many machines and facilities at Dunlop Metalastik are old, of poor quality and suffer from lack of maintenance. With a mixture of old and new equipment trouble spots will occur at the weakest operation, normally an old or ill-maintained machine.

To the author, procedures for introducing new equipment and processes appear to be informal with pressures of immediate production use forcing shortcomings in standards.

b) Inadequate or poor process and material specifications

Most specifications are made on either past experience in similar circumstances or as a result of development, under ideal laboratory conditions. Problems can creep in if unforseen differences happen between presumed similar products and processes or if the R and D work has not allowed enough 'lee-way' for the scaling up operation and for shop-floor conditions.

At Dunlop (PED) existing specifications are changed and new ones introduced to alleviate emergency troubles on a day to day basis rather than to alter the root causes of problems. Often trial and error methods are used to determine the suitability of a new specification.

c) Human Error

Failures still occur even when equipment and specifications are adequate because of human error, especially with a large number of products and processes. Poor batch identification and control often result in the mistakes going unnoticed and only the symptoms of the error are recorded.

Operatives have been known to carry on making an obvious mistake if it was advantageous to them in terms of shift and bonus allowances.

d) Non-adherance to specified procedures

In the environment already described, strict cost limits, dirty conditions and a policy of dehumanisation it is no surprise that operative(and staff) loyalties are low. In this case Hertzberg's 'Motivation and Hygiene Theory'[57] would predict that the Metalastik worker is very dissatisfied with work and this is reflected in the general levels of operative abuse and union activity.

Nearly all operations suffer from some operative 'modification' and only an intimate knowledge of the daily shop-floor situation would reveal them all. Poor supervision makes the situation worse as many illegal practices go unchecked.

Unfortunately the areas where the abuse is most serious are the moulding shops and here operatives regularly reduce cure times in order to finish their shift quota early thus exaggerating bond failure levels.

Operative abuse can never be fully quantified because operatives, unions and line management will refuse to acknowledge that abuse exists.

9.3.2 General Bonding Problems

Most of the bonding problems are found throughout the product range, including non-bushes where a zero shrinkage stress situation may be the case.

The problems are listed below in order of operations:

- Metal Preparation

Low quality incoming metal parts, with deep weld scars and cutting edge defects that act as stress concentrators at the bond interface, are commonplace.

Reclaimed metals, together with a few new metals, are covered in carbon deposits which the chemical cleaning plant has difficulty removing, so increasing the risk of metal/primer bond failure.

Adhesive spray machines are notoriously difficult to adequately control and frequently the spray gun partially blocks producing an irregular adhesive coating. Poor metal jigs serve to make the problem more acute.

The bonding agent dipping plant achieves consistent average coating weights at the expense of a thickness gradient from top to bottom due to poor adhesive draining, characteristic of adhesive dipping, and again inadequate metal jigs.

- Moulding

Problems with moulding pressures, cure temperatures and cure times are the main troubles. The specified press loads acting on transfer moulds are not adhered to, partly because the operator chooses to work at low pressures ensuring easier mould dismantling and partly due to deficiencies of the hydraulic pumps.

The steam heated, uncontrolled presses show a large variation between the nominal press platen temperature and the inside temperature of the mould, particularly if the mould is unshielded from shop-floor draughts, etc. Fans which serve to keep the workforce cool sometimes are allowed to play directly onto the mould surfaces. Problems still arise with controlled presses if the operative leaves the mould out of the press during the changeover period for longer than about 5 minutes.

Cure times may be around 20-50% shorter than specified on the uncontrolled presses which are open to operative abuse. It is also possible for cure time cutting to occur on controlled presses when the operative gains access to the time switches. (All timers should be locked on controlled presses). The emergency 'press open' button is also used to circumnavigate controlled press cure times.

The quality and condition of the moulds themselves vary considerably. The older loose moulds have suffered damage due to rough handling exaggerated by illegal techniques of removing parts from the mould. These illegal methods are employed by the operatives to save time and frequently impose substantial stress on the hot bond.

Moulds worn by continual use, begin to exhibit problems of excess rubber flash, and movement of inserts and parts during the moulding cycle, which will tear the rubber-to-metal bond.

Contamination of metal parts during moulding is a serious cause of bond failures. Dirty tote bins, a dirty and dusty atmosphere and dirty moulders' gloves all contribute towards the problem. The moulding operative is required to wear two pairs of gloves, one of clean cotton for handling the prepared metals prior to moulding, the other pair, of heat resistant material, for removing the moulded part and for handling the hot dirty moulds. Many operatives save the changing time by wearing both pairs at once!

The design of the mould is important as a poor design can result in air trapped in the mould cavity, or can produce 'not made' parts where the rubber hasn't fully flowed throughout the cavity due to the lack of rubber or low rubber pressure. Some bond failure problems are associated with the 'not made' situation.

- Post Moulding Operations

Most cases of bond failure will have occurred soon after the moulding stage or when the bond is stressed as part of the shop-floor bond failure test.

The test cannot reveal failures deep inside the part (although these will have a minimal effect on the service properties of bushes). Furthermore the method of reporting test results coupled with the time lag between moulding and testing means that a particular bond failure problem may go unchecked for several days and serious scrap levels allowed to continue.

Other post moulding operations do not influence bonding performance.

- Other Problems

Quality variations are bound to arise in all materials used in the manufacture of rubber-to-metal bonded products.

Bonding agents vary from batch to batch in their bonding performance and sometimes the standard of a material falls to levels which cause serious bonding problems. Due to the lack of product batch identification (it is impossible to determine with 100% certainty operations prior to moulding) the identity and quality of the bonding agents are difficult to check.

The quality of the rubber is generally high, however rubber problems do occur - mainly the results of mistakes in mixing the unvulcanised rubber.

In general, operatives do not adhere to instructions on processing documentation through the shop-floor and documents become separated from their work. Then the next operations are carried out using local judgement on the proper procedures for the undocumented parts.

Other problems exist which occur from time to time, these are listed here:-

Use of excess mould lubricant which causes bonding inhibitors to be present at the bond interface. A similar problem is found when rubber anti-tacking agents are used in excess.

Cured rubber contamination from excess rubber flash and transfer pips left in the mould from the previous charge.

The use of a bar to prise parts from the mould, thus stressing the bond and damaging the rubber.

Operational problems with multidaylight presses (i.e. containing more than one mould).

Excess storage times of unvulcanised rubber and prepared metals.

Use of badly pitted reclaimed metals.

9.4 Problems which influence bush bond failure

It was reported in Chapter 4 that the average scrap level for all products is approximately 2.7% while for bushes the figure is around 6%.

The following section re-examines some of the general bonding problems in the bush context to help explain the higher-than-average scrap levels experienced with bushes.

Many bush metals are cut from tubing by the company. Sometimes metal edge defects will initiate bond failure at the bush ends where the localised shrinkage stresses are high.

Dirty prepared metals and their associated problems are prevalent in bushes. The inner metals are piled into tote-bins where considerable damage may occur to the unprotected bonding agent film. On the outer metals the application of the bonding agent to the inside of the tube can prove awkward especially if the spraying method is employed.

The design of the bush mould necessitates the satisfaction of several requirements, only one of which is adequate heat transfer. Often the shape of the mould hinders efficient curing of the rubber/metal bond even though the rubber bulk may be sufficiently cured. Bush transfer moulds are nearly always cylindrical and many contain more than one cavity. Figure 9.1 shows a simple bush transfer mould.

The two press platens act as the heat source and heat flows to the bush via contact with the mould ends. Heat flow from the top platen can be restricted by too much rubber remaining in the feeder cup, a result of overweight rubber blanks or low moulding pressure.

During curing, the inner metal is surrounded by an insulating barrier of rubber except for the contact with the mould core pins. Therefore if the bush is long, the centre of the inner metal will be significantly cooler than the ends or the outer metal and any cure time/temperature reduction may initiate bond failure on the inner metal yet will produce a fully cured rubber section.

Mould damage problems are critical when moulding bushes because damage such as burrs and rough edges around the piston and cavity walls hinder the speedy dismantling and reassembly of the mould between charges thus allowing heat to be lost from the mould. Sometimes if a bush sticks in the mould considerable force is demanded and operatives then resort to unspecified techniques to remove it, including the use of a prepared metal as a hammer or by dropping the mould onto a suitable object. So although mould damage and part jamming do not directly cause bond failure (unless the bond is stressed to breaking point) the loss of heat may not be regained in the next cure cycle, resulting in insufficient bond curing.

The bush G.T.cell employs the new Hydramoulds and presses which are multicavity compression moulds contained in automatic and controlled presses. Bushes, pre-filled with rubber, are loaded into the mould by placing each part on a core pin. The mould is then closed bringing a top set of core pins to bear. Unfortunately heat can only readily transfer via these pins as voids exist in the mould between each part, as shown in figure 9.2.

Here the heat is insulated by a barrier of air from entering the outer metal with a higher probability of outer bond failure.

9.5 Analysis of Factory Bond Failure Data

A sample representing all bond failures in concentric bushes recorded over a 3 month period forms the basis of this study. A list of these bushes and their failure levels together with relevant specifications is given in Appendix No. 7.

Data, obtained from factory scrap records, show the trends in bond failures and are used to examine the effect of shop-floor problems on bush bond failures. Testing errors and the statistical sampling methods utilised by the Testing Department are not thought to affect the general trends presented below.

The relation of the sample to the population of bushes has been established taking into account that products in the sample are only those which exhibited bond failures during the 3 month period (i.e. products with a 0% failure level are excluded).

Figure 9.3 which compares the average shrinkage stress, bush length, rubber hardness and bond failure levels of the population and data sample demonstrates that a significant difference exists in terms of the shrinkage stress between the 108"problem products" and the remainder.

9.5.1 Shrinkage Stress and Bond Failure Relationships

As the majority of bushes are produced using similar metal preparation methods, similar rubber compounds and cure conditions it would be expected that the ultimate hot bond strength would also be similar for the majority of products. Therefore ignoring shop-floor deficiencies, one would anticipate that the stress acting against the bond would influence failure levels.

Figure 9.4 shows a scatter diagram of the percent bond failure (dependent variable) and shrinkage stress (independent variable).

This diagram in fact indicates that little or no correlation exists between these variables for the whole sample.

Any correlation might be masked by the different moulding operations used in bush manufacture. Therefore a similar exercise was carried out on a section of the sample representing those bushes manufactured by one mould type. (see figure 9.5).

Again no correlation is evident between shrinkage stress and bond failure levels.

9.5.2 The Relationship between Bond Strength Variables and the levels of Bond Failure

The main factors influencing bond strength are heat input, bonding agent type, rubber hardness and rubber moisture.

The amount of heat input is a critical factor in producing a satisfactory bond and if the heat transfer to the inner metal is restricted then one might expect failures on the inner bond. Examination of the bond failure data in the sample reveal that 80% of failures are reported on the inner bond. A scatter diagram linking the length of the inner metal with bond failure is shown in figure 9.6.

Regression analysis of the effect of this variable on bond failure levels indicates a significant relationship. Analysis of the inner metal thickness influence also reveals a significant effect on bond failure levels.

Most cure times are fixed to arbitrary values, e.g. 10', 20', 15', 30' to achieve optimum rubber cure while allowing for easier scheduling and loading operations.

The bond failure levels for parts moulded at 15 minutes or less are compared with those receiving greater than 15 minutes.

Cure time	Sample Size	Mean (% bond failure)	Variance (% bond failure)
≤ 15'	62	10.29	237.7
> 15'	46	15.67	359.5

The Student's(t) test predicts that the difference between these means is significant at the 80% confidence level but not at the 90% level. Cure temperature changes are not accounted for here and may bias the results.

Bonding Agents in ideal conditions influence the hot bond strength. For this study the sample size of each bonding agent is too small for a detailed investigation, instead the standard 3 coat system (Chemlok 205/Chemlok 220/Thixon AP 1559) is compared to the remaining systems.

Bonding Agent	Sample Size	Mean (% bond failure)	Variance(% bond failure)
205/220/1559	36	19.25	517.1
Remainder	14	11.90	152.0

Statistical tests indicate that the means are different at an 80% confidence level but not at 90% confidence level. The remaining bonding systems are generally introduced to combat serious bond failure problems and include Chemlok 252, Chemlok 205/Chemosil X2311 which have a higher hot bond strength than Chemlok 205/Chemlok 220/Thixon AP1559.

The rubber hardness plays an important role in both the shrinkage stress and the bond strength. The dependence of bond failure on hardness has been investigated and the results shown in the scatter diagram (figure 9.7) indicate that no links between the hardness and bond failure exist.

No data is available on the moisture content of unvulcanised rubber and this aspect is not statistically examined.

9.5.3 The Influence of Moulding Conditions on Bond Failure

The large variation in moulding conditions, found in the factory,are reflected in the variation of bond failure levels between bushes manufactured in different moulding shops. Figure 9.8 lists the bond failure levels for each mould group.

The most obvious difference lies between the controlled and uncontrolled moulding areas (the difference in means is significant at a 97.5% confidence level).

It has been already mentioned that the length of the inner metal effects the probability of the bond failing; detailed analysis indicates that the size and output of the bush is also related to bond failure. Again the heat transfer phenomenon is thought to be responsible, in particular the heat flow through large single cavity moulds compared to multicavity moulds. Metals in multicavity moulds have time to warm up when the mould is loaded prior to moulding.

Therefore it would be expected that multicavity moulds would produce lower failure rates than single cavity moulds. The table in figure 9.9 demonstrates that failures decrease as the number of cavities increase.

Chapter 9 has described some of the general problems and the more serious specific problems experienced by the company. This is by no means an exhaustive list but will help explain the discrepancies between theoretical and actual bond failures. Individual problems form only a small part of the overall picture but nevertheless all are important in influencing bush bond failure levels.

CHAPTER TEN

IMPLEMENTATION

The laboratory work described earlier in this thesis formed the basis for a number of recommendations which have been subsequently implemented by the Company.

Section 10.1 reports the main change, which is the introduction of a new bonding agent for manufacturing bushes.

Changes that have been made to meet the demand for better cure time and temperature specifications are described in section 10.2.

Finally section 10.3 outlines the communications to the Company regarding some of the research findings.

10.1 Replacement of the Existing Adhesive(s) with Chemlok 252

Why is an adhesive change necessary ?

The following reasons show how the introduction of a new bonding agent was justified.

a) The existing, hybrid, 3 coat system was only originally introduced as a temporary measure.

b) The pressing need to reduce high scrap levels.

c) Change in other areas, e.g. part design, rubber compounding and process technology to alleviate rubber-to-metal bond failure require considerable use of resources, whereas an adhesive change produces a substantial effect for comparatively less effort.

d) A large improvement has been made in bonding agent technology during the last few years.

10.1.1 Preliminary Investigations

All major commercially available bonding agents were examined in terms of their hot bond strength and the results reported in Chapter 6 (see figure 6.6).

Obviously in the bush situation, the higher the hot bond strength the better the bonding performance. Therefore the 6 adhesive systems with the highest bond strength were chosen for further appraisal and are listed below (Megum V11658 and Chemlok 205/Chemlok CH83 were eliminated due to supply problems).

Thixon OSN-2 ; Thixon P7/Thixon OSN-2
Chemlok 252 ; Chemlok 205/Chemlok 252
Chemlok 205/Chemosil X2311; Chemlok 205/Chemlok 220/Thixon AP 1559
(+ Chemlok 205/Chemlok 220 as a control).

10.1.2 Detailed Examination of the Selected Adhesives

Bushes moulded in the laboratory using each bonding agent confirmed the test-piece results, but also revealed some new failure characteristics, e.g. the Thixon P7/Thixon OSN-2 system exhibited significant primer-cover coat failure not encountered with the hot bond test.

A major criterion for good bush bonding, in view of the general shop-floor problems, is the influence of heat input and for this reason the bushes were moulded over a range of cure times.

The results are given in figure 10.1.

Chemlok 205/Chemlok 252 gives the best performance while, as expected, the control performs the worst.

For a material to find large scale use in the factory both reliability and a proven record are important. Chemosil X2311 has suffered in the past from a batch to batch variation in bonding performance, while some Thixon adhesives have shown a lack in consistency regarding general properties. The hybrid Chemlok 205/ Chemlok 220/Thixon AP1559 system composed of both Chemlok and Thixon products shows significant performance variability in use, especially when the adhesive coating weights vary. Although Chemlok adhesives are very reliable, Chemlok 252 is a relatively new and untried material which was introduced to the UK market in September 1979.

Financial considerations must be taken into account and the price of each adhesive system is given below. However, the ultimate material cost will also depend on the optimum adhesive thickness and on the solvent usage.

Adhesive System	Relative Cost (£ per litre)
Chemlok 205/Chemlok 220/Thixon AP1559	7.09
Thixon OSN-2	3.26
Thixon P7/Thixon OSN-2	≃ 5.20
Chemlok 252	3.60
Chemlok 205/252	5.52
Chemlok 205/Chemosil x2311	8.72

General performance characteristics of each material have been examined by Dunlop (PED) technical personnel (not by the author) and their findings include (i) an inferior environmental resistance for Thixon OSN-2 when used without the Thixon P7 primer (ii) lack of pre-bake resistance with Chemlok 252 and (iii) the substantial versatility of Chemlok 252 when compared to other adhesive systems.

All major factors governing the choice of the most suitable material are shown in figure 10.2.

The adhesive system chosen for the large scale evaluation on the factory shop-floor was Chemlok 205/Chemlok 252, mainly because of this adhesive's reactivity, good hot bond strength and general versatility.

10.1.3 Large Scale Evaluation of Chemlok 205/Chemlok 252

A few bushes were moulded on the shop-floor using Chemlok 205/ Chemlok 252, but under close technical supervision. The results of this limited experiment were very encouraging in terms of the good bonds achieved at both specified and reduced cure times.

A large scale trial was then possible, to subject the new bonding system to normal factory conditions and operative abuse. No technical supervision of the moulding operation was allowed although other operations together with the bond failure levels were monitored.

The trial took place over a period of 2 weeks and concerned all bush production. In the majority of cases only the inner metal preparation was affected as most outer metals passed through the dipping plant which could not be readily converted to Chemlok 252.

Five adhesive systems were replaced by Chemlok 205/Chemlok 252 over the trial period and during which the total bond failure level for the products concerned fell by approximately one third. Figure 10.3 gives a summary of the fall in bond failures, while a detailed list of failures appears in Appendix No. 8.1.

The main conclusion stated that Chemlok 205/Chemlok 252 should replace all existing bonding agents specified for bushes for the reasons given below:-

a) A 40% reduction in both bond failures can be achieved, resulting in an annual direct cost saving in the order of £50,000.

b) Annual material costs can be reduced by £9,000 (see section 10.1.4 for an up-to-date financial appraisal).

c) Rationalisation of adhesives used throughout the factory is possible due to the improved versatility of Chemlok 252. At least 4, probably 6 older bonding systems can be discontinued.

d) Shorter cure times are possible, probably to times within the optimum rubber cure.

e) Unlike other bonding agents Chemlok 252 is 'Non-flammable' thus handling and storage are made easier.

10.1.4 The Introduction of Chemlok 205/Chemlok 252 into General Production

As the exercise required that Chemlok 205/Chemlok 252 be introduced on most Metalastik products (not only bushes) a substantial general appraisal of the material was undertaken before the management decided to implement the above recommendation.

During this time the author acted in an advisory capacity only; decision and organisation of the implementation remained with the Production Management personnel.

However due to production pressures the new adhesive was specified for a few problem bushes prior to the above decision being made (e.g. the 13/1935/00 bush whose scrap level fell from 80% to 7%).

The introduction of the new material was in 3 stages, first the dipping plant was converted, followed by the main spraying areas and finally the hand painting and specialist areas of the factory.

To date over 95% of bush manufacture has been affected and the fall in general bond failure levels are shown in figure 10.4. These figures apply to all products, as the method of recording bond failures makes it difficult to give values for bushes alone. The graph shows a fall of approx. one third in bond failures after Chemlok 252 was introduced. (Recent results may be high due to the problems encountered with a 4 day working week).

For a number of products, percent bond failure levels specific to each batch of parts are given in Appendix No. 8.2.

10.1.5 Problems Associated with the New Material

Such a radical and widespread change is bound to produce unforseen difficulties. Two important problems have arisen.

a) Mould Fouling

Mould fouling, basically the adhesion of the rubber to the mould wall is enhanced when the adhesive ingredients vaporise and coat the mould metal surface. Unfortunately, the main attribute of Chemlok 252 lies in its faster rate of reaction with the rubber caused by a trebling of the active ingredient (p-dinitrosobenzene) concentration.

This problem has only arisen with certain moulds and very few bushes are affected.

b) Rubber 'Lamination'

This problem is found mainly in bushes and is characterised by weak areas within the rubber section. The extreme case is evident by a splitting of the rubber at the bush ends.

Again the problem is due to the faster reaction rates causing premature curing of the rubber during injection into the cavity.

The worst cases were found to be a consequence of the poor shop-floor control of moulding pressures (causing slow rubber transfer) and the problem reduced to acceptable levels once specifications were followed.

10.1.6 A Financial Appraisal of the Change to Chemlok 205/Chemlok 252

The complex manufacturing methods, well over 5,000 products and the 'evolved' accounting methods make if exceedingly difficult to assess completely the financial advantages of introducing this material. However, some costs are available, e.g. the direct material costs, and are given in Appendix No. 8.3.

A summary of these costs comparing the main 3 coat system with Chemlok 205/Chemlok 252 are given below:-

		Annual Costs (£)	
		AP1559 Chemlok 205/Chemlok 220/Thixon	Chemlok 205/Chemlok 252
Material		119,400	108,200
Labour		8,100	6,100
Overheads	(Spray)	27,300	23,200
(factory)	(Dip)	25,700	16,800

10.2 Changes in cure Specifications

In the past cure times and temperatures were based on the optimum cure of the rubber compound. Problems with bond failures and other production difficulties led to arbitrary increases in cure times or temperatures for many products.

The new bonding agent (C205/C252) requires less reaction heat than the older conventional bonding agents therefore in principle long cure times may be reduced with no harmful effects.

Although the hot bond strength v s. cure time curves plotted from laboratory experiments (see figure 6.15) indicate the relationship between rubber optimum cure and bond heat requirements, any cure conditions for bushes must take into account the relative masses of the rubber and metal and efficiency of the mould. Therefore practical methods are the best for determining the optimum heat input.

10.2.1 An Investigation into Cure Specifications

For each group of moulds a number of cure determinations have been carried out on a selection of bushes. In practice the optimum cure was determined by moulding a number of bushes over a range of cure times and examining the parts produced for any sign of bond failure. No attempt has been made to alter the cure temperature as this would considerably complicate shop-floor procedures. Whenever possible the rubber compound was also checked for the state of cure. NB. These experiments were undertaken on the shop-floor moulding facilities after the full introduction of Chemlok 205/Chemlok 252.

A number of general observations are given in this chapter while the actual experimental results are listed in Appendix No. 8.4.

Observations

a) The Hydramould Area

For a bush manufactured in the Hydramould area the cure time will have been selected from a scale of 1 minute increments after a technical evaluation exercise when the bush operation specification was transferred from the conventional moulding shop.

With the change in adhesive to Chemlok 205/C.252 these cure times can all be safely reduced by 10% except for present cure times of less than 10 minutes. These short cures are normally for small bushes where the optimum rubber cure is critical and where the bonding agent is only just reacting with the rubber. Any time reduction on these small bushes should be only after further evaluation on an individual product basis.

On some bushes already tested, e.g. 13/1920, a 20% reduction would be feasible but this is not recommended due to problems with operative abuse (the margin of error is insufficient to withstand operator shortened times).

b) <u>The Conventional Moulding Area</u>

A number of set cure times and temperatures exist for conventional moulding, two of which account for the majority of bushes. They are 15 minutes at 170°C and 20' at 170°C. The results of this exercise indicate that 15 minutes could be reduced to 12-13 minutes and the 20 minutes cure to 15-16 minutes. Although in nearly all cases no problems will arise, for some bushes the reduced cure times may be very near the optimum rubber cure and will affect the properties of the vulcanised rubber. Of course with reduced times the margin of error is smaller and greater control would be necessary to ensure adherence to specifications.

The greatest cure time reductions are on the 'problem' bushes, i.e. those which in the past have given high failure levels and subsequently have been grossly overcured to ensure that adequate heat reaches the bond.

The reductions now possible on 5 products are listed below, for other 'problem' bushes reductions can only be made following an individual evaluation of each product.

Bush No.	Present cure time	Recommended cure time
13/1928	45' @ 170°C	25' @ 170°C
13/1935	30' @ 170°C	15' @ 170°C (30' @ 160°C)
13/2045	45' @ 160°C	25' @ 160°C
13/2053	45' @ 170°C	30' @ 170°C
13/687	60' @ 153°C	40' @ 153°C

The above observations are of an objective nature and formed part of a report to management recommending specific changes.

A more subjective observation or recommendation would be that all cure times may now be reduced to a value based on the optimum cure time of the bulk rubber, as the new adhesive system requires less heat to bond than the rubber needs for adequate vulcanisation.

10.2.2 Implementation of reduced cure specifications

Some of the recommended changes have already been put into practice, these include the 10% cure time reduction of Hydramould production and 4 of the 5 specific reductions mentioned above.

Other reductions will depend on management decisions reflecting other factors, e.g. operator payment schemes.

10.3 General Guidelines for Manufacturing Bushes

To aid designers predict high shrinkage stresses early on in the development of new bushes a computer program has been written which is similar to that described for calculating shrinkage stress in Chapter 5. Only regular, concentric bushes can be examined in this way.

The list of shrinkage stresses for products now in production (given in Appendix No. 3.3) has also been made available to the Company.

Work reported in Chapter 6, together with the results of the bond failure prediction exercise(linking the shrinkage stress with the hot bond strength) described in Chapter 8 have been communicated to the Company.

Finally a report setting out general guidelines for improved methods of manufacturing concentric bushes has been presented to Dunlop (PED) Ltd.

CHAPTER ELEVEN

DISCUSSION

The evidence presented so far may suggest to the reader that a wide disparity exists between the ideal and actual conditions of bush manufacture.

Chapter 11 discusses the magnitude of bush bond failures and the differences which are evident between predicted and recorded failure levels. The reasons why bushes have higher failure levels than other Metalastik products are examined in section 11.4.

The last part of this chapter takes a wider approach to the problem and finally indicates how the main objective of the research, the reduction of bond failure levels, should be achieved.

11.1 Bond Failures - Ideal v s. Actual Conditions

Discussion in Chapter 8 centered on a comparison of shrinkage stress with the hot bond strength to enable predictions to be made on whether or not a bush will fail under ideal conditions.

It was concluded that less than 20 of concentric bush products manufactured by Dunlop (PED) would under ideal conditions, exhibit bond failure.

In contrast the actual bond failure levels for bushes are very much higher; around 75% of bush products have occasional bond failure problems with many products showing a high number of failures in every batch manufactured.

The predicted failure levels are based on the ideal performance of the relevant materials and processes. Constant relationships can be drawn between the factors which influence bond failure, e.g.

shape factor, adhesive strength and rubber hardness, and the predicted failure levels. Thus in theory a part should either pass or fail and all similar parts in the batch should do likewise, i.e. either a 0% or 100% bond failure level.

For actual conditions the above factors are found not to be directly related to bond failure and the failure levels are entirely random in distribution. In practice only a proportion of the parts in a batch will fail and furthermore a considerable variation in failure levels exists between batches of parts.

For individual products, comparisons may be made between the theoretical situation and actual bond failure levels by referring to Appendices 6 and 7.

Ideal conditions exclude the 'real-life' problems described in Chapter 9 so that it can be assumed that as shop-floor problems decrease then the real situation would tend towards the ideal situation and the predicted failure levels would become more meaningful.

The influences of shop-floor problems on bush bond failures are discussed in the next section.

11.2 The Influence of Shop-floor Problems on Bond Failure Levels

The scatter diagram of shrinkage stress v s. % bond failure (see figure 9.4) demonstrates that the bond failure levels are apparently not related to the amount of shrinkage stress. This would also agree with the fact that shrinkage stresses are, in most cases, not sufficient to cause bond failure under adequate conditions. Therefore the randomness of bond failures must be caused by variations in the bond strength which in turn are influenced by shop-floor inadequacies.

Shop-floor bond failure problems can be split into two groups. i) heat dependent and (ii) heat independent problems.

11.2.1 Heat Dependent Problems

The experimental work in Chapter 6 revealed a major factor influencing the hot bond strength to be the heat required for sufficient rubber/adhesive cross-linking.

Several criteria examined in Chapter 9 dealt with the amount of heat reaching the bond, e.g. bush length, number of mould cavities, etc.

The restraints on heat flow through a transfer mould make matters worse with the longer the bush, the taller the mould and the greater heat loss between the press platens and the centre of the mould. The scatter diagram (see figure 9.6) shows that the longer the bush the higher the bond failure levels and examination of failed parts often reveals the area of separated bond near the centre of the part.

A similar correlation is achieved when the inner metal thickness is compared to bond failures and here bushes with thick metals are prone to failure. Two reasons can be postulated for the thickness effect (i) the metal acts as a heat sink resulting in the inner bond warming up more slowly than the rest of the part, and (ii) during cooling the inner bond is hotter than the rubber (see the discussion in section 8.4).

As multicavity moulds take a considerable time to load and unload many of the metals will have sufficient time to warm up before the cure cycle begins. The improved bond performance due to the enhanced heat input is shown in the figure 9.9, where multicavity moulded products have relatively low bond failure levels.

Lack of machine or operator control can also be responsible for insufficient heat reaching the rubber to metal bond in view of the arbitrary reduction in cure times by the operator so that he can finish his shift early. It is thought that some operators have finished their quota after 6 hours of an 8 hour shift. The control of presses is mentioned in Chapter 9 and figure 9.8 compares the average bond failure levels for products manufactured on each type of press showing that the uncontrolled (i.e. no time controller) presses give by far the highest failure levels.

Other factors are obviously involved in reducing heat input, e.g. method of press heating (by steam or electricity), size of press, temperature controls, air flow through the factory and the environmental temperature. These factors are either so random that they cannot be equated with bond failure levels or are considered insignificant in relation to the main variables examined above.

11.2.2 Heat Independent Problems

Of the heat independent causes of bond failure, those relating to metal cleaning, adhesive application and 'difficult' rubber compounds occur regularly at Dunlop (PED).

Chemical cleaning of metals cannot remove very heavy carbonaceous surface deposits caused by certain metal fabrication process. Metals where the surface contamination is so bad that adhesive/metal bond failure is likely are re-routed through the mechanical cleaning process prior to adhesive dipping. Unfortunately the re-routing results in considerable inconvenience to the shop-floor routine and so only happens when extreme levels of bond failure are encountered.

When the adhesive coating is very thin no bond will form. Areas of very thin adhesive occur on certain parts due to incorrect metal jigging design during spraying or dipping and the moulded bushes will show areas of apparent bond failure.

Bond failures (or again no bond formation) also result from the use of certain rubber compounds. These are the very soft, non-polar compounds employed in a few bushes.

Other non-heat related problems are given below:-

- Contamination of prepared metal surfaces and rubber blanks
- Mould pressure irregularities
- General operator abuse and damage
- Causes attributed to mistakes in the use of materials or in the loading of machines.

11.3 "Cause and Effect"

Although some of the above problems can be linked to bush bond failure trends, the situation is generally more complex.

Many direct causes of shop-floor problems are themselves the outcome of indirect or fundamental causes; these are:-

a) Primary(indirect) causes having a fundamental bearing on the problem.

b) Secondary (direct) causes seen as the immediate reasons for bond failure.

Primary causes are often not readily identifiable and can be subjective in nature. In some instances a number of primary causes may all contribute towards a more tangible secondary cause. Conversely a number of secondary causes may be the symptoms of only one fundamental cause.

A number of typical problems with their primary and secondary causes are listed in figure 11.1

The present Company policy of 'day-to-day trouble-shooting' together with a general cover-up attitude by Production Dept. personnel and with limited investigatory resources (bond failure problems are normally investigated using a hack-saw, knife and magnifying glass) tend to mask primary causes by discouraging in-depth investigations. Regrettably solutions to problems are often found by altering another aspect of the situation to alleviate the effect of the secondary cause while not removing the primary cause. Then short term gains can be made until the primary cause again begins to influence the situation. Typically a problem will persist for years with operatives and management 'living' with it and only dealing with the symptoms when the situation becomes intolerable.

11.4 The Reason for the Higher Level of Failure in Bushes

Although bushes (and bush like products) have substantially higher levels of bond failure than other products manufactured by the Company, all products are subjected to similar shop-floor problems and so the influence of high shrinkage stresses in bushes is the fundamental cause of this phenomenon.

On the other hand figure No. 9.4 showed that no direct correlation existed between shrinkage stress and bond failure in bushes.

So why are concentric bushes difficult to manufacture correctly?

The answer lies in the concept of low bond strength resulting from general shop-floor inadequacies combined with high stresses due to the rubber shrinkage and part configuration. In fact the introduction to the research in Chapter 4 postulated that both stress and bond strength have a bearing on bond failure (see figure 4.1) but with the emphasis perhaps on the high shrinkage stress.

However the research has revealed that except for a few bushes, the shrinkage stress cannot alone separate the bond formed under ideal conditions and that most failures arise due to a weak hot bond strength.

In non-bushes even when the hot bond strength is low no appreciable shrinkage stress is present and the bond will cool intact to give a cold bond strength much greater than the rubber tear strength. Here only shop-floor problems which either inhibit bond formation or cause weaknesses in the cold bond will precipitate failure and these problems are responsible for the base level of 1-2% failures found in all the Metalastik product range.

The above explanation may serve to show why bushes are different from other products but a further question arises of, 'why does a bush show a wide failure variation from batch to batch ?'

11.5 Bond Failures - Batch Variations

The theoretical viewpoint that a product will have either a 0% or 100% batch failure level is not borne out in practice where normally only some parts in a batch fail.

Except for the case where the shrinkage stress and bond strength are almost equal so that the bond fails occasionally, one would expect a 'bad reactor' bush to be constantly bad. This doesn't happen because the inherent variability of each factor influences the whole situation at any given point during the part cooling phase. In fact a wide variation exists between batches of the same product.

Some examples of variability are shown in figure 11.2.

Factors influencing the shrinkage stress, e.g. rubber hardness, shape factor, temperature change, can all be considered relatively constant when compared with the significant variation of factors which influence the hot bond strength due to shop-floor variations, e.g. cure time, contamination, etc.

Therefore for a specific product the distribution of shrinkage stresses is narrow, while the distribution of hot bond strengths is large. Figure 11.3 portrays the situation for 3 bushes.

The diagram assumes that the bond strength distribution is the same for 3 products, while 3 typical shrinkage stress distributions are given representing a low (i), medium (ii) and high (iii) shrinkage stresses.

Three situations then arise:-

a) For a low stress bush (i) the bond will only fail when catastrophic shop-floor inadequacies occur thus pushing the bond strength distribution curve far to the left. This often produces very high levels of failure, e.g. 13/1519.

b) For a medium stress bush (ii) the stress distribution lies in a similar region as the bond strength distribution. Either slight loosening or tightening of shop-floor practice will move slightly the bond strength, either to the left or right, giving a large change in the bond failure level from batch to batch accompanied by high failure levels, e.g. 13/1935.

c) For a high stress bush (iii) catastrophic failures predominate until manufacturing specifications are up-graded allowing the bond strength curve to move to the right of the stess distribution. Often an 'over' specification; e.g. an extremely long cure time, is needed.

The bond strength distribution will also be narrowed as control tightens and then most parts are satisfactorily produced with little batch variation in failure levels, e.g. 13/1928.

The shape of both distributions are important, although in practice the bond strength variation is the most critical because the lack of shop-floor control leads to uncertainty in future bond failure levels for each product.

11.6 The Effect of Uncertainty

For a specific bush, bond failure levels can be:-

i Constantly low

or ii Constantly high

or iii Fluctuating between high and low

To the Production Manager/Controller the third category is by far the worst as the uncertainty makes increased demands on his skill.

Uncertainty about levels of failure in future batches of each bush give rise to problems in scheduling and loading, raw material and finished goods inventories, and in quoting delivery dates.

A simple illustration of how variability can affect these functions is given below.

A problem bush has a mean failure level of 50%. Individual batch failure levels vary from 25% to 75%.

An order is received for 100 parts.

Should the factory schedule be made out for a batch of

i 100 parts

or ii 200 parts

or iii 133 parts

or iv 400 parts ?

Alternatively should an economic batch quantity be found using probability statistics and then more than one batch scheduled ?

How many metal parts should be ordered and what re-order level will be employed ? This aspect is further complicated by the Company policy of recycling the metals from failed parts.

Finally, can an accurate delivery date be given ? This depends on the finished goods inventory policy.

The whole situation makes life much more difficult in controlling these aspects of production planning and is further compounded by some of the cumbersome methods used for scheduling and stock control employed by Dunlop (PED).

A further effect of bond failure uncertainty lies in the computation of a product's unit cost.

11.7 General Discussion

11.7.1 Links between theoretical, ideal and actual bond failures

Although bushes fail during manufacture the project was originally presented to the author as a purely technical problem, i.e. a high shrinkage stress was thought to be mainly responsible, assisted by the thermoplastic nature of some bonding agents.

However following from the research presented in this thesis one could argue that, as few products should fail in this manner under ideal conditions, the Company has got the technology of bush manufacture about right. On the other hand the manufacturing methods and production conditions leave a great deal to be desired.

These points are confirmed by referring to the study of bushes moulded under laboratory conditions (section 8.6) and comparing the results with shop-floor data. Figure 11.4 shows these results for

3 bushes under theoretical, ideal and actual conditions, indicating the differences between theory and practice.

A number of other bushes have been examined and attempts made to equate the theoretical predictions with actual failure levels but again significant differences exist.

Therefore one cannot, from theoretical or ideal (laboratory) information alone, predict with any accuracy the percent bond failure level of any batch of parts.

11.7.2 Limitations in the Present Technology

The technology of bonding rubber to metal is, in general, well advanced at Dunlop (PED) Ltd. The main exceptions have been the non-use of the most suitable adhesive systems and the apparent disregard for the importance of heat input to the initial bond, both of which are shown in Chapter 8 to be important factors in determining the hot bond performance.

Adhesive suppliers have always claimed that the original bonding agent systems, e.g. Chemlok 205/Chemlok 220, need the same heat to reach optimum cure as the bulk rubber. However this research has demonstrated that the "older" bonding agents require more heat than the rubber for sufficient bond crosslinking to provide adequate bond strength during demoulding.

New adhesives, in particular Chemlok 252, are faster curing and require less heat than for the optimum rubber cure to produce satisfactory hot bonds.

The management of heat flow during moulding is a subject considered relatively unimportant by past company technologists. At present, on conventional presses the specified temperature relates to the temperature (quoted in steam pressure) of the steam heated press platen. The mould temperature is generally assumed to be uniform and $10^{\circ}C$ lower than the platen.

In fact, due to the different mould designs, types of press and size of bush metals the actual temperature at the rubber to metal bond can vary significantly from product to product. Mould and press designs must allow for the loss of heat and specifications should be based on mould rather than platen temperatures.

Ideally the cure time control should depend on the exact amount of heat reaching the bush. The author has witnessed such a technique in the U.S.A. where a manufacturer (Lord Corporation, Erie, Pennsylvania) employs microprocessor controlled presses supplied with temperature information from thermocouples placed inside the mould and adjacent to the bush. No cure time or exact cure temperature is recorded, instead specifications relate to the amount of heat required for optimum vulcanisation and bonding of each product.

Another method of improving the present technology would be to alter the temperature distribution of a bush during cooling by flash cooling the metal components using solid carbon dioxide, chilled air or chilled liquids. Here the bond would cool much faster than the rubber and the bond would reach adequate strength before maximum stress is developed.

The bush bonding problem could be largely eliminated by using one of the alternative bonding technologies described in section 3.5. With post-cure bonding, in particular, no significant shrinkage stresses are developed as the rubber section is moulded separately and then forced between the metals prior to bonding. However a change to this and other technologies would require a major investment programme and the accompanied benefits would not be sufficient to justify this if improvements in the present technology would bring about similar benefits for considerably less capital investment.

11.7.3 Moulding Problems

Rupture at the rubber/adhesive interface is by far the commonest form of bond failure and is normally associated with limitations during the moulding operation.

This section examines how shop-floor moulding practices effect the levels of bond failure, by presenting 2 scenarios relating to the moulding operation, for problems may be insignificant in isolation but all contribute to an overall moulding performance.

Scenario One (Efficient Moulding)

A modern semi-automatic press with full cure time and temperature control is used. The mould is directly heated and fully enclosed within the press during the cure cycle. Mould surfaces are undamaged.

Well prepared bush metals, with tight dimensional tolerances are stored in clean bins, adjacent to the press (the metals may be pre-filled with rubber.) The operator opens the mould, places the metals and rubber in the appropriate sections and re-assembles the mould. The mould easily slides back into the press and the press automatically closes thus starting the cure cycle. After the alloted time the press opens allowing the operator to remove the mould which he opens with the minimum of effort. The moulded parts are quickly taken out and carefully placed in the correct receptacle. All rubber flash and pips are easily removed from the mould.

The time for unloading and reloading the mould is around one minute.

Scenario Two (Inefficient Moulding)

The press is one of a line of presses, all of which are steam heated and have water hydraulic pistons. The whole line has only one temperature and pressure control.

The loose fitting mould is badly designed in terms of heat retention or flow and is very heavy to handle. It has also suffered from considerable wear and damage, so that the operator has reduced the press pressure (from the specified value) to aid removal of parts from the burred cavities.

The operator removes the mould from the press and dismantles the complex mould components. Metal parts, taken from dirty tote bins are forced into the mould cavities using a liberal application of mould lubricant. Further damage to both metals and mould may ensue as the operator assembles the mould.

When the mould is in the press, the platens are closed and the operator notes the time on a nearby clock. The mould temperature will be 15-20°C lower than specified due to the factorydraughts playing on the unshielded mould. Rubber flash inside the mould hinders heat flow to the part.

The operator opens the press after a period of time convenient to him has elapsed and removes the mould. Considerable force and time is needed to remove the bushes from the mould owing to the damage incurred when the metal parts were loaded. In extreme cases the operator uses a hammer or any nearby tool for this purpose, thus applying a bond tearing stress to the newly moulded bush. The bushes are then thrown into a tote bin.

Time for unloading and reloading the mould is in excess of 5 minutes, allowing the mould to significantly cool prior to the next cure cycle.

In practice the newer Rep, Meterjet and Hydramould moulding shops are similar to scenario one while work in the main conventional moulding shop is typical of scenario two. The effect of the problems encountered in scenario two can be demonstrated by referring to figure No. 9.8 where the average failure level for small loose moulds (conventional presses) is 19% compared with 5% for the Hydramould presses.

Many of the larger, low volume, bushes are still manufactured on the conventional presses although the Company is planning to transfer most bushes to the Hydramould bush line by 1983.

11.7.4 Reduction of Bond Failure Variability

Here some changes in general policy, required to reduce bond failure variability, are discussed:-

a) Monitoring of Operations

The operative, foreman and line manager all have one common objective, that of completing their specified work quota within the allowed time. Unfortunately this increases the incidence of shop-floor malpractice.

The best way to limit malpractice or abuse is to introduce a comprehensive machine control system. However automation on this scale would be costly and the author doubts the feasibility of, for example, using microprocessor control units on out-dated, worn-out presses.

Alternatively, malpractice may be reduced by installing a complete operation monitoring system (e.g. using instrumentation and recorders) backed up by increased supervision.

For instance, although it is common knowledge in the company that cure times are cut by the moulding operative, what is not known is exactly by how much and how often. The fitting of monitoring devices to moulding presses would produce cure time records which could be used to cajole or reprimand the operator in the event of short cure times. Probable trade union pressure against such action would lessen the impact of the exercise but nevertheless the information gained would be invaluable to the technologist and manager in future decision making.

Monitoring of other operations would also produce useful information and show where, when and what variations or deviations exist.

b) Monitoring of Product Batches

Information from the monitoring of operations must be complemented by knowledge of the flow of materials through the factory in order to enable the technologist to combat high bond failure levels.

At present both the rubber blanks and metal parts are documented until they reach the moulding shop where identification is lost as many operators fail to transfer these documents to the moulded products. Similarly moulding documents are discarded at the finishing stage due to a political decision of the finishing manager. Unfortunately a gap of several days between moulding and bond testing is usual and when failed parts are discovered it is near impossible to trace (i) when, by whom and where they were moulded, (ii) the rubber batch used and (iii) the metal preparation history.

The only way to improve the present situation is to ensure that all documents are transferred to the next operation. Alternatively a new batch I.D. system could be introduced based on a concept of a unique identifier for each batch of parts and utilising shop-floor computer facilities to monitor the flow of materials.

c) Rationalisation of Materials and Processes

The large number of different materials and process routes employed by the company contributes towards the variation in bond failure levels mainly through increasing the probability of mistakes occurring.

Careful planning and customer education can eliminate the need for some process permutations and product variants.

The introduction of Chemlok 252 is one example of a rationalisation measure, as a number of older adhesive systems have been phased out.

d) The Approach to Problem Solving

The present policies at Dunlop (PED) encourage immediate action on day to day problems but leave no room for longer term in depth problem solving.

The daily 'Morning Meeting' of shop-floor managers considers one or two problem products (in terms of bond failure) and a solution must be presented by the Works Technical Manager at the following Morning Meeting. This normally results in a remedy of the symptom not a correction of the root cause.

The author feels that a policy of longer term bond failure investigations should be re-introduced by examining in depth (i) all operations concerned with a small number of high volume high scrap products and/or (ii) a specific operation or machine for a period of several weeks, irrespective of the products fabricated on it. The short term daily investigations should still continue to handle sudden 'out of control' bond failure situations.

The policy alterations discussed in this section are necessary in view of the subjective problems (mentioned in Chapter 9), especially the continual change experienced throughout all aspects of the Metalastik organisation.

CHAPTER TWELVE

CONCLUSIONS

The following conclusions can be drawn from work presented in this thesis. The first 5 sections should be considered with the theoretical discussion in Chapter 8.

12.1 Shrinkage stresses in concentric bushes depend on the bush shape factor, rubber hardness and the temperature change during cooling. The the main direct stress (normal to the bond interface) has 3 maxima, one at the centre and two highly localised maxima at the bush ends.

12.2 Results obtained using the hot bond test, developed specifically for this research, have demonstrated that the bond strength on demoulding mainly depends on the rate of molecular cross-linking between the rubber and adhesive during the cure cycle. In practice the main variables which influence the hot bond strength are (i) the bonding agent reactivity,(ii) the heat input during moulding, (iii) the rubber hardness and (iv) the rubber moisture content.

12.3 At Dunlop Metalastik the cure time and temperature values are based on the heat required for optimum rubber cure. This research has shown that the adhesives employed prior to June 1980 normally require more heat than the rubber cure for optimum bond formation, while the new adhesive system (C205/C252) introduced in June 1980 will achieve adequate bond strength before the rubber has reached optimum cure, thus reducing the likelihood of bond failure.

12.4 A study of the bush cooling characteristics has identified 3 general categories of bush:

i) Thin rubber and metals (uniform cooling)

ii) Thick rubber (Bonds relatively cooler than the rubber)

iii) Thick inner metal (Inner bond relatively hotter than the rubber.

12.5 The shrinkage stress and bond strength value for each bush have been compared to show that, under ideal conditions, very few bush products should fail as a result of the high shrinkage stress/weak hot bond situation.

12.6 In contrast to the above, under actual conditions, most bush products exhibit bond failure, often with a considerable variation in bond failure levels between batches of the same product. These higher than predicted failure levels can be explained by reference to the following shop-floor problems encountered at Metalastik:-

a) Efficient heat flow from the press platens is hindered by excess rubber in the conventional transfer moulds and air gaps in the Hydra-moulds.

b) A thick inner metal acts as a heat sink resulting in an incomplete reaction taking place at the inner metal/rubber bond. Similarly bushes with long inner metals are prone to bond failure due to the inability of enough heat to reach the bush centre when the heat sources are placed at the ends on the mould.

c) Conventional moulds are slow to load and unload and in an unfavourable factory environment, e.g. air draughts etc, considerable heat is lost from the mould.

d) Lack of machine or operator control is also responsible for insufficient heat reaching the rubber-to-metal bond, in view of the arbitrary reduction in cure times by moulding operatives.

e) The chemical cleaning of metals cannot remove very heavy carbonaceous deposits from the metal surface which, if left, will act as a barrier to formation of the bond.

f) Incorrect adhesive spraying and jigging of metals will produce thin areas of adhesive where no bond will form.

g) Surface contamination of prepared metals is a problem especially when operatives handle these metals without wearing the correct gloves.

h) The Company lacks suitable batch identification and process monitoring systems which has the effect of increasing variability and hindering the investigation of specific bond failures.

The short term investigatory methods used at present, often fail to solve a problem and only provide a remedy for the symptoms.

12.7 The variation in the percent bond failure levels between batches of the same product originates from the relative distributions of shrinkage stress values and hot bond strength values for the parts in each batch.

Three idealised cases have been identified:-

i) Low stress bush - high failure levels only when catastrophic shop-floor problems occur.

ii) medium stress bush - a large batch to batch variation affected by slight shop-floor problems.

iii) high stress bush - the over specification needed to efficiently manufacture this product results in a low batch variability.

CHAPTER THIRTEEN

RECOMMENDATIONS

The following recommendations propose improvements in the manufacture of concentric bushes at Dunlop (PED) Ltd. Some are also applicable to other bush manufacturers and to non-bush products.

13.1 Technical Aspects

a) If the cure time and temperature continue to be based on optimum rubber cure then a more reactive adhesive system must be employed. Furthermore there is a need for a rationalisation of bonding agent systems to reduce shop-floor variability and associated failures. (These recommendations have already been implemented with the introduction of Chemlok 252).

b) With the introduction of a more reactive adhesive, the cure times/ temperatures of some products may be reduced to the optimum rubber cure conditions.

However short cure times accompanied by high cure temperatures should be avoided as any gains in improved heat input are off-set by a hotter, and thus weaker, bond.

c) In future the design of moulds must account for the insulating effect of excess rubber and air gaps within the mould by the use of tighter tolerances and longer metal core pins.

Special consideration should be paid to the moulding of high shrinkage stress bushes with long and thick inner metals. This should include:-

i) More control on the moulding operation (these parts given special supervision).

ii) Pre-warming of the inner metals.

iii) Low temperature (140°C), long cure time conditions.

d) Bush metals covered with carbonaceous deposits or fabricated from smooth 'cold drawn steel' tubing should be wheel abrated prior to chemical cleaning.

e) A test for the hot bond strength based on the test-method used in the research should replace the old, arbitrary test-bobbin method for development work.

13.2 Production Aspects

a) A number of steps can be taken to minimise the heat loss from conventional presses and moulds (these also apply to a lesser extent to the new press lines).

- i) complete shielding of the press
- ii) insulation of the mould external surfaces and of the press platens
- iii) discriminate use of shop-floor ventilation systems
- iv) use of single daylight presses for tall bush moulds
- v) a maximum time specified for unloading and loading a mould, if exceeded the mould should be returned, empty,to the press for reheating.

b) Machine and process control must be improved, in particular the cure times must be completely controlled. Present time switches which can be easily 'by-passed' should be replaced by timers which are difficult for the operator to abuse and will visibly indicate when deviations have occurred.

Other areas that could be improved include the chemical cleaning solutions where automatic chemical analysis equipment would be desirable and the operation of the auto adhesive spray machines where the determination of the spray characteristics should be removed from the operator to the machine.

c) Contamination of prepared metals should be reduced by lining all tote bins with paper, storing heavy metals on their ends rather than on their sides and ensuring that operators wear the proper gloves.

13.3 General Aspects

a) More emphasis should be placed on improving existing shop-floor operations, by use of technical know-how backed up by an operations monitoring system, rather than on evaluating new materials and processes.

b) A system of batch identification must be introduced whereby all operations are traceable and individual operatives identified when high bond failures arise, to assist in the speedy elimination of the problem.

c) An improvement in the supervision of operatives is necessary to ensure that specifications are complied with. There is a case for employing better educated foremen who have a working knowledge of technical considerations.

d) A policy of long term investigatory procedures is required to ensure that the fundamental causes of problems are sought.

It would be beneficial if a more sophisticated shop-floor bond test were sought as the present visual test does not reveal bond failure in the bush centre.

CHAPTER FOURTEEN

FUTURE WORK

The future work described below is necessary either to investigate in more detail topics studied in this thesis or to explore new areas of research identified by the present work. Topic 14.1 has widespread implications and would be applicable to the whole rubber/metal bonding industry; the other topics are more specific to bushes and Dunlop (PED).

14.1 It has already been concluded that although the modified hot bond test described in Chapter 6 is adequate for this research it does lack sophistication.

Some conceptual designs for a test more representative of the bush stress situation are given in Appendix No. 4.1. and work on a new test could proceed along these lines. Alternatively the modified test-piece could be improved to allow general technical personnel to use it and yet still give reproducible results. This test could then be used to evaluate new adhesives and to study in more depth the reaction rates and mechanisms of rubber-to-metal bonding.

14.2 In the present research project the heat flow into and out of the bush during curing and cooling respectively has been only briefly studied. Further work is needed, including finite element analyses and experimental evaluation using laboratory facilities, to gain more confidence in assessing the exact amount of heat reaching the bond.

14.3 Similarly more work is required to study the heat flow from the press to the bush during moulding. Some problems encountered in this thesis relating to moulding have not been fully quantified due to the lack of time. A number of techniques are available to investigate heat flow during moulding, these include:-

i) Use of thermocouples placed inside moulds and press platens.

ii) Computer simulation of heat flow.

iii) Use of infrared video equipment.

iv) Use of heat sensitive pigments, included in the adhesives and rubber.

14.4 To study further the causes of moulding control problems and to quickly identify the reason for sudden high failure levels, a mobile facility for monitoring the operation should be developed. This could consist of a pressure transducer placed inside the press hydraulic line and linked through a bridge/amplifier unit to a chart recorder. By interpretation of a chart drawn over a whole shift one could ascertain the:Cure time

Mould pressure

Rubber transfer time (for transfer moulds)

Mould loading and unloading time

Number of bushes moulded in the shift

Addition of a temperature measuring device to the system would also be an advantage.

Monitoring of other operations would produce useful information, especially the introduction of chart recorders or computers to continually record all the variables of each process.

14.5 Other topics of a more academic nature are worth further consideration, they include:-

a) the application of newly developed elasticity formulii, developed after the experimental work described in Chapter 5 was completed, to the empirical calculation of shrinkage stresses.

b) An examination of the effect of shear stress on bond failure in bushes.

c) The determination of the ingredients of commercially available bonding agents and the feasibility of 'in house' adhesive production.

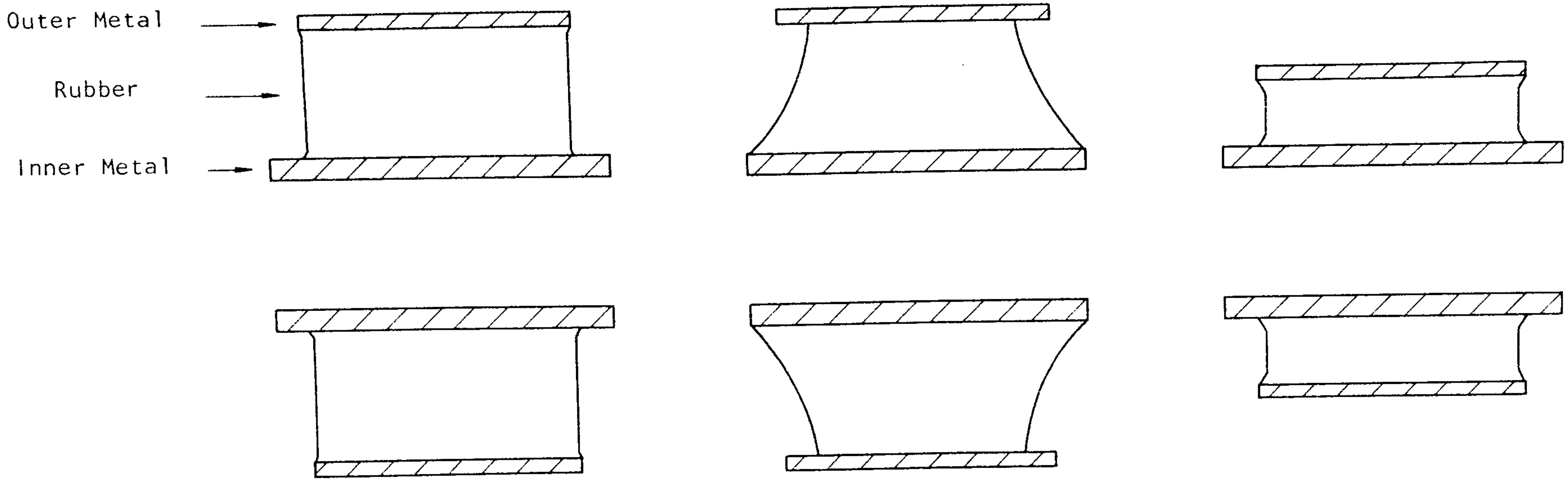
d) A study of rubber to metal adhesion kinetics.

e) An evaluation of the moisture content in unvulcanised rubber and the apparent inhibiting effect on cure rate.

f) The ease of batch identification in the G.T. bush 'line' compared to the Process orientated production areas.

Figure 1.1

Concentric Bush Types



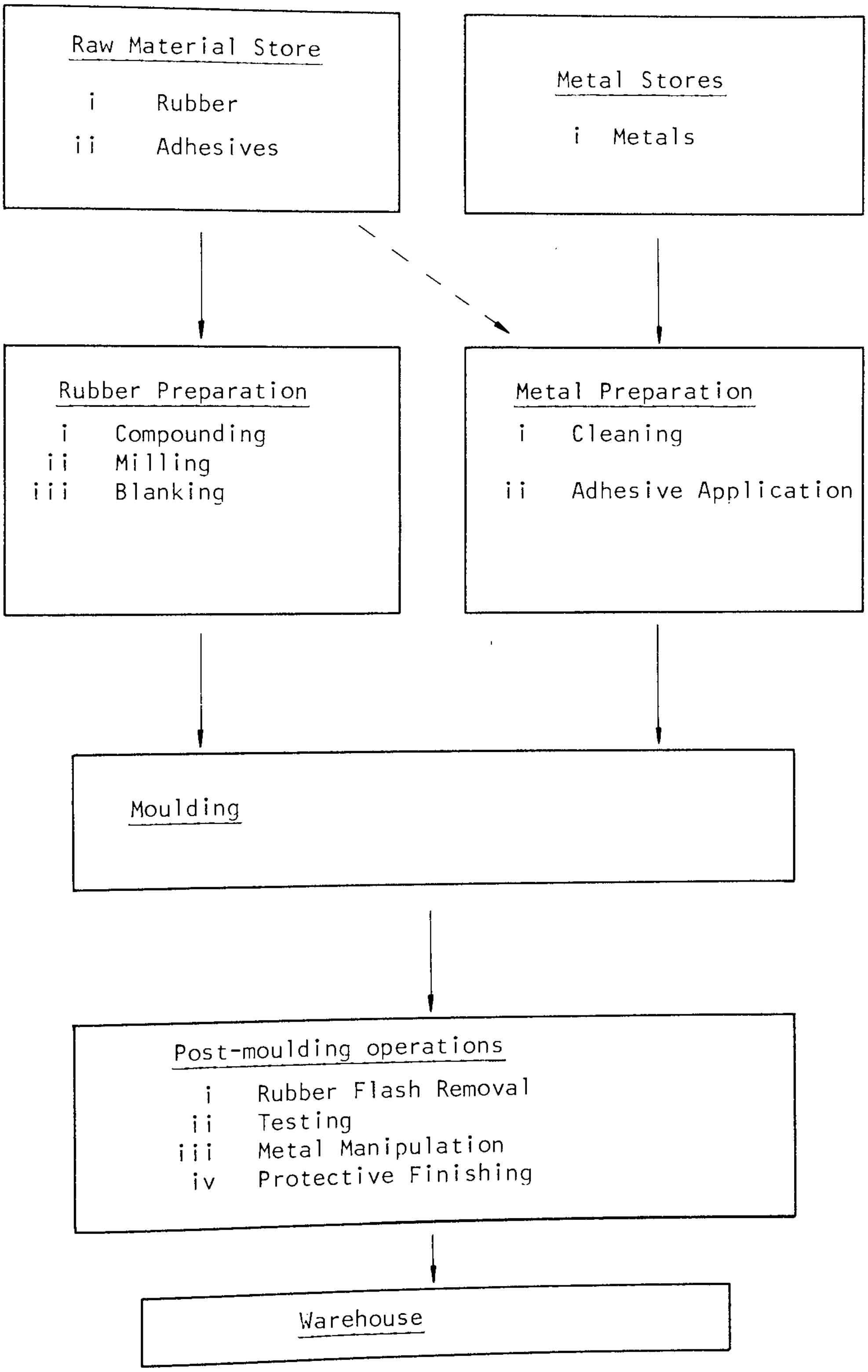
(a) Constant Rubber Length

(b) Decreasing Rubber Length

(c) High Radial Stiffness

Figure 3.1

Metalastik Total Process Chart



NB: Some minor processes are omitted from this diagram.

Figure 3.2

Rubber Compound Ingredients

Conventional Sulphur Curing Compound	P.h.r.*
Carbon Black	40
Zinc Oxide	
Pentachlorothiophenol	1
N-cyclohexyl-2-benzothiazl sulphenamide	
Sulphur	3
Stearic Acid	3
Diphenylamine / acetone condensate	
Aromatic Oil	5
Natural Rubber	100
Semi E.V. Compound	
Carbon Black	45
Zinc Oxide	
N-isopropyl-N'-phenyl-para-phenylenediamine	1
Pentachlorothiophenol	
Sulphur	2
N-cyclohexyl-2-benzothiazl sulphenamide	4
Diphenylamine / acetone condensate	
Microcrystalline Paraffin Wax	5
Aromatic Oil	
Natural Rubber	100
E.V. Compound	
Carbon Black	35
Zinc Oxide	
Sulphur	0.7
N-oxydiethylene benzothiazl sulphenamide	3
Tetrabutyl thiuram disulphide	
Stearic Acid	4
Diphenylamine / acetone condensate	
Synthetic Polyisoprene	100

* P.h.r. = Parts per hundred parts rubber

Figure 3.3

Cross-section of a Transfer Mould

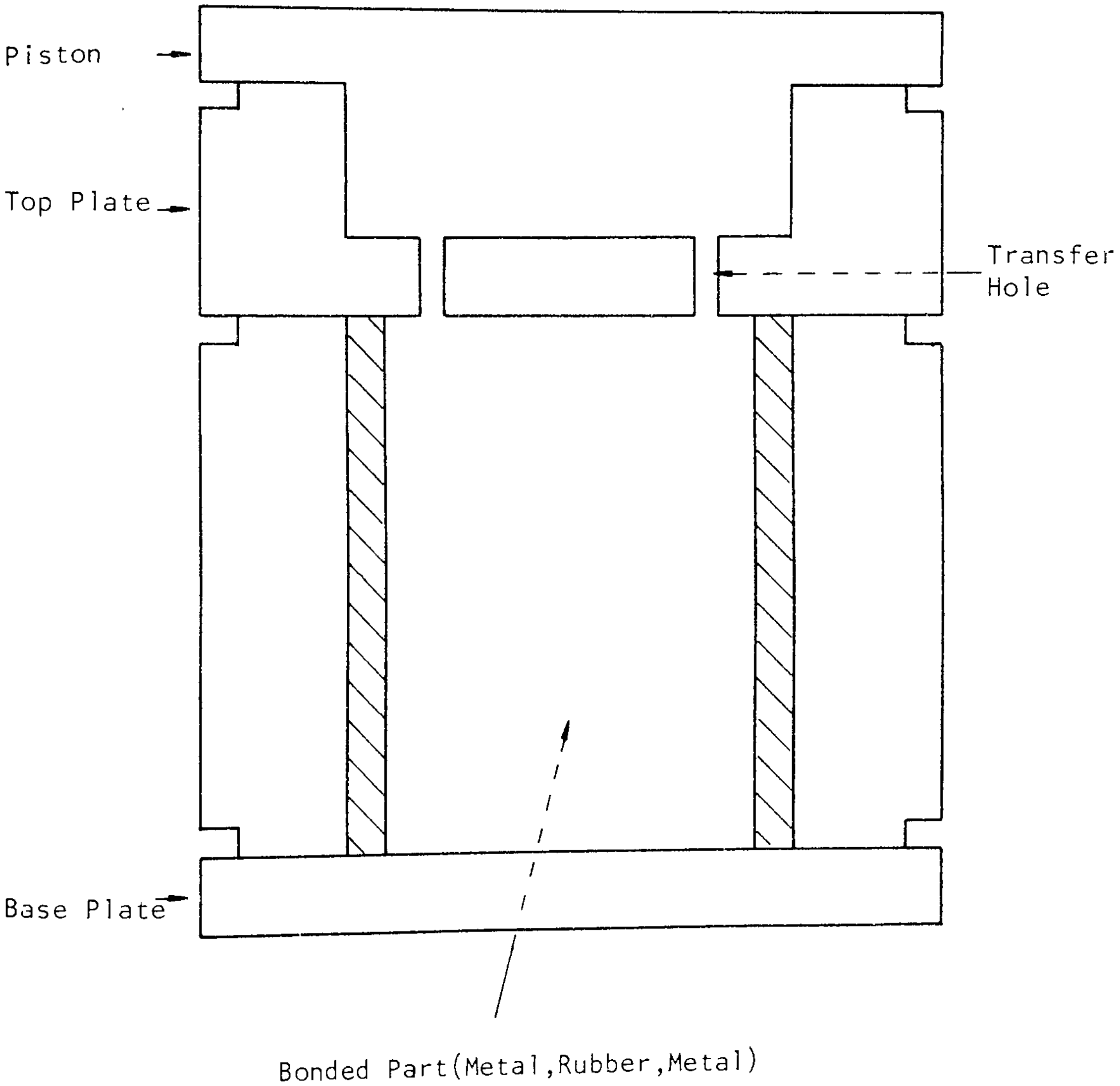
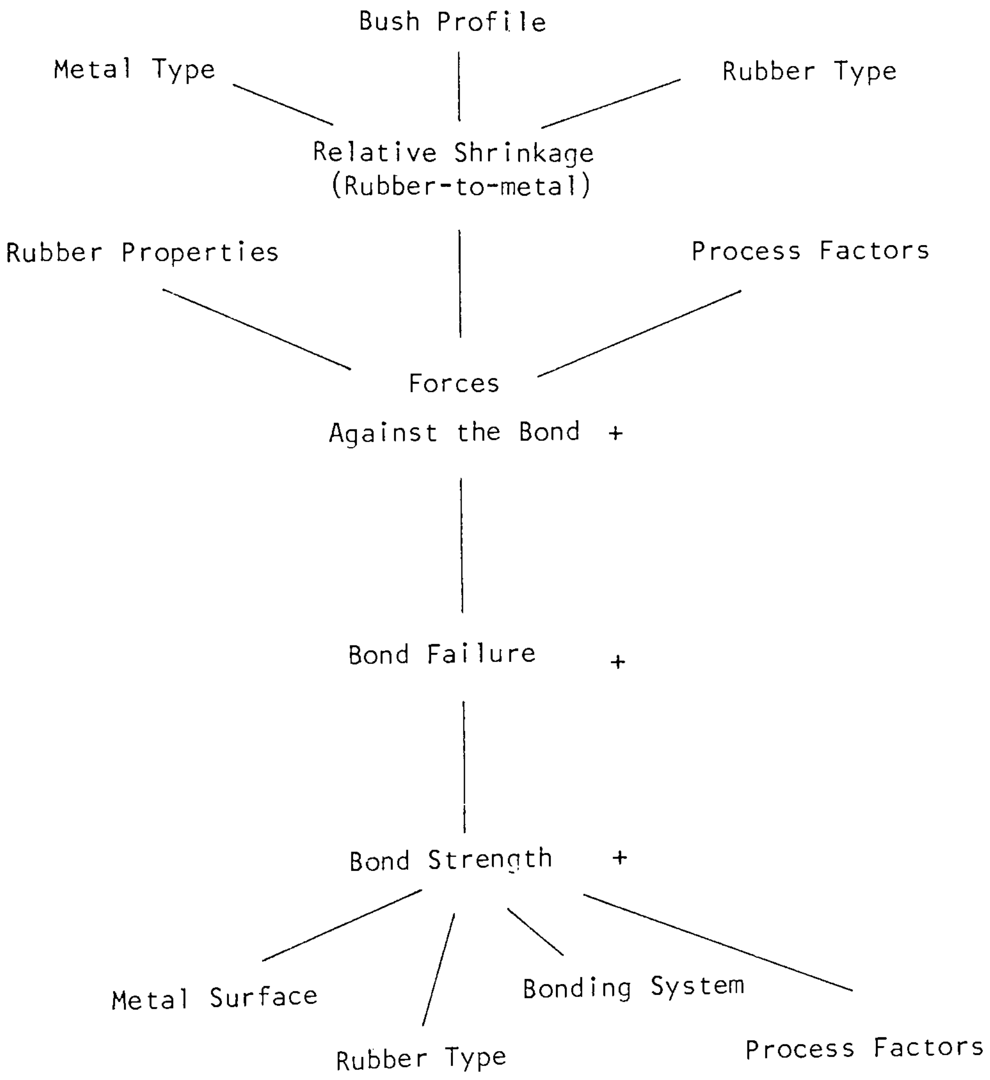


Figure 4.1

Some Factors Influencing Bond Failure



+ Direct Measurement Possible

Figure 5.1

Shrinkage of Unrestricted Rubber (ex Thorpe)

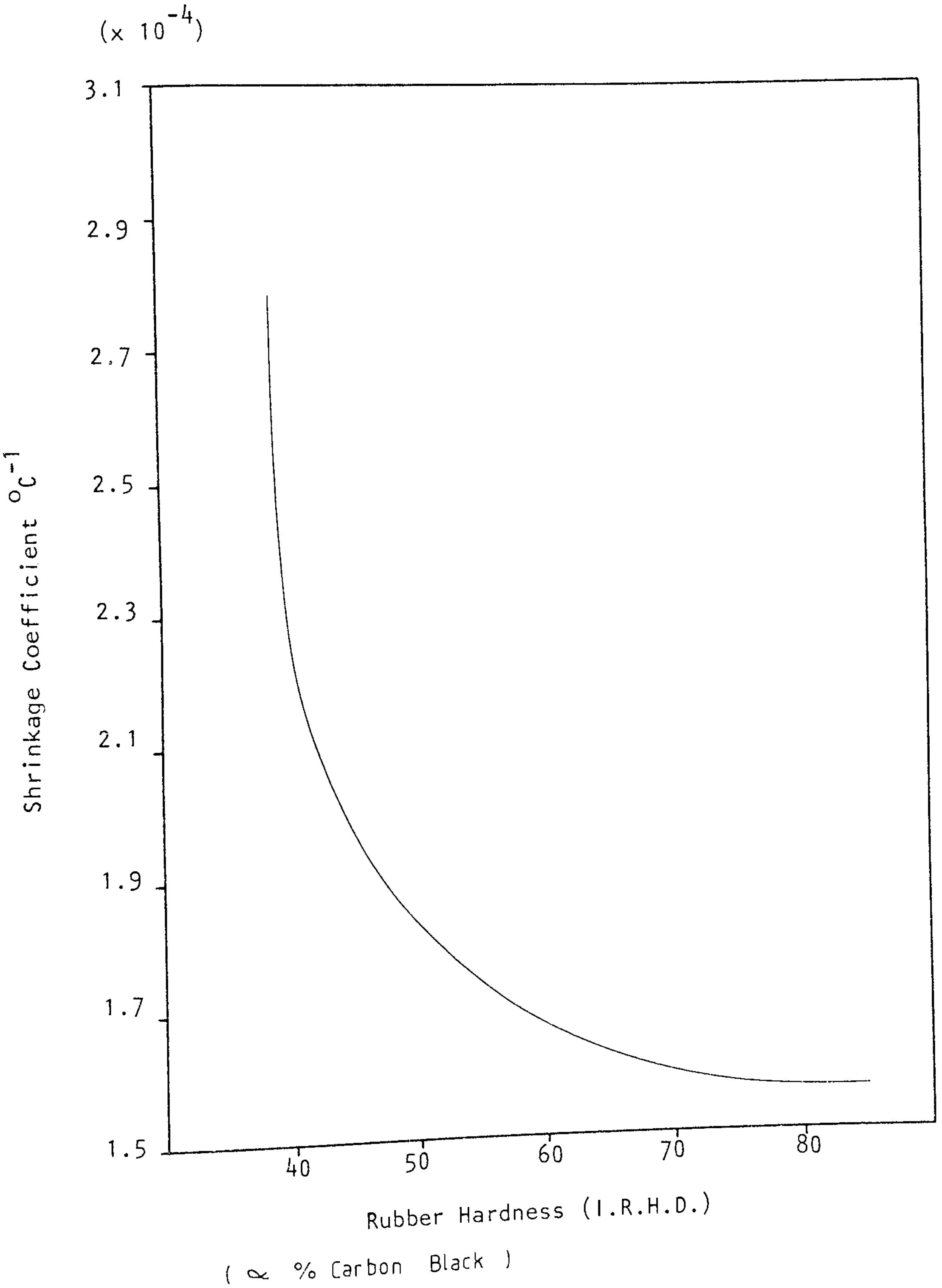


Figure 5.2

Hardness and Elastic Moduli* (ex Lindley)

Hardness (I.R.H.D.)	Young's Modulus Eo (MN/m²)	Shear Modulus G (MN/m²)	k	Bulk Modulus E_∞ (MN/m²)
30	0.90	0.29	0.93	1000
35	1.16	0.36	0.89	1000
40	1.47	0.44	0.85	1000
45	1.77	0.53	0.80	1000
50	2.16	0.63	0.73	1030
55	3.19	0.79	0.64	1090
60	4.37	1.04	0.57	1150
65	5.74	1.34	0.54	1210
70	7.21	1.70	0.53	1270
75	9.22	2.18	0.52	1330

* Based on experiments on natural rubber spring vulcanisates containing (above 48 IRHD) SRF black as a filler. Note that hardness subject to an uncertainty of about ± 2 deg.

Figure 5.3

Complete Uniaxial Extension and Compression Curve

(ex Treloar)

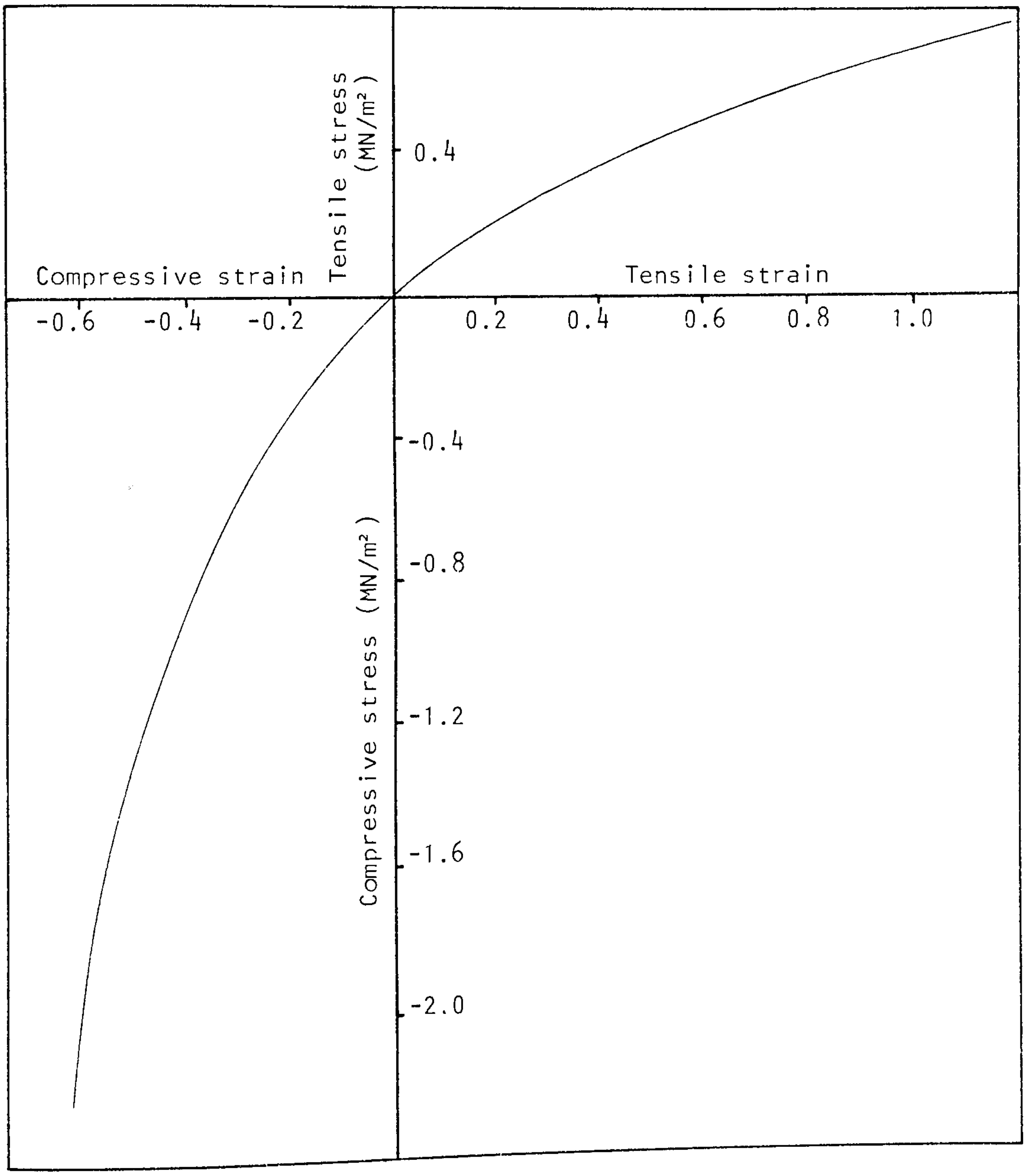
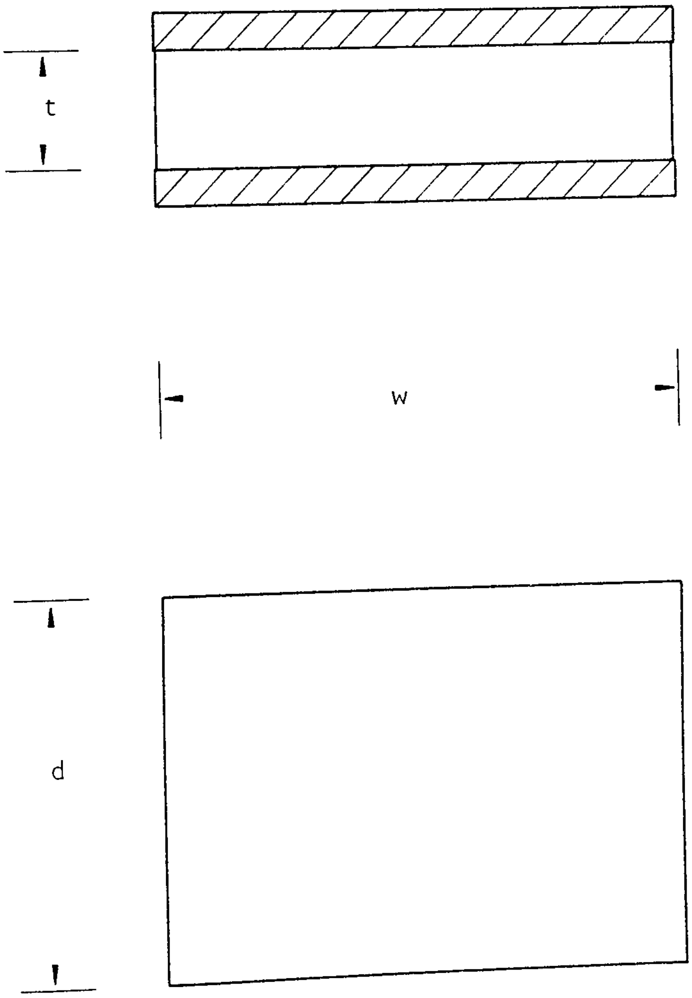


Figure 5.4

Shape Factor (S) of a Sandwich Mounting



$$S = \frac{w \times d}{2t(w + d)}$$

Bush cross-section showing F.E.M. model (section A)

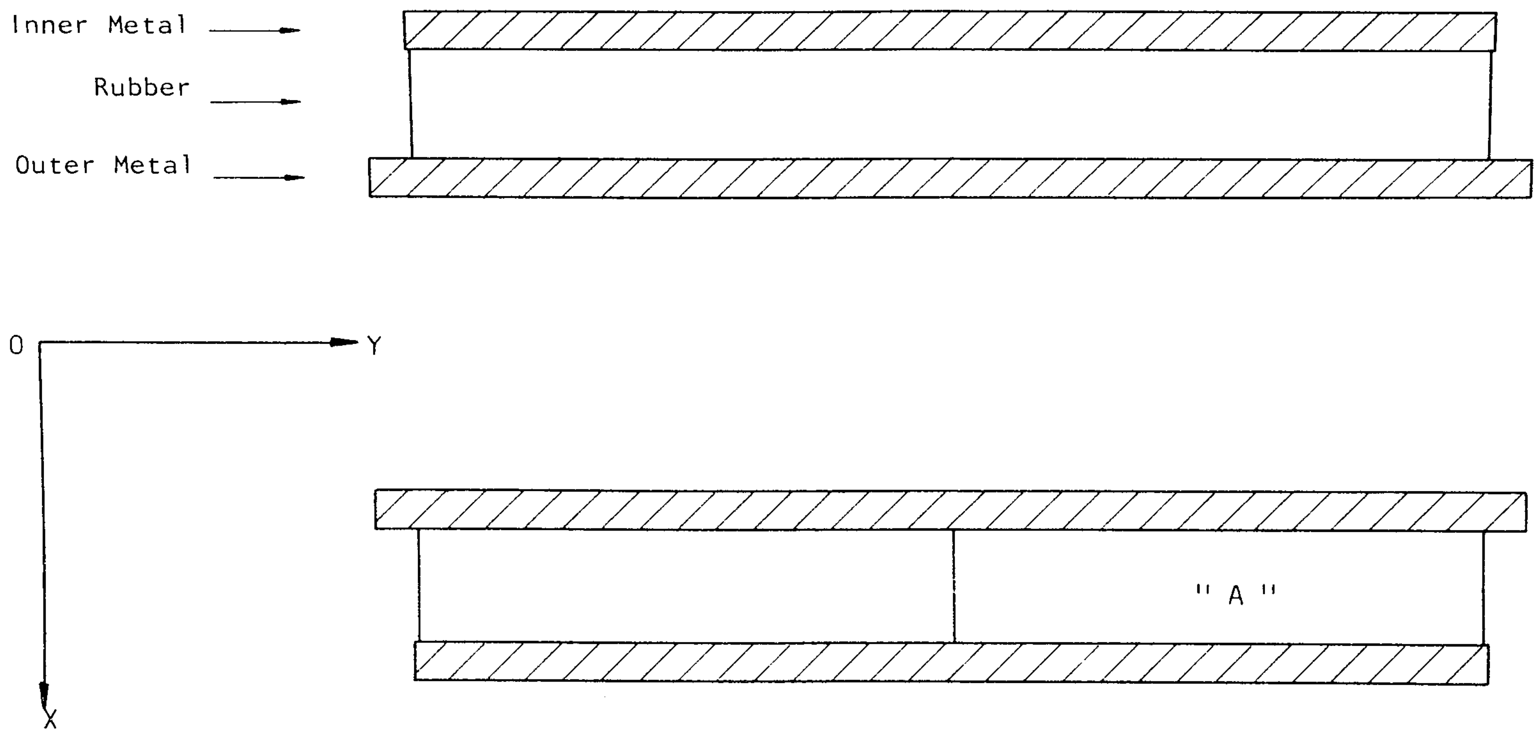


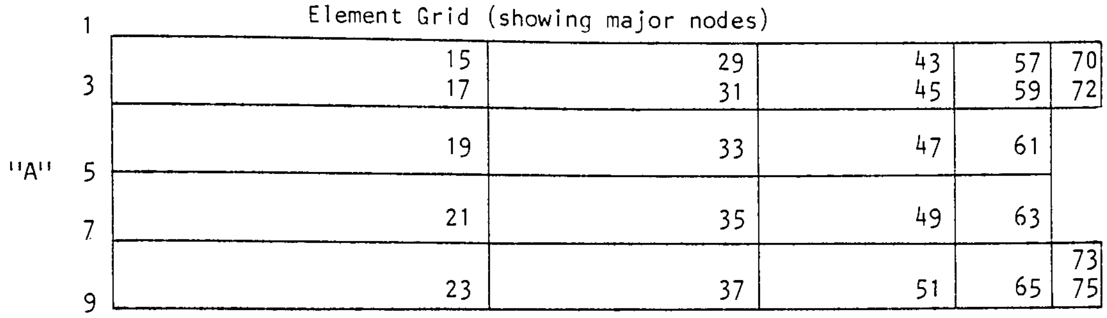
Figure 5.5

Figure 5.6

F.E.M.Results - Bush No. 13/1914

(See figure 5.5 for section "A" position)

Element Grid (showing major nodes)



Nodal Displacement in the Y Direction (mm)

	-0.42	-0.75	-1.01	1.21	0.25
	-0.55	-0.98	-1.34	-1.34	
	-0.40	-0.75	0.95	0.96	0.45

Stress in the X Direction (MN/m²)

13.7	11.75	7.89	3.64	4.21	4.0
13.82	11.84	7.61	3.42	1.06	4.6
13.8	11.87	7.62	3.63	0.70	
13.84	11.82	7.69	3.63	2.62	-0.1
13.66	11.71	7.78	2.74	0.42	1.03

Von Mises Stress Concentration

0.12	1.62	2.93	4.00	3.47
0.20	0.80	1.40	2.01	3.42
0.25	0.28	0.29	0.56	0.95
0.18	0.81	1.48	2.08	3.49
0.12	1.49	2.73	3.63	2.24

Figure 5.7

Tensile Stress Distribution at the Bond Interface

NB: Rubber ends are not contoured

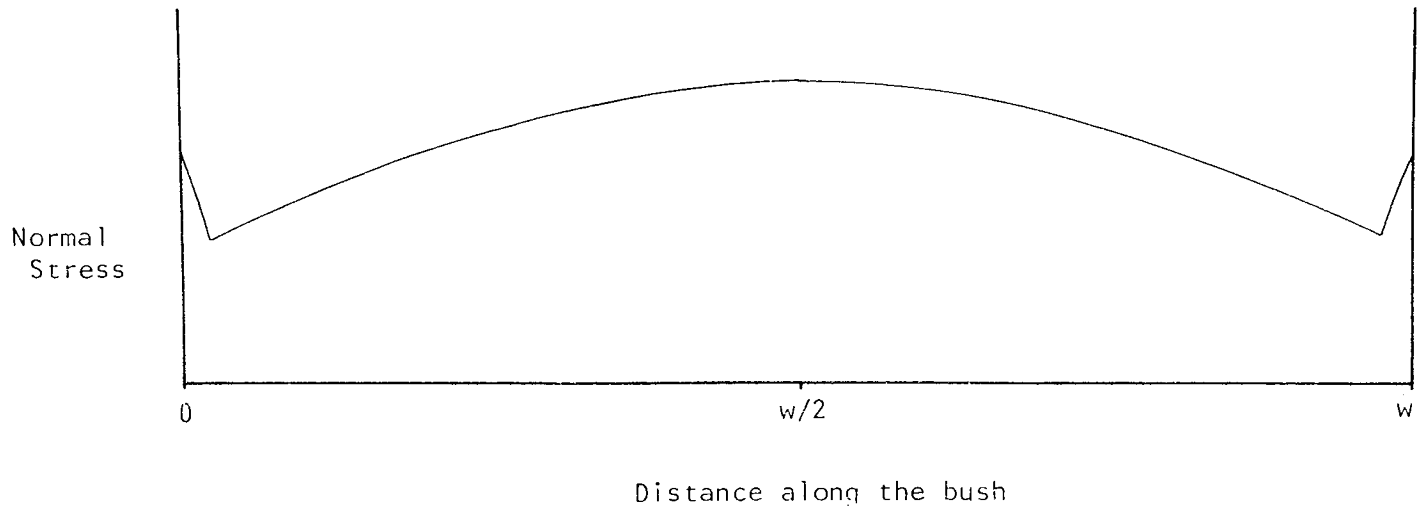


Figure 5.8

F.E.M. Results - Bush No 13/665

(see figure 5.5 for the section "A" position)

Element Grid (showing major nodes)

	1 3	15 17	29 31	43 45	57 59
"A"	5	19	33	47	61
	7	21	35	49	63
	9	23	37	51	65

Nodal Displacement in the Y Direction (mm)

-0.79	-1.43	-1.83	-2.11
-1.00	-1.76	-2.42	-2.46
-0.71	-1.29	-1.63	-1.96

Stress in the X Direction (MN/m²)

12.51	10.62	6.22	0.36	7.44
12.78	10.74	6.83	3.24	-0.76
12.63	10.79	6.54	2.52	-0.27
12.75	10.74	6.88	3.32	-0.77
12.64	10.56	6.06	0.27	7.77

Von Mises Stress Concentration

0.21	2.32	4.16	5.33	6.33
0.42	1.08	1.86	2.59	1.70
0.45	0.52	0.50	0.90	1.04
0.38	1.15	2.01	2.78	1.94
0.23	1.92	3.44	4.32	5.40

Figure 5.9

F.E.M.Results - Modified Test-Piece

(see figure 5.14 for the section "A" position)

Element Grid (showing major nodes)

"A"

1	15	29	43	57	71	85
3	17	31	45	59	73	87
5	19	33	47	61	75	89
7	21	35	49	63	77	91
9	23	37	51	65	79	93

Nodal Displacement (mm)

-0.57

0.78	0.67	0.27	-0.08	-0.35	-0.55
0.74	0.62·	0.25	-0.08	-0.33 ·	-0.52·
0.62	0.49·	0.20	-0.06	-0.27 ·	-0.41·
0.44	0.29·	0.12	-0.04	-0.16 ·	-0.22·

(Position of figures)

Stress in the Y Direction (MN/m²)

-0.29

0	1.08	2.48	2.83	1.94	0.61
0.10	1.10·	2.48·	2.83·	1.94 ·	0.62·
0.37	1.18·	2.50 ·	2.85·	1.94 ·	0.66·
0.08	2.01·	2.61 ·	2.71·	2.03 ·	1.14·
5.91	-1.01	2.05	2.69	1.59	-0.82

3.86

Von Mises Stress Concentration

0.70	0.82	0.41	0.31	0.25	0.36	0.39
0.64	0.91·	0.43·	0.29·	0.36 ·	0.54	0.39
1.00	1.17·	0.48·	0.24·	0.56 ·	0.89	0.36
1.76	1.09·	0.63·	0.22·	0.84 ·	1.45	1.03
3.04	1.77	0.84	0.32	1.15	1.46	2.16

Figure 5.10

Shrinkage Stress v s. Shape Factor

Hardness = 60 (IRHD); Temperature Change = 120°C

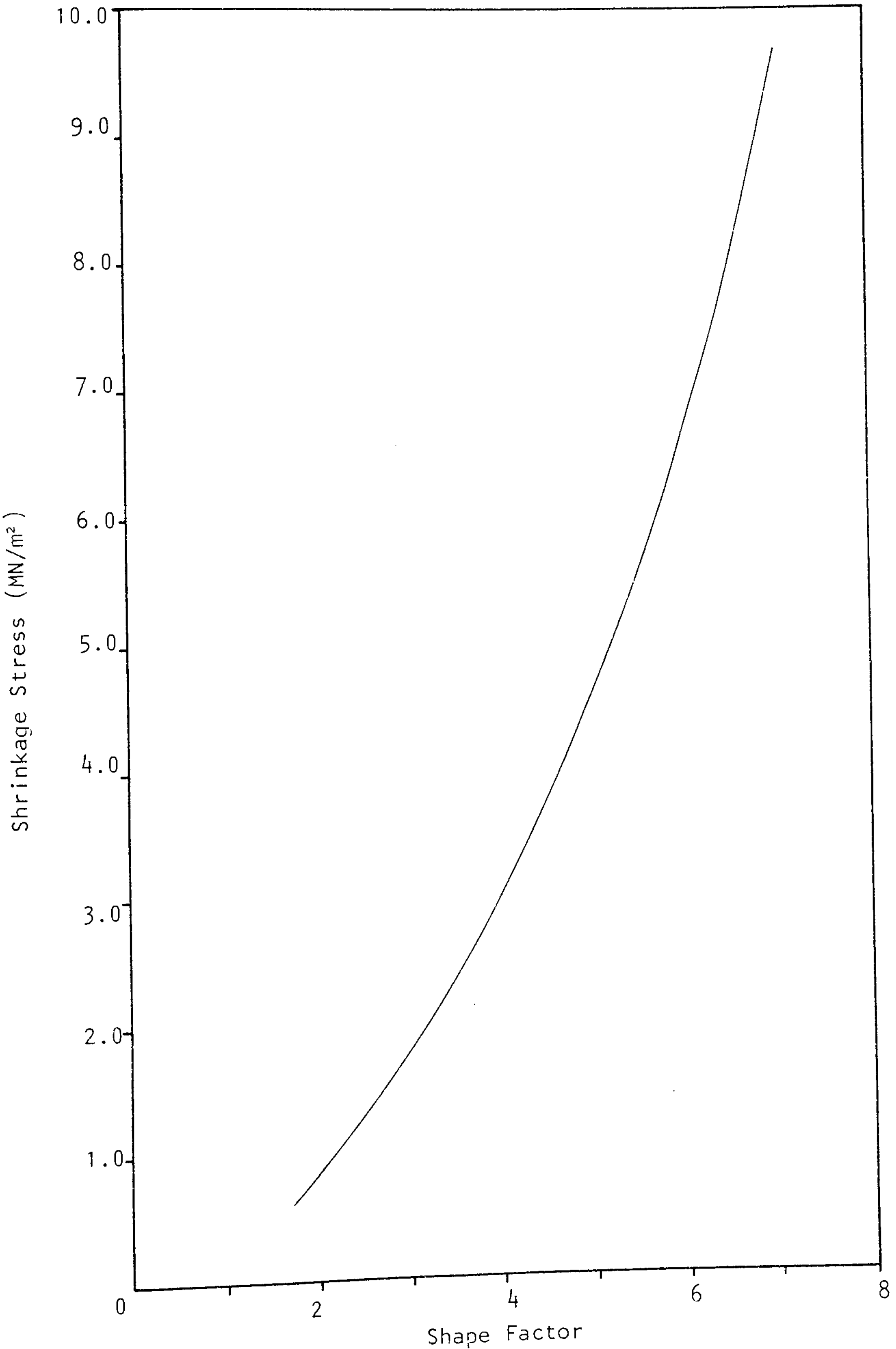


Figure 5.11

Shrinkage Stress v s. Hardness

Shape Factor = 3.8 ; Temperature Change = 120°C

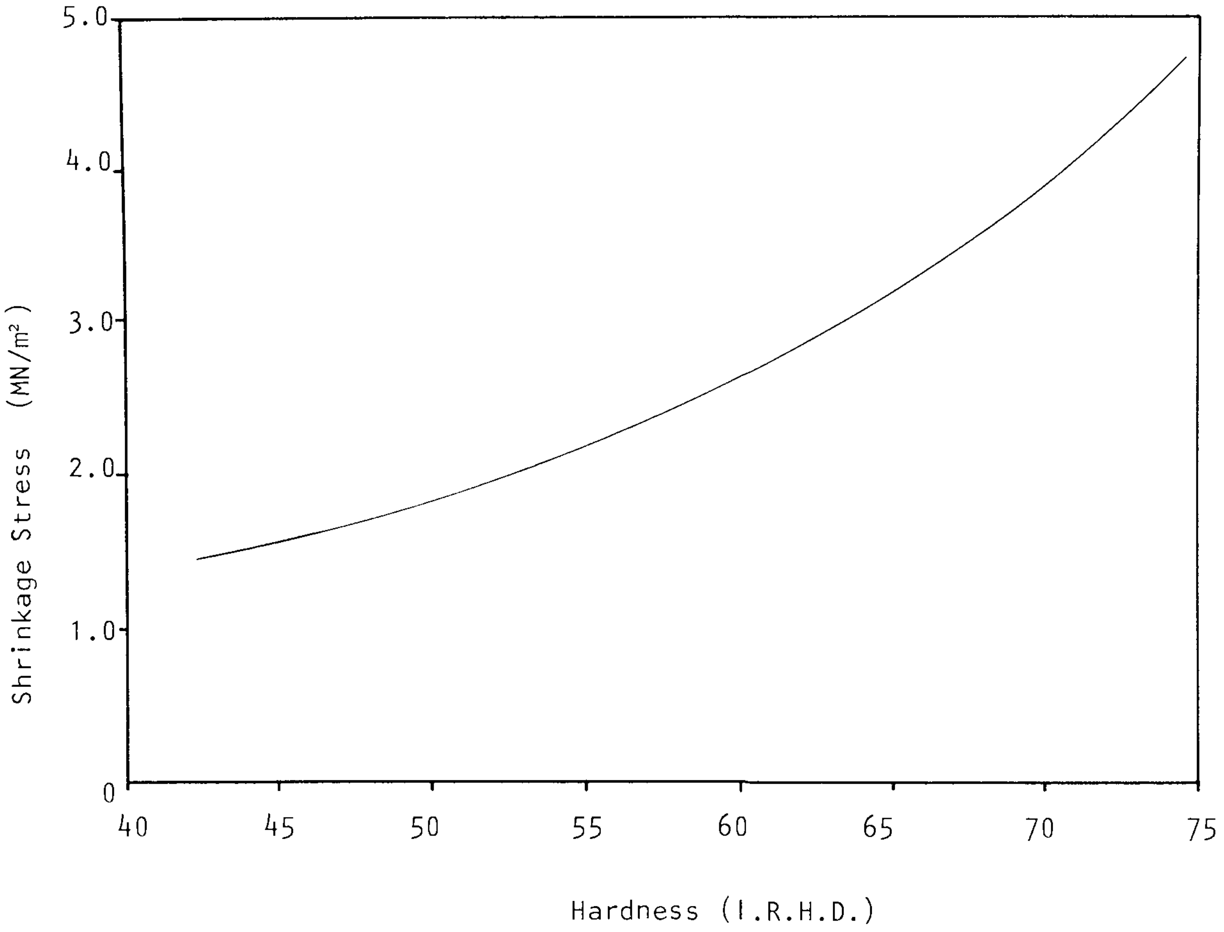


Figure 5.12

Shrinkage Stress v s. Temperature Change

Shape Factor = 3.7 ; Hardness = 60 (I.R.H.D.)

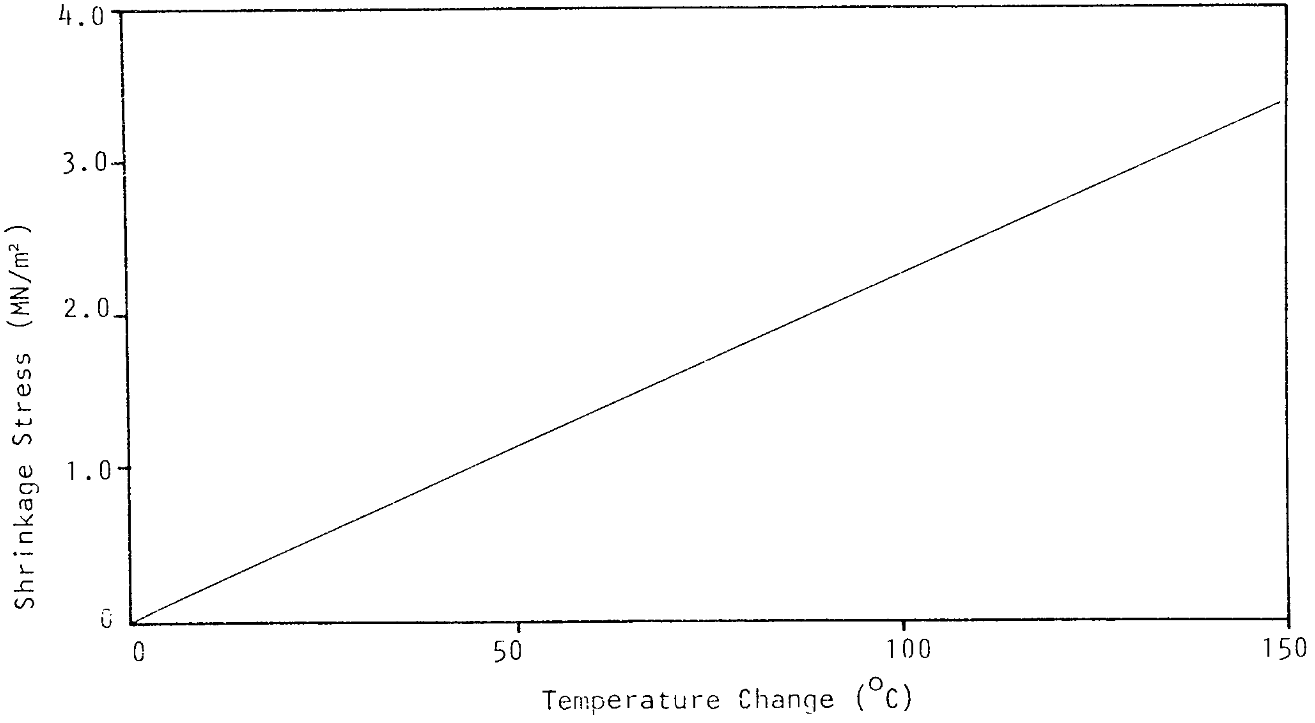


Figure 5.13

The Distribution of Shrinkage Stress Values for Metalastik Bushes (Total Number = 525)

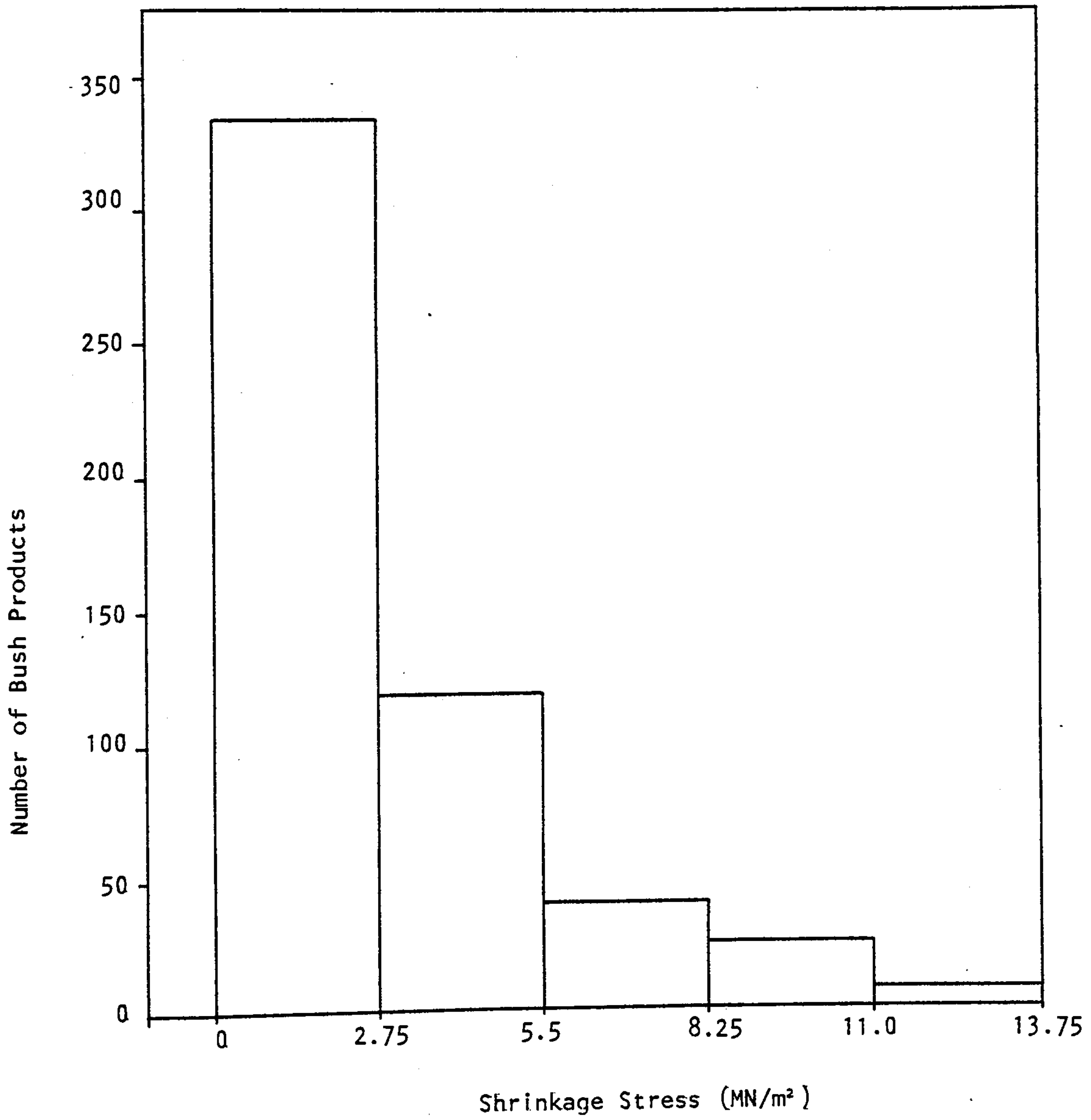
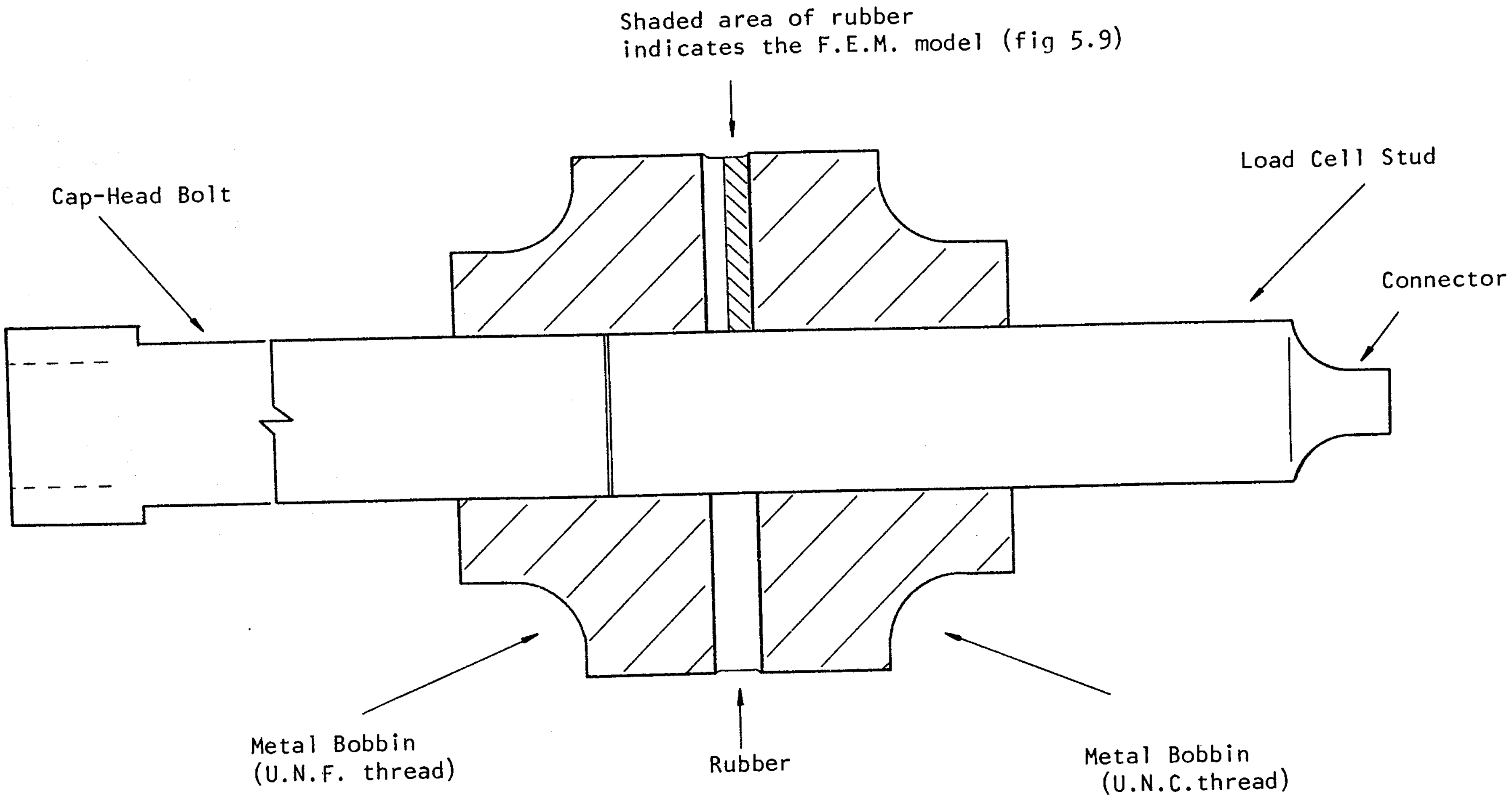
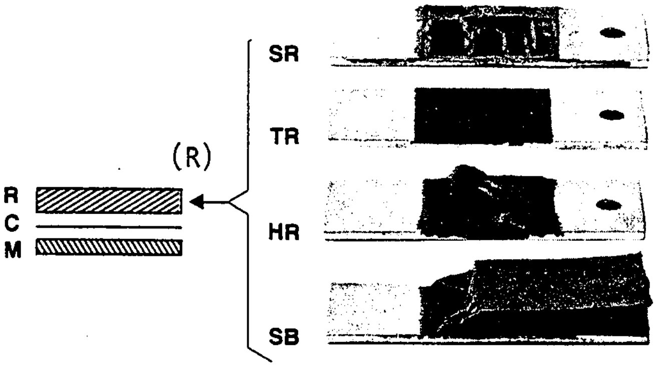


Figure 5.14

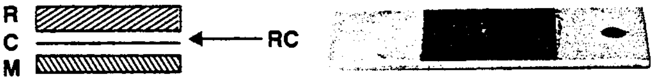
The Modified Test-Piece (Cross-section)



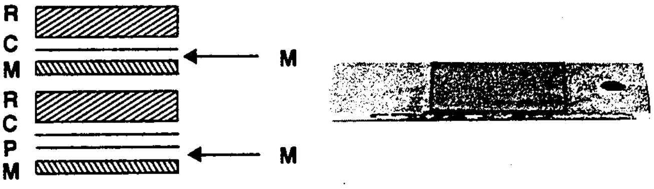
Types Of Failure (ex Peterson)



— Rubber failure. Drawing at left shows, in cross section, elements of rubber-to-metal bond: rubber (R), cement (C) and metal (M). Photos at right illustrate types of rubber-bond failures: spotty rubber (SR), thin rubber (TR), heavy rubber (HR) and stock break (SB).

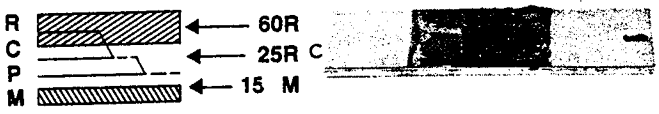


— Rubber-cement failure. Cross-sectional view in drawing indicates site of separation at rubber-cement interface. Photo at right shows appearance of metal after such separation—relatively glossy and hard surface with little or no rubber visible.



— Cement or primer-metal failure. At left are elements of two rubber-metal bonds, one of which includes primer cement (P). Photo at right illustrates the clean separation between metal and adhesive which indicates no adhesion has occurred between cover cement and metal (CM), or primer cement and metal (PM).

— Cement-primer failure. Cross sectional view in drawing indicates site of separation at primer-cover cement interface. Photo at right shows appearance of metal after cement-primer failure caused by lack of time for solvents in primer to evaporate before cover cement is applied.



— Composite failure. Drawing shows typical rubber-to-metal failure in which 60 per cent of bond area shows failure in rubber (60R), 25 per cent failure between rubber and cement (25RC), and 15 per cent failure between cement or primer and metal (15 M). Appearance of failure is seen in photo at right.

Figure 6.2

A.S.T.M. Test-Pieces (D429-73)

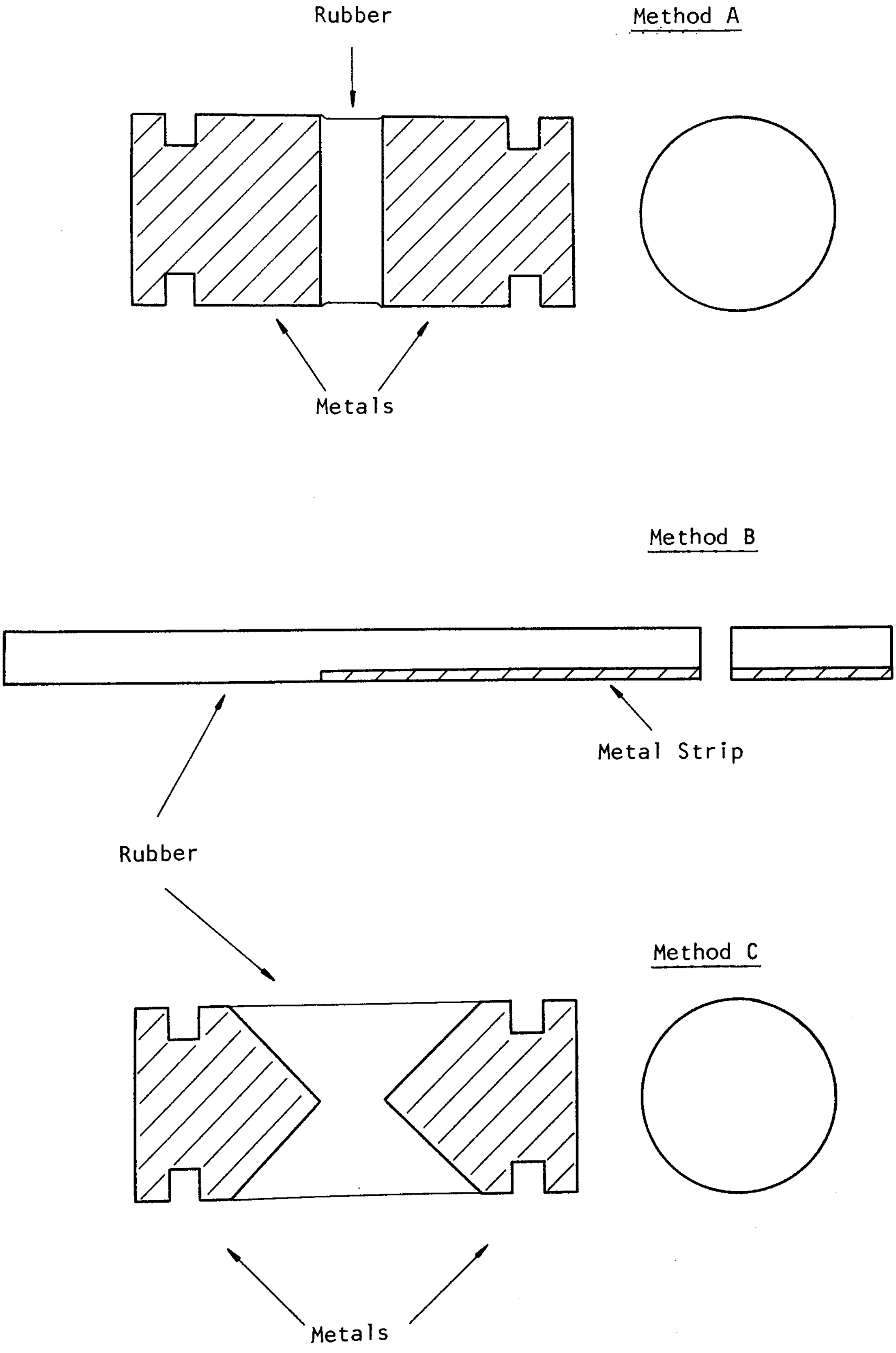
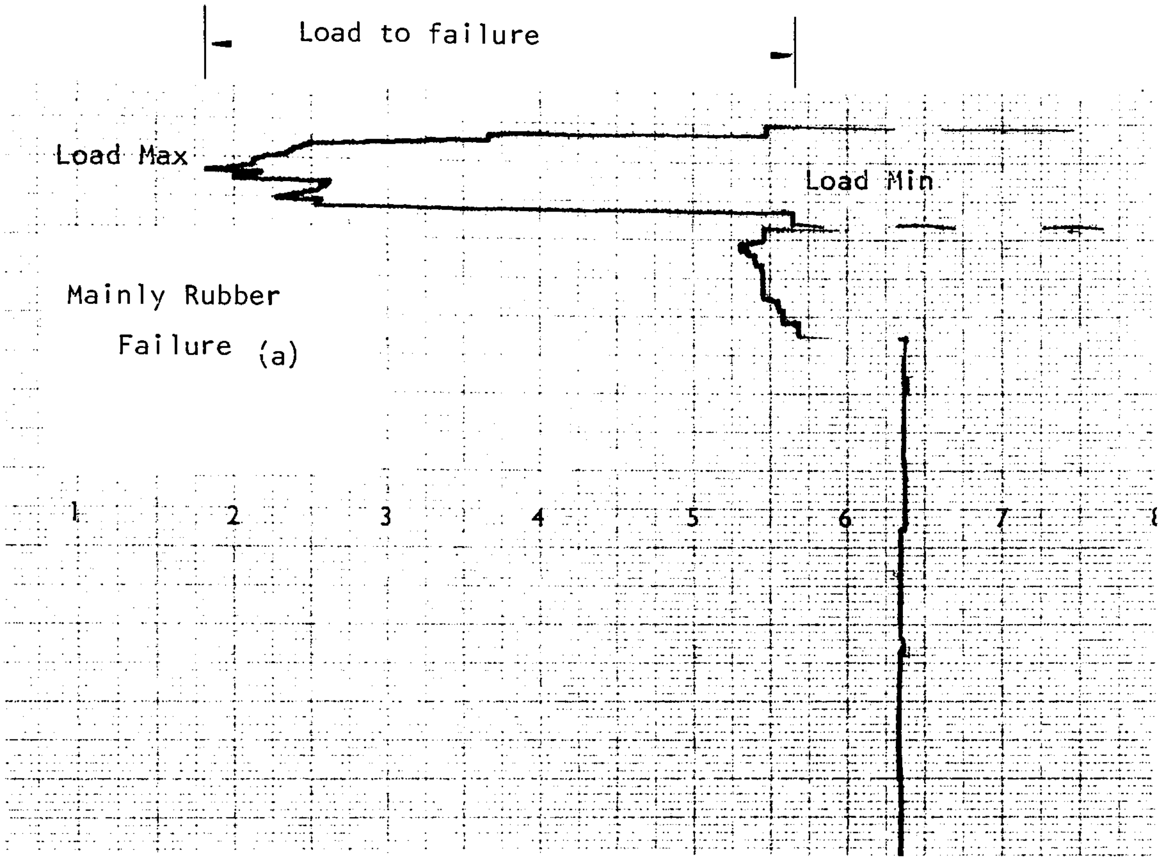


Figure 6.3

The Hot Bond Test - Typical Chart Recordings



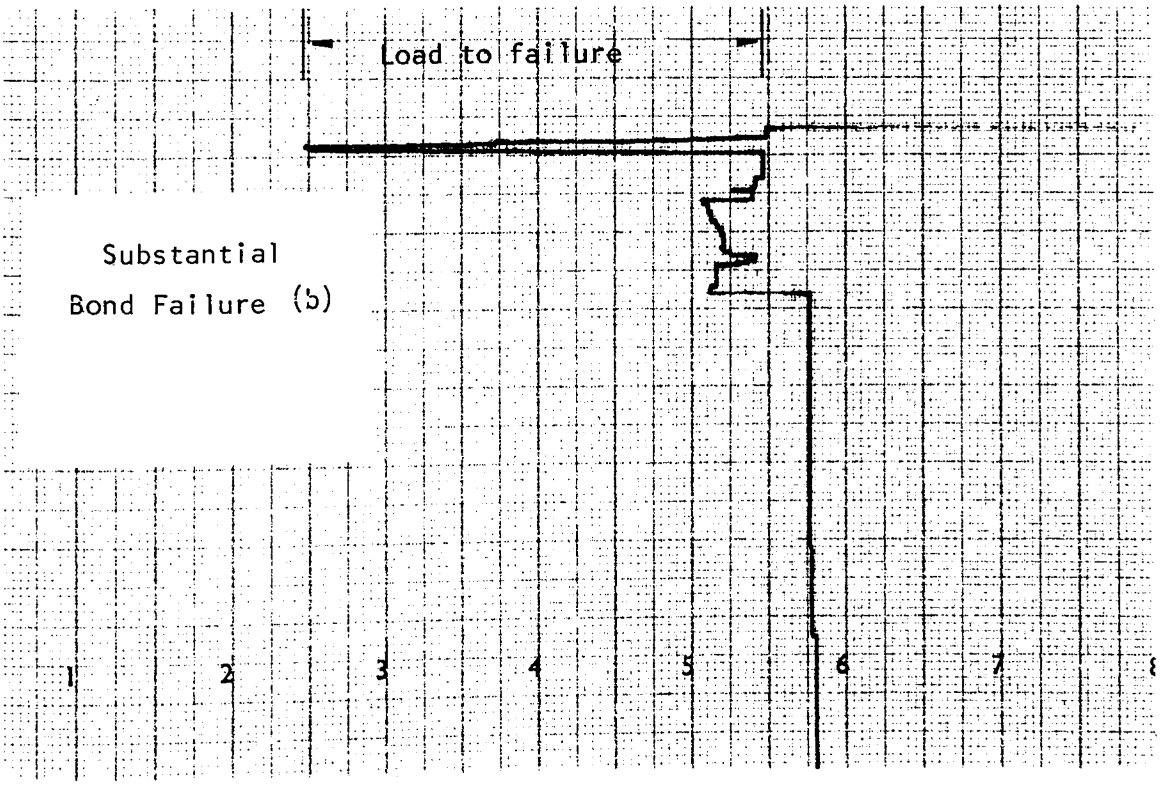


Figure 6.4

Interfacial Reactions (ex Sexsmith)

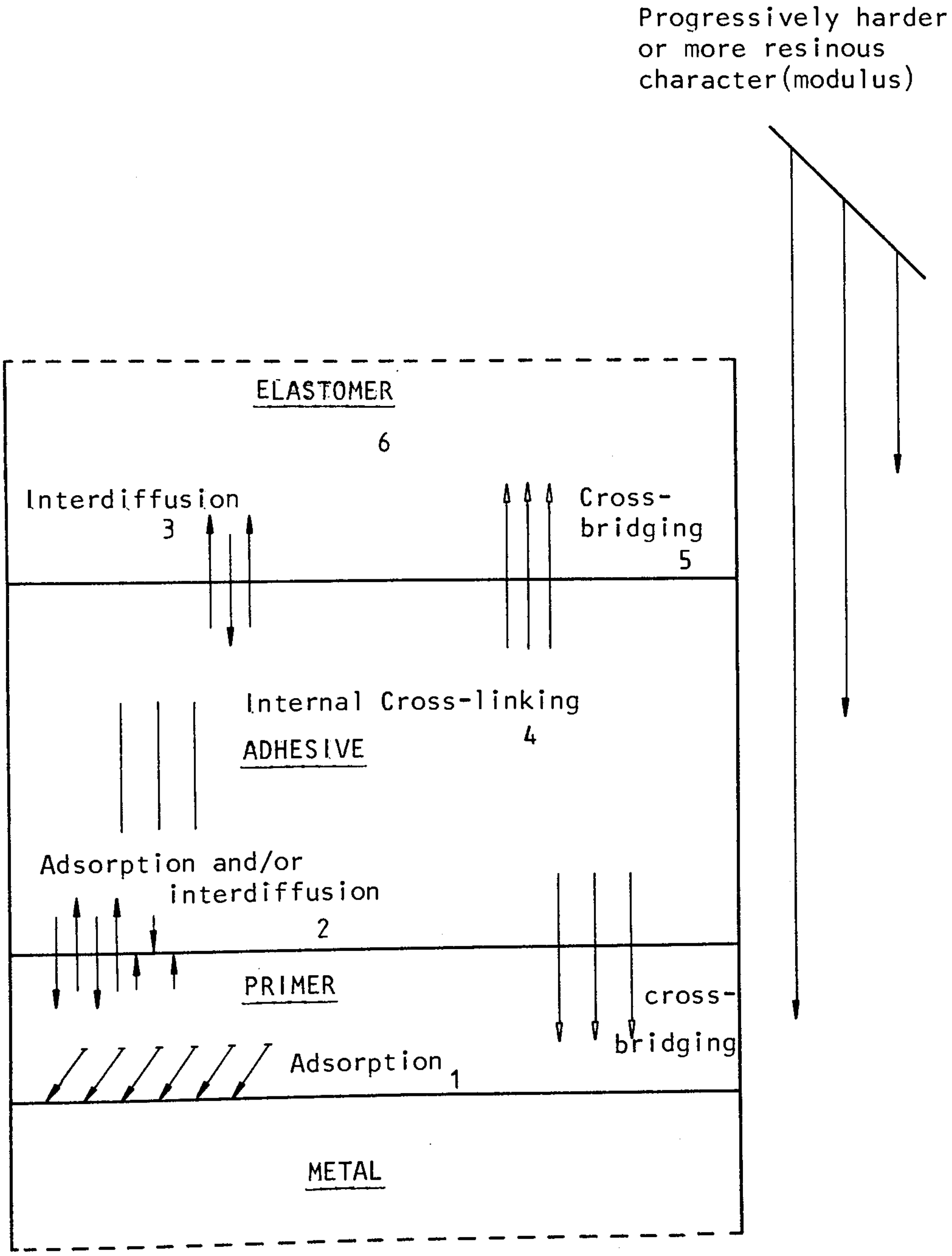


Figure 6.5

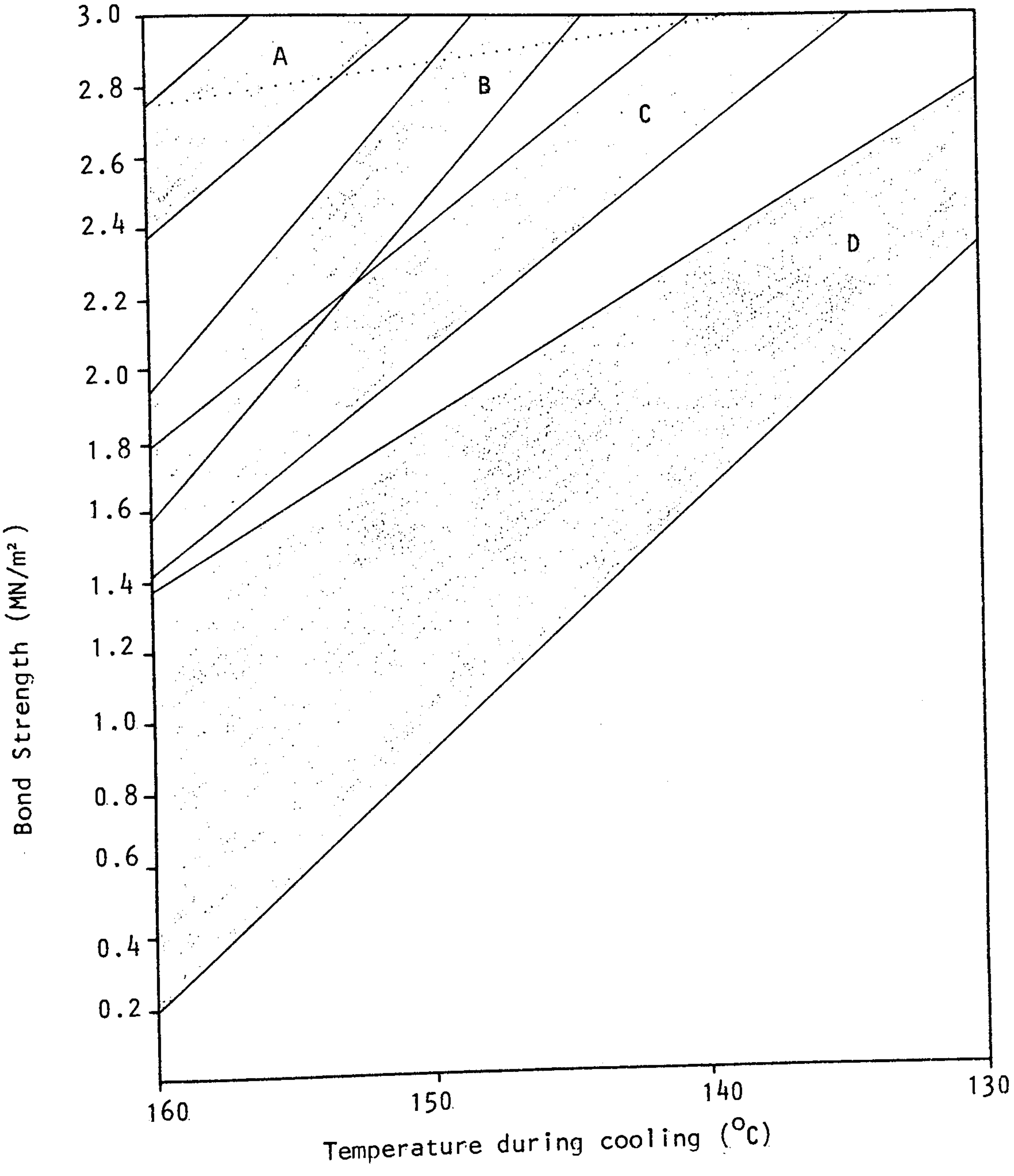
The Proprietary Bonding Agent Systems Studied in this Research.

Primer	Cover Coat (or single coat)	Third Coat	Group
Chemlok 205	Chemlok 220	Thixon AP1559	B
Chemlok 205	Chemlok 220	Typly RC	C
Chemlok 205	Chemlok 220	Chemosil X2311	B
Chemlok 205	Chemlok 220		C
Chemlok 205	Chemlok 234		D
Chemlok 205	Chemlok 252		A
Chemlok 205	*Chemlok CH47		C
Chemlok 205	*Chemlok CH83		A
Chemlok 205	*Chemlok CH84		D
Chemlok 205	Chemlosil X2311		A
Thixon P7	Thixon OSN-2		B
Typly T	Typly Q		D
Typly UP	Typly RC		D
	Chemlok 250		C
	Chemlok 252		A
	Chemlok 255		C
	Thixon OSN-2		B
	Thixon OSN-1		C
	Megum VI1658		B

* Experimental adhesives (not commercially available)

Figure 6.6

The Relative Hot Bond Strength of Proprietary Bonding Agent Systems



(See figure 6.5 for the adhesives in each group A - D)

.... = Rubber Strength

Figure 6.7

The Influence of the Metal Preparation on the Hot Bond Strength

Adhesive System = Chemlok 205/Chemlok 220

Adhesive Application = Brushed

Adhesive Thickness = (Primer) 7.0 g/m^2, (cover) ≏18.0 g/m^2

Rubber Compound = Semi E.V. Type (19060)

Cure Conditions = 15 minutes @ 150°C

Metal Preparation	Temperature of test(°C)	Bond strength (MN/m^2)	Bond Failure			
			%R	%RC	%CP	%M
Alumina Blast	152	1.834	55	45		
"	152	1.8138	50	50		
"	140	2.434	75	25		
"	133	3.138	95	5		
"	124	2.724	95	5		
Wheelabrate	152	1.662	55	40	5	
"	151	2.021	55	45		
"	145	2.255	70	25	5	
"	138	2.724	60	40		
"	132	2.662	55	45		
Chemical Cleaning	152	1.814	60	40		trace
"	145	1.869	55	45	trace	
"	143	2.289	60	35	5	
"	138	2.503	50	50		
"	128	3.096	99	1		

Figure 6.8

The Influence of the Rubber Compound on the Hot Bond Strength

Metal Preparation = Degrease Alumina Blast, Degrease

Adhesive Application = Brushed

Adhesive Thickness = (Primer) 7.0 g/m^2,(single/cover) 18.0 g/m^2

Cure Conditions = 15 minutes @ $150^{\circ}C$ (⊕ 25 minutes)

Test Temperature = $150^{\circ}C$

(* Rubber Lamination)

Rubber Compound		Bonding System	Bond Strength (MN/m^2)	Bond Failure			
Base Polymer	Mix Ref.			%R	%RC	%CP	%M
N.R.	16 x 60	Chem 205/220	2.157	70	15	15	
"	16 x 60	"	2.094	80	15	5	
"	01 x 60	"	2.000	55	45	trace	
"	01 x 60	"	2.324	60	20	20	
SBR/NR. ⊕	43 x 60	"	2.069	60	40		
⊕	43 x 60	"	1.855	70	30		
N.R.	16 x 60	Thixon OSN2	2.441	70	30		
"	16 x 60	"	2.669	70	30		
"	01 x 60	"	3.130	75	25*		
"	01 x 60	"	2.938	75	25*		
SBR/N.R. ⊕	43 x 60	"	2.041	75	25		
" ⊕	43 x 60	"	2.152	90	10		
N.R.	16 x 60	Chemlok 252	2.752 +	100			
"	16 x 60	"	2.979 +	100			
N.R./Poly-isoprene	16 x 60	"	3.165 +	100			
"	16 x 60	"	3.089	100			
N.R.	01 x 60	"	2.827 +	95	5		
"	01 x 60	"	2.979	95	5		
SBR/NR. ⊕	43 x 60	"	2.393	99	1		
" ⊕	43 x 60	"	2.276	99	1		

Figure 6.9

The Influence of Rubber Hardness on the Hot Bond Strength

Metal Preparation = Degrease, Alumina Blast, Degrease
Adhesive Application = Brushed
Adhesive Thickness = (Primer) 7.0 g/m², (single/cover) 18.0 g/m²
Rubber Compound Type = Semi E.V.
Cure Conditions = 15 minutes @ 150°C
Test Temperature = 150°C

Rubber Hardness (IRHD)	Bonding Agent System	Bond Strength MN/m²	Bond Failure			
			%R	%RC	%CP	%M
48	Chemlok 205/220	1.311	85	15	trace	
59	" "	1.823	50	50		
76	" "	2.617	50	10	40	
48	205/X2311	1.724	100			
59	" "	2.825	100			
76	" "	3.471	80	20		
48	205/220/AP1559	1.582	95	5		
59	" " "	2.374	60	20	20	
76	" " "	2.726	10	80	10	
48	Thixon OSN-2	1.393	85	15		
59	" "	2.329	95	5		
76	" "	3.410	75	20	5	
48	Chemlok 252	2.859	100			
59	" "	2.973	100			
76	" "	3.110	75	25		

Figure 6.10

The Influence of Moisture on the Hot Bond Strength (Initial Investigation)

Metal Preparation = Degrease, Alumina Blast, Degrease

Adhesive Application = Brushed

Adhesive Thickness = (Primer) 6.0 g/m², (Cover/single) 15.0 g/m²

Rubber Compound = Semi E.V. (19060 Mix)

Cure Conditions = 15 minutes @ 150°C

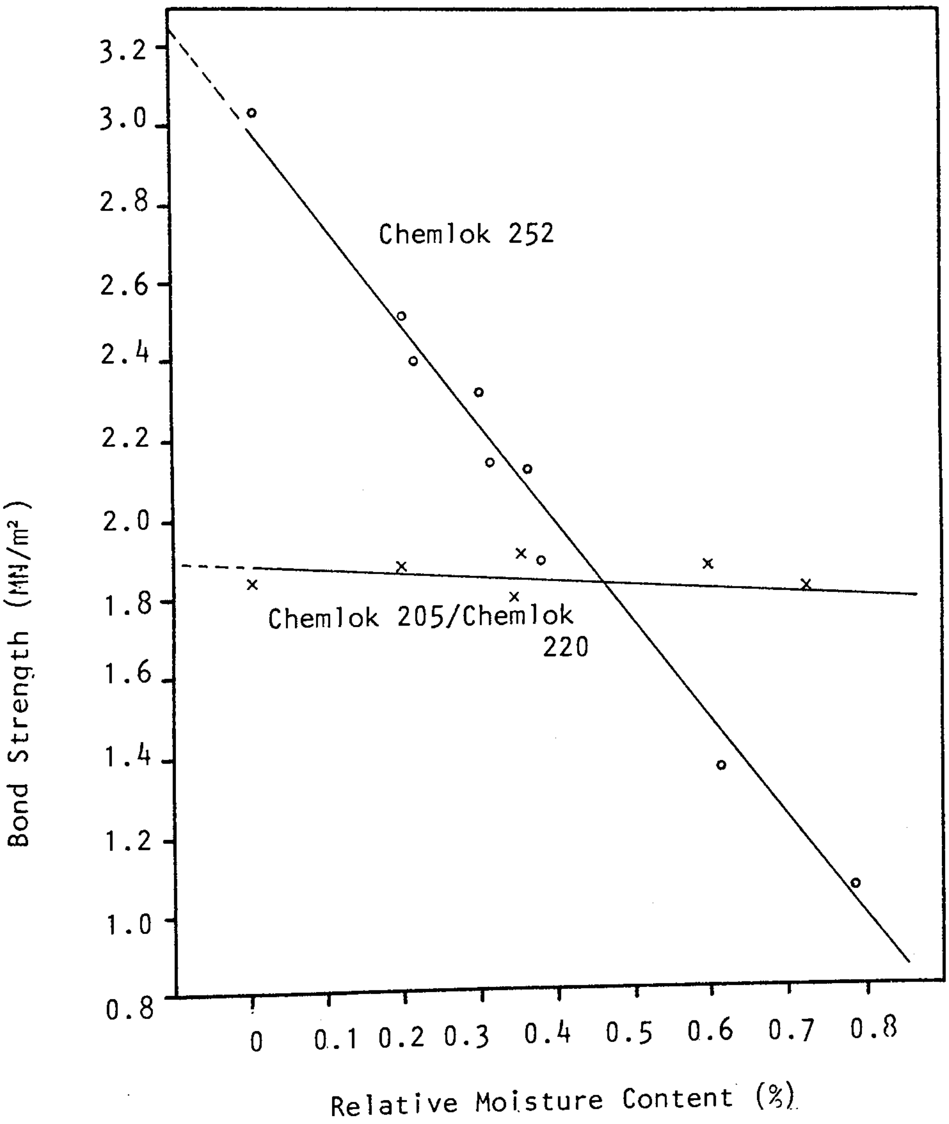
Test Temperature = 150°C

Moisture Content (%)		Bonding Agent System	Bond Strength MN/m²	Bond Failure %R	%RC	%CP	%M
D	0.0	C.205/220	1.976	65	30	5	
N	0.2	" "	1.907	65	35	trace	
W	2.4	" "	1.838	45	40	5	
D	0.0	Thixon OSN-2	2.386	70	10	20	
N	0.2	" "	2.338	70	5	25	
W	2.4	" "	1.424		50	50	
D	0.0	C.205/X2311	2.234	90	10		
N	0.2	" "	2.059	55	45	trace	
W	2.4	" "	1.355	70	20		10
N	0.2	Megum VI1658	2.365	90			10
W	2.4	" "	0.924	40	60		trace
N	0.2	Chemlok 250	1.993	90	10		
W	2.4	" "	1.259	65	35		trace
N	0.2	Chemlok 252	2.862	100			
W	2.4	" "	0.545	30	70		trace

D = "Dry" rubber batch
N = "Normal" rubber batch
W = "Wet" rubber batch

Figure 6.11

The Influence of Moisture on the Hot Bond Strength (Quantitative Investigation)



(Conditions similar to those in figure 6.10)

Figure 6.12

The Influence of "Substance X" on the Hot Bond Strength

Metal Preparation = Degrease, Alumina Blast, Degrease

Adhesive System = Chemlok 205/Chemlok 220

Adhesive Application = Brushed

Adhesive Thickness = (Primer) 7.0 g/m^2, (Cover) 18.0 g/m^2

Cure Conditions = 15 minutes @ $150^{\circ}C$

Test Temperature = $150^{\circ}C$

Rubber Batch	Bond Strength (MN/m^2)	Bond Failure %R	%RC	%CP	%M
No 1 (a)	1.743	80	20		
" (b)	1.878	75	25		
" (c)	2.008	75	25		
No 2 (a)	1.984	50	50		
" (b)	2.008	15	85		
" (c)	1.857	20	80		

Batch No 1	Low Content of "Substance X"
Batch No 2	High Content of "Substance X"

Figure 6.13

The Influence of Adhesive Application on the Hot Bond Strength

Metal Preparation = Degrease, Alumina Blast, Degrease

Adhesive Thickness = Varies depending on application

Rubber Compound = Semi E.V. (19060)

Cure Conditions = 15 minutes @ 150°C

Test Temperature = 150°C

Application Method	Bond Strength MN/m^2	Bond Failure			
		%R	%RC	%CP	%M
Brushed (a)	1.676	50	50	trace	
" (b)	1.807	45	55	trace	
Sprayed (a)	1.862	45	55		
" (b)	1.793	55	45		
Dipped (a)	1.759	50	50		
" (b)	1.827	45	54		1

Figure 6.14

The Influence of Adhesive Thickness (coating weight) on the Hot Bond Strength

Metal Preparation = Degrease, Alumina Blast, Degrease

Adhesive Application = Brushed

Rubber Compound = Semi E.V. (19060);*Conventional(11060)

Cure Conditions = 15 minutes @ 150°C

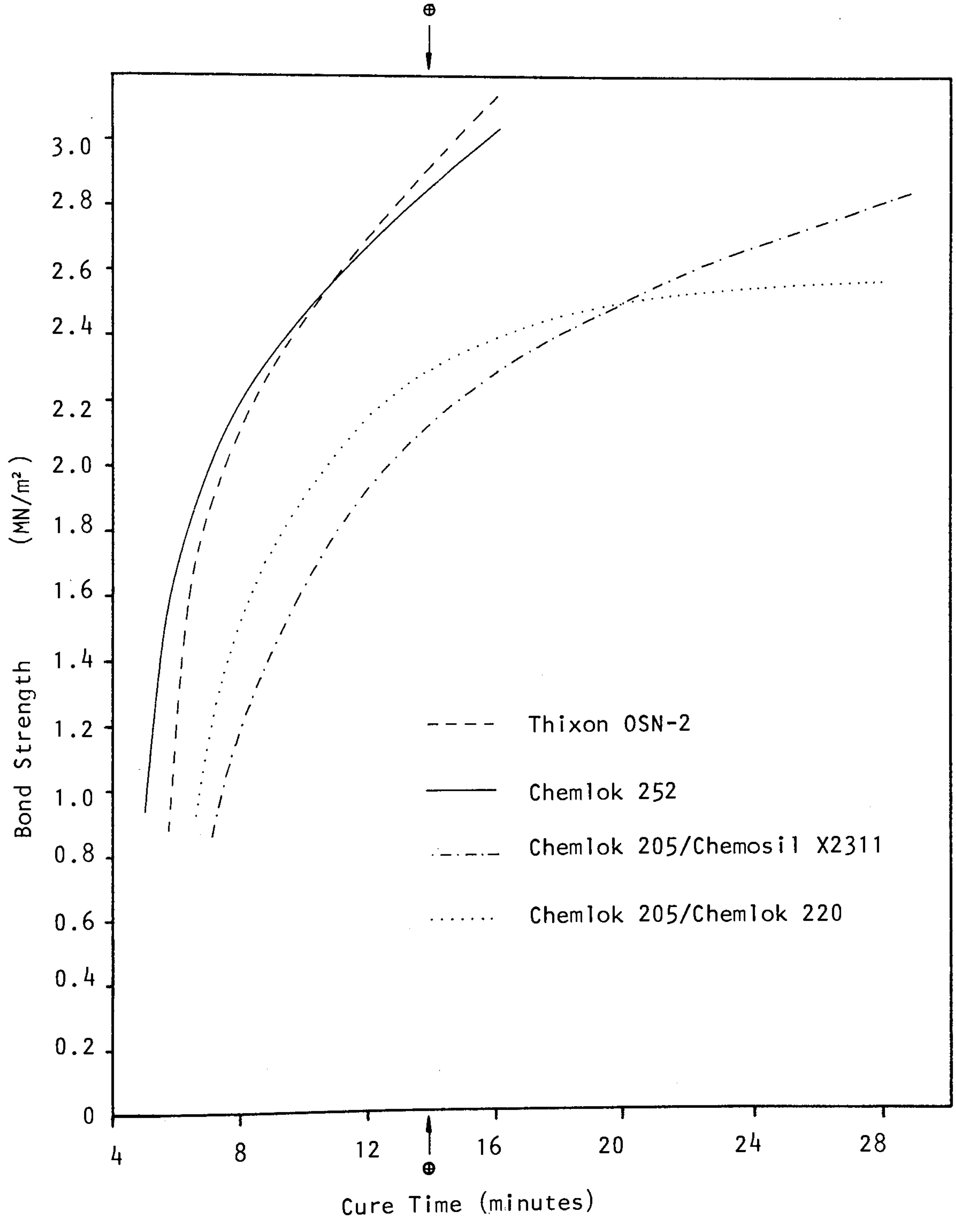
Test Temperature = 150°C

Coating Weight(g/m^2) Single/ Covercoat	Third Coat	Bonding Agent System	Bond Strength MN/m^2	Bond Failure %R	%RC	%CP	%M
7.03		C205/C220	1.800	50	50		
15.65		" "	1.821	50	50	trace	
25.43		" "	1.955	55	40	5	
16.19		Thixon OSN 2	2.383	90	5		5
37.62		" "	2.262	65	35		
59.99		" "	2.138	60	40		
6.68	4.66	205/220/AP1559	2.593	20	50	30	
16.94	5.48	" "	2.248	20	60	20	
8.27	24.35	" "	2.172	50	50		
18.86	28.48	" "	2.442	40	60		
10.08	44.60	" "	2.407	85		15	
21.55	50.63	" "	2.414	95		5	
7.00		*205/X2311	2.511	95	5		
15.11		* " "	2.510	98	2		
28.87		* " "	2.700	100			
8.10		* C.252	2.745	65	5		30
16.85		* "	2.993	94	5		1
26.35		* "	2.317	100	trace		
37.92		* "	2.669	100			
7.84		* C.205/252	3.241 +	100			
17.02		* " "	2.728	95	5		

Figure 6.15

The Influence of Cure Time on the Hot Bond Strength

(Cure Temperature = 150°C)

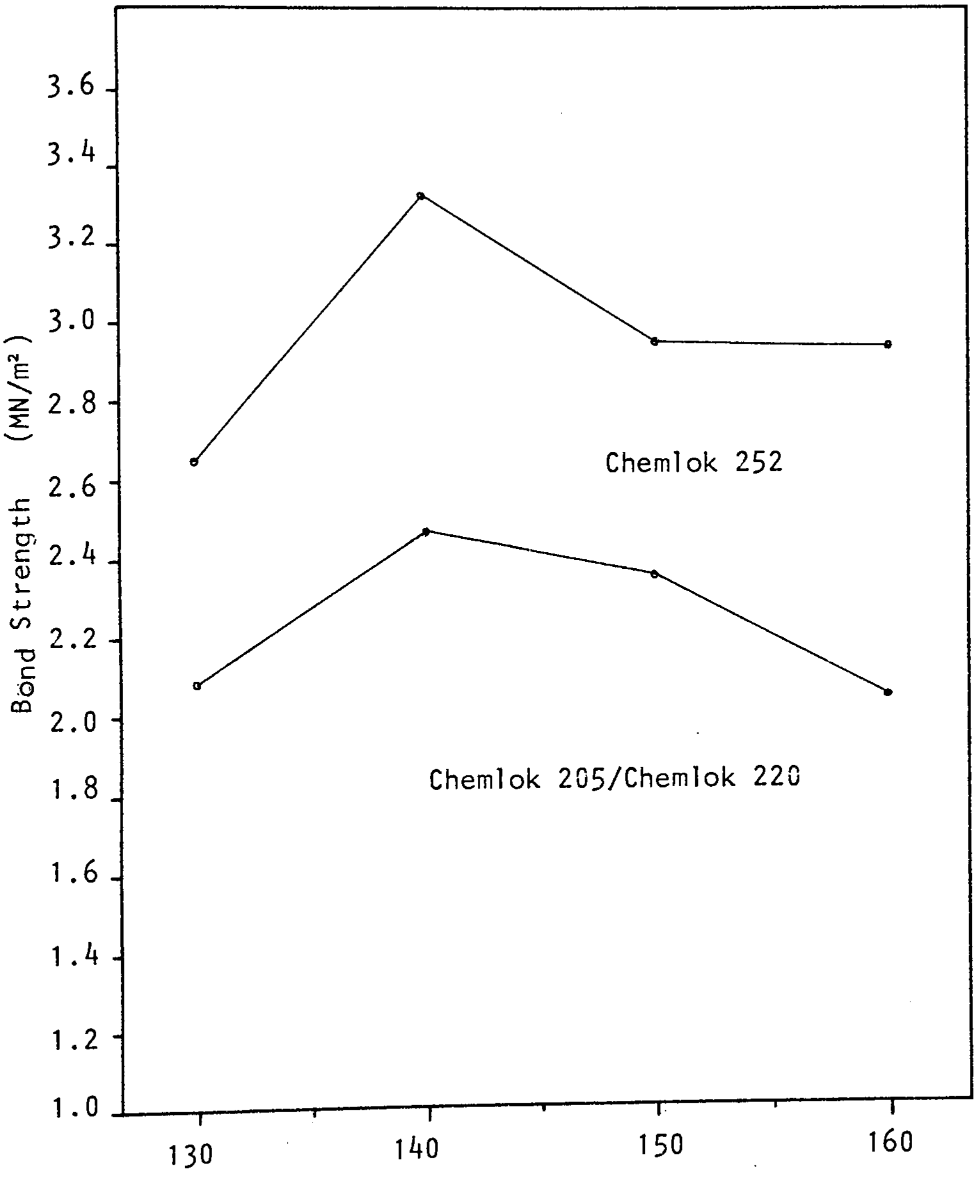


⊕ = Opt. Rubber Cure

Figure 6.16

The Influence of Cure Temperature on the Hot Bond Strength

(Cure Time = 15 minutes)



Cure Temperature (°C)

Figure 6.17

The Influence of Moulding (Press) Pressure on the Hot Bond Strength

Metal Preparation = Degrease, Alumina Blast, Degrease

Adhesive Application = Brushed

Adhesive Thickness = (Primer) 7.0 g/m^2, (Cover) 18.0 g/m^2

Adhesive System = Chemlok 205/Chemlok 220

Rubber Compound = Conventional (11060)

Cure Conditions = 15 @ 150°C

Test Temperature = 150°C

Moulding Pressure		Bond Strength	Bond Failure			
P.S.I.	MN/m^2	(MN/m^2)	%R	%RC	%CP	%M
500	3.448	1.431	35	65		
750	5.172	1.878	55	45		
1000	6.896	2.039	50	50		
1250	8.621	1.922	50	50		
1500	10.344	1.971	80	10	10	

Figure 6.18

The Influence of Adhesive "Prebake" on the Hot Bond Strength

Metal Preparation = Degrease, Alumina Blast, Degrease

Adhesive Application = Brushed

Adhesive Thickness =(Primer) 6 g/m² (Cover) 15 g/m²

Cure Conditions = 15 minutes @ 150°C

Rubber Compound = Semi E.V. (19060)

Test Temperature = 150°C

"Prebake" (minutes)	Bonding Agent System	Bond Strength (MN/m²)	Bond Failure %R	%RC	%CP	%M
5	C.205/C.220	1.999	65	35		
10	" "	1.826	75	25		
15	" "	2.191	65	35		
5	C.205/C.252	2.687	97	3		
10	" "	2.790	98	2		
15	" "	2.449	95	5		

Figure 7.1

Cross-Section of a Bush, showing the Elemental Grid

(Used for Finite Element Heat Transfer Analysis)

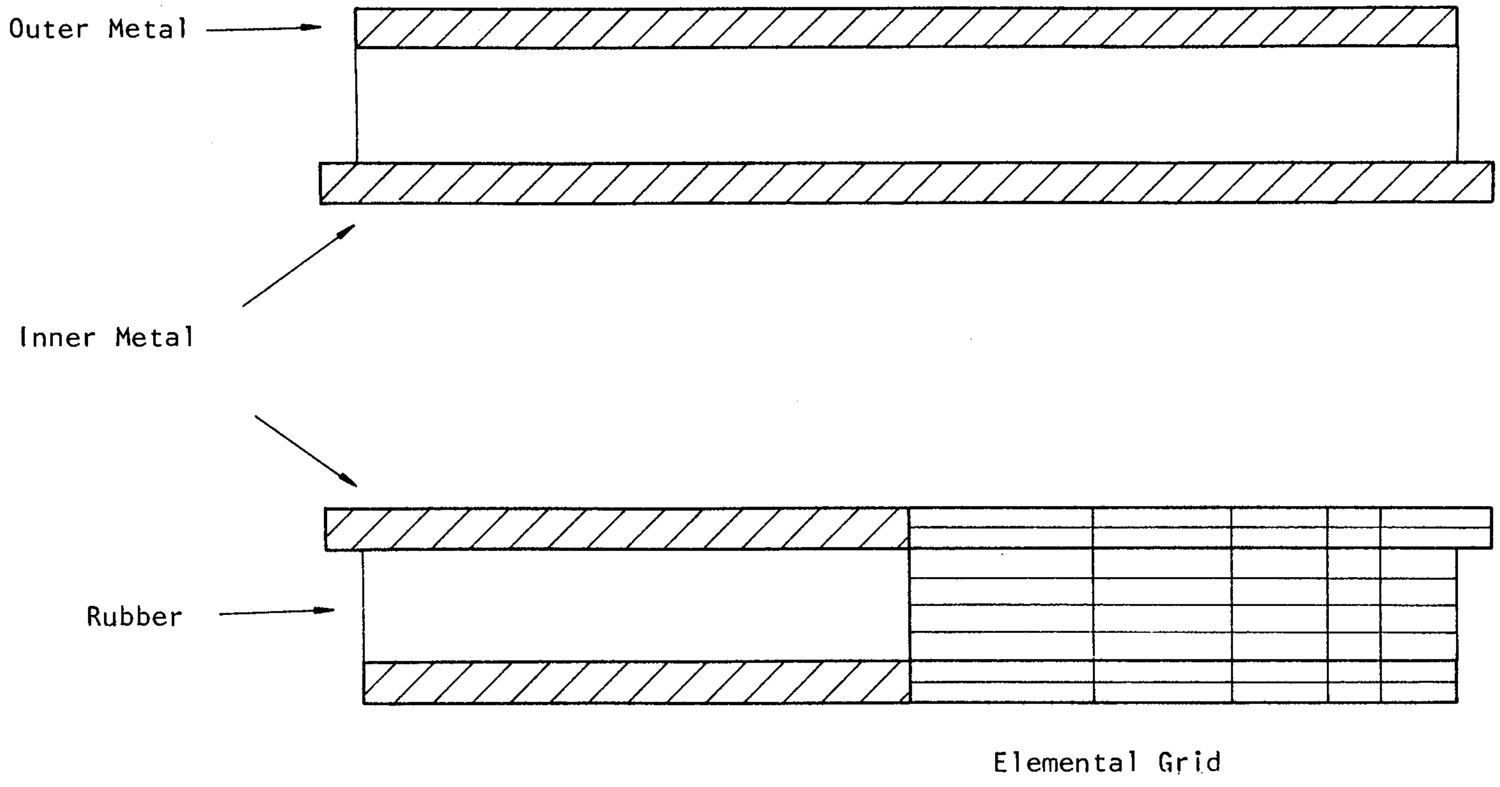


Figure 7.2

The Cooling Curve for Bush No. 13/1914 (i)

Initial Uniform Temperature = 150°C

Ambient Temperature = 30°C

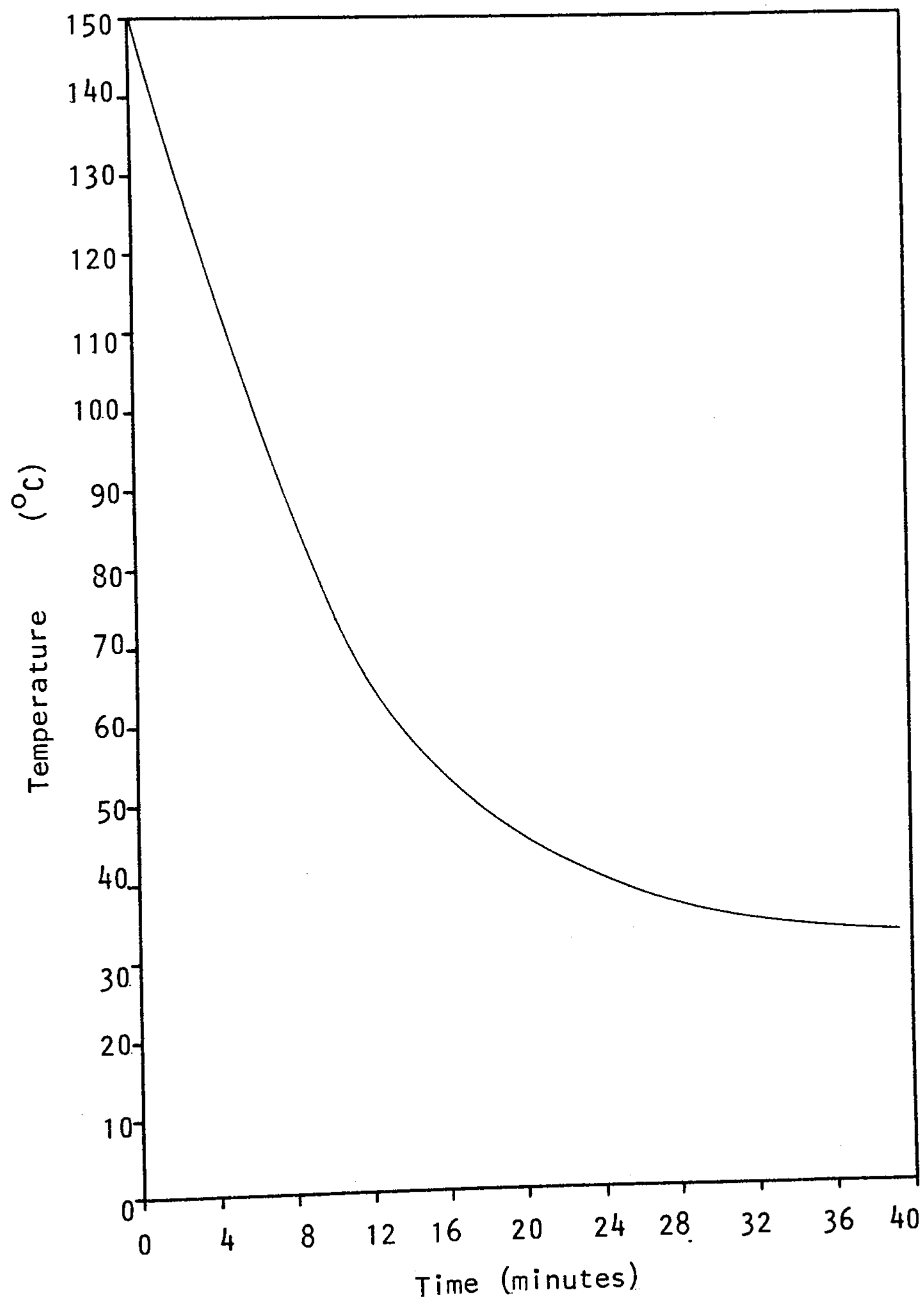


Figure 7.3

The Cooling Curve for Bush No. 13/1914 (ii)

Initial Uniform Temperature = 160°C

Ambient Temperature = 20°C

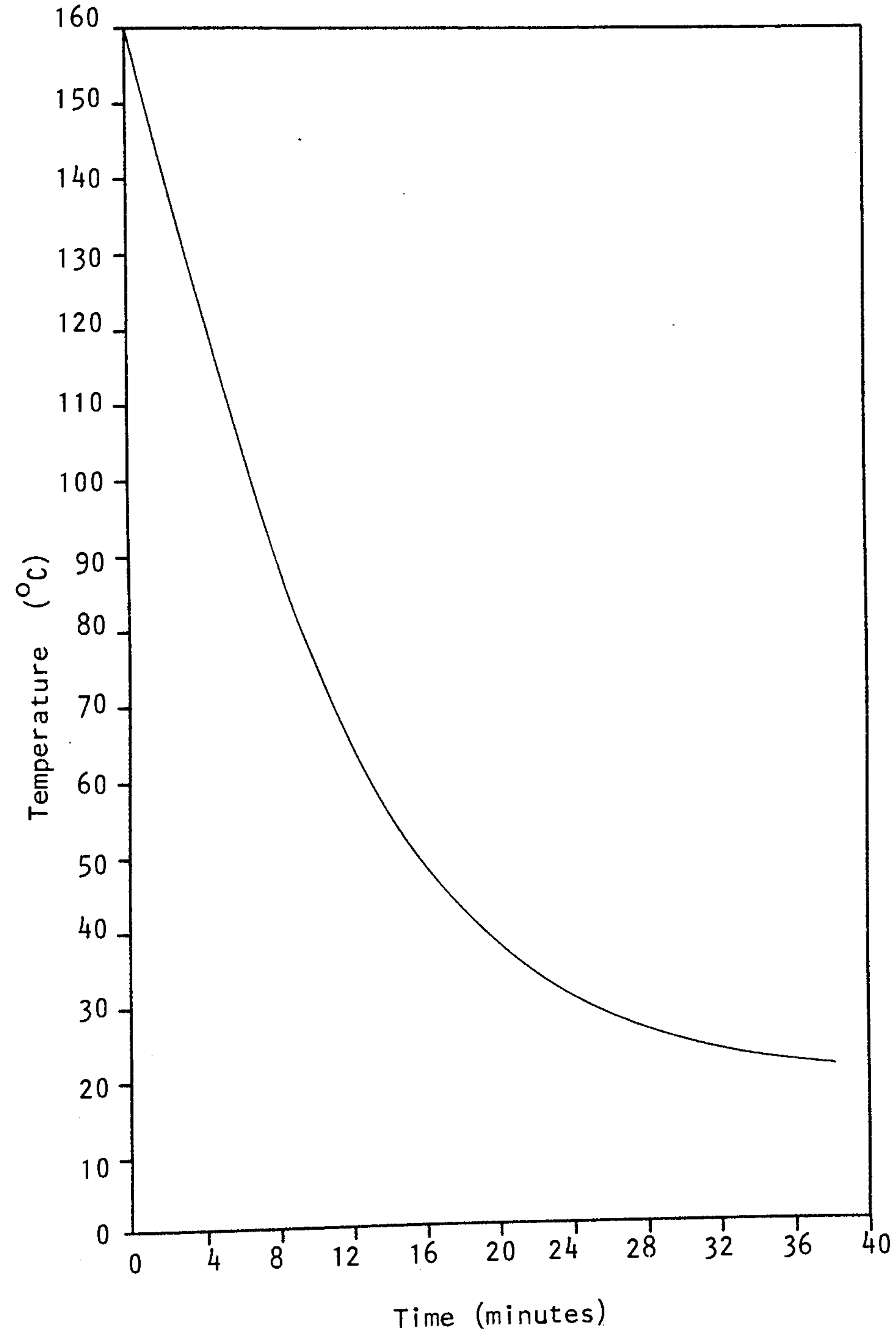
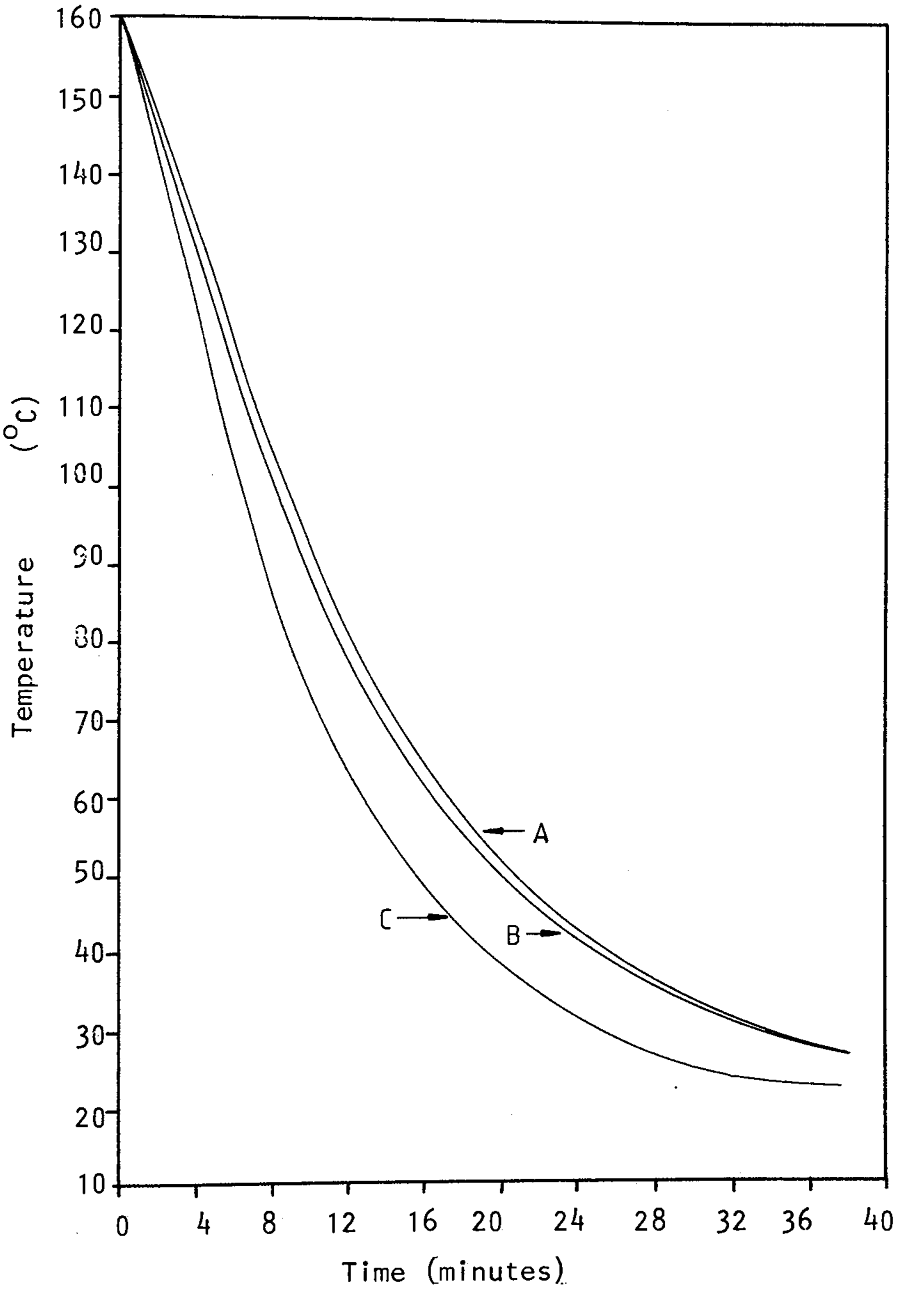


Figure 7.4

The Effect of a Thick Inner Metal on the Bush Cooling Characteristics

Initial Temperature = 160°C

Ambient Temperature = 20°C



A = Thick metal (Inner Bond Temp.)

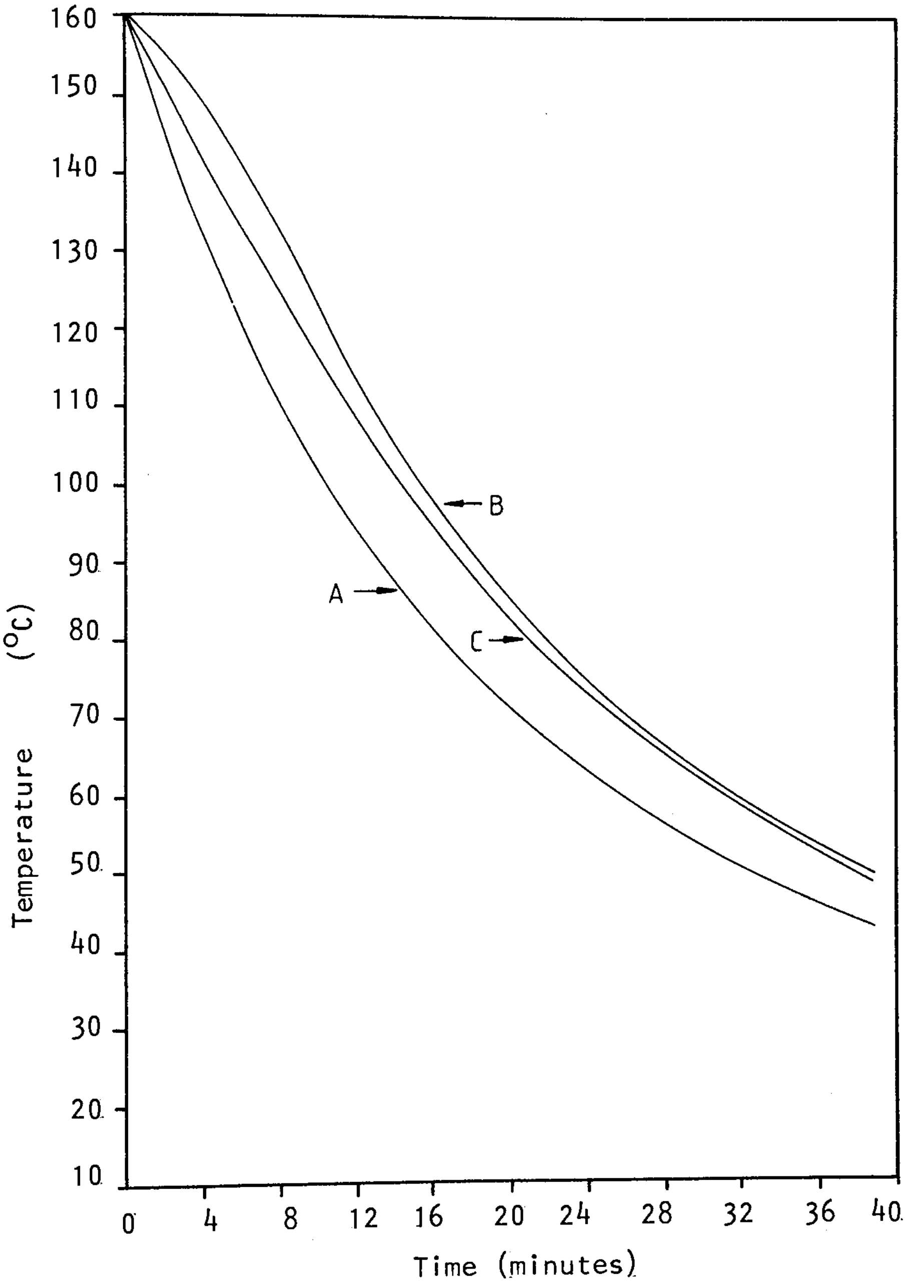
B = " " (Rubber Temp.)

C = Normal Metal (Inner Bond and Rubber Temp.)

Figure 7.5

Cooling Curves for Bush No. 13/1983

Initial Temperature = 160°C
Ambient Temperature = 20°C



A Outer Metal Temperature

B Rubber "

C Inner Metal "

Figure 7.6

F.E.M.Model of the Modified Test-Piece

(1/4 section of Assembly)

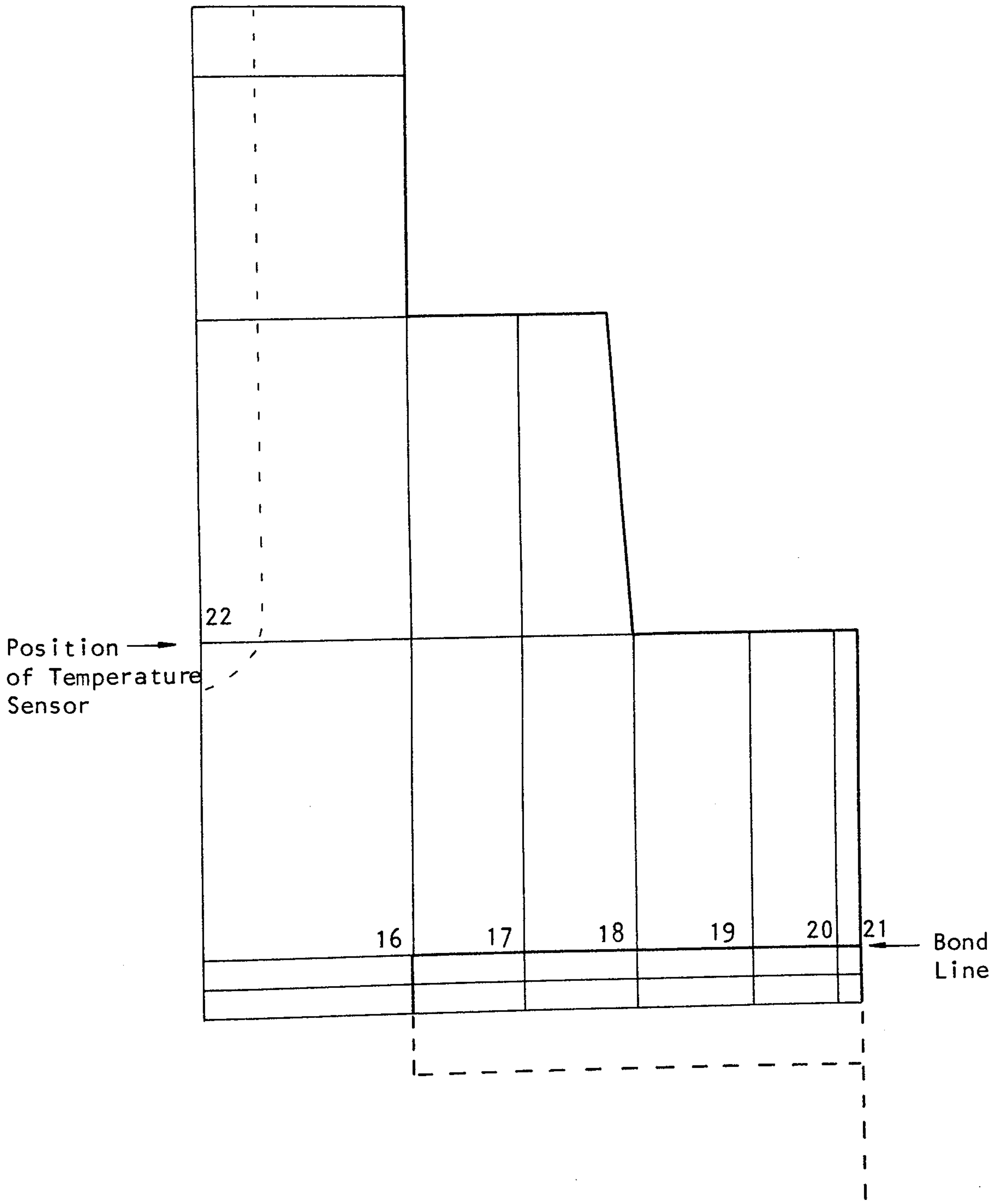


Figure 7.7

The Sensor/Bond Line Temperature Relationship
(During Cooling of the Test-Piece)

Initial Temperature of test-piece = 150°C

Ambient Temperature = 30°C

(All temperatures in °C)

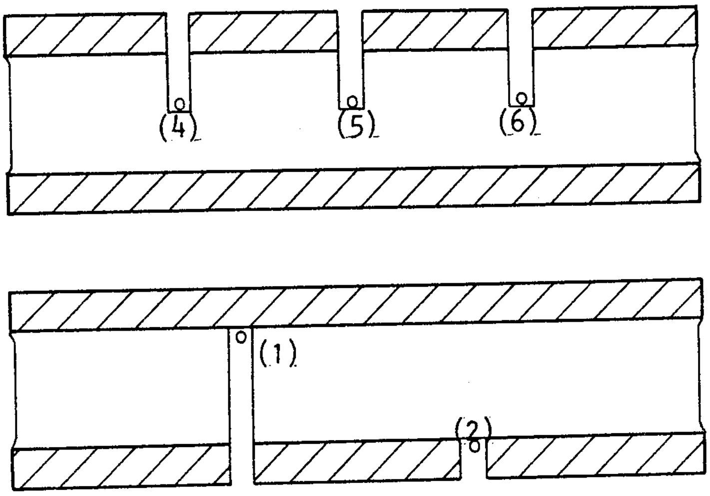
Node Number	Time after Demoulding (minutes)					
	0	4	15	33	51	90
22 (temperature sensor)	150	133.6	90.6	53.6	38.8	30.3
16 (bond line)	150	133.7	90.7	53.6	38.8	30.3
17 " "	150	133.6	90.6	53.6	38.8	30.3
18 " "	150	133.5	90.6	53.6	38.8	30.3
19 " "	150	133.4	90.5	53.6	38.8	30.3
20 " "	150	133.2	90.4	53.6	38.8	30.3
21 " "	150	133.2	90.4	53.5	38.8	30.3

(Refer to figure 7.6 for node locations)

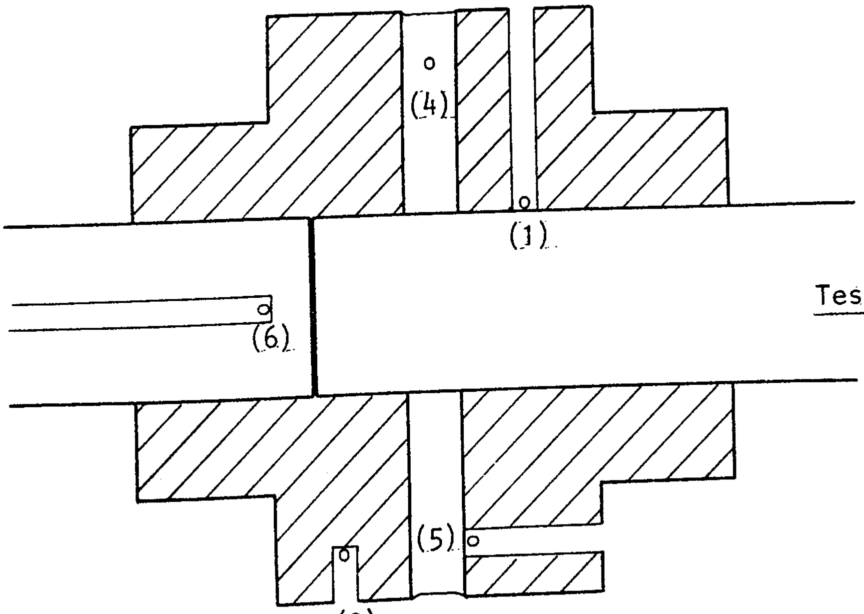
Figure 7.8

The Location of Thermocouples

o = Thermocouple position



Bush



Test-Piece

Thermocouple (3) exposed to ambient conditions

Figure 7.9

Experimental Cooling Curves

For Thermocouple (T.C.) Positions refer to figure 7.8

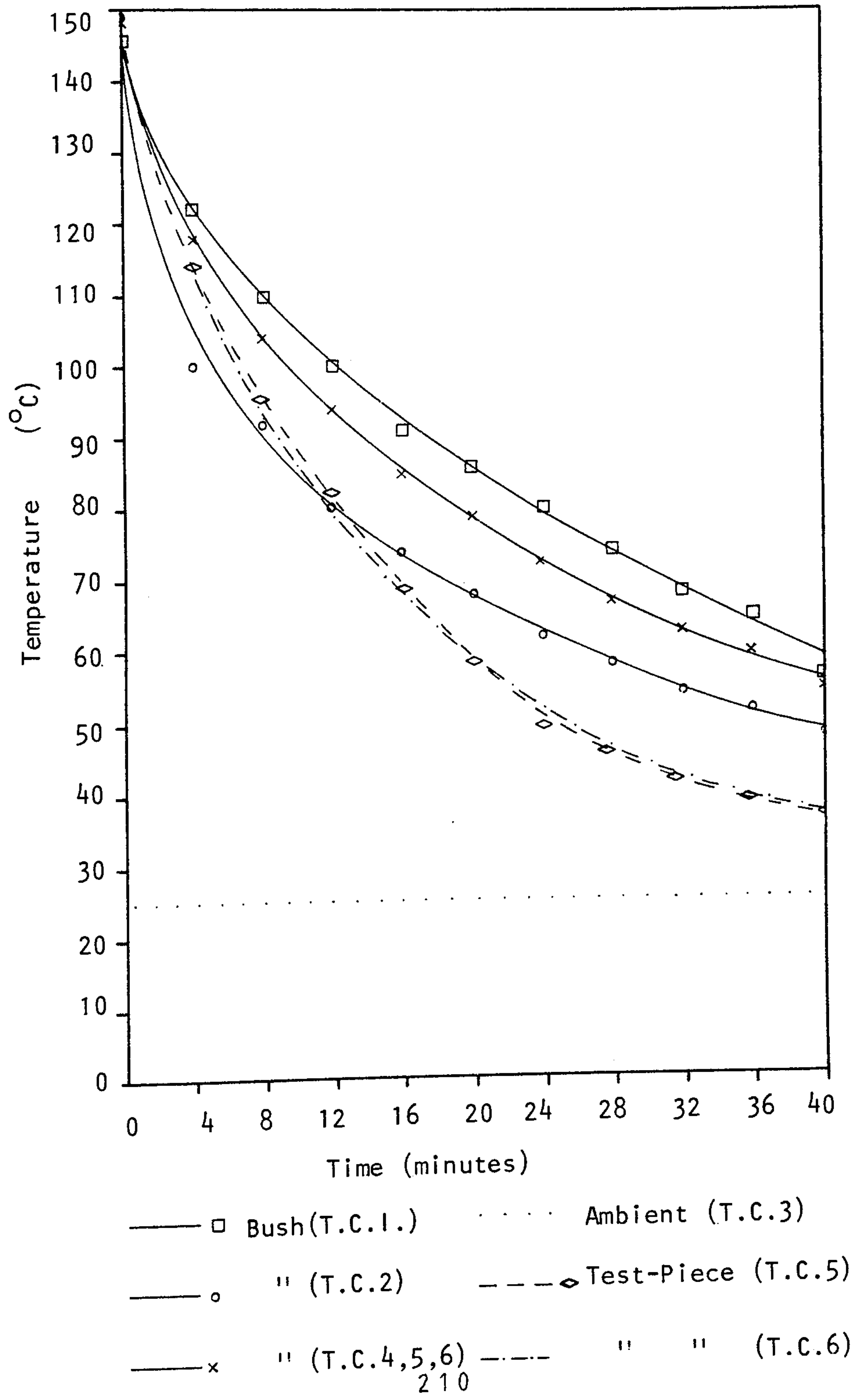


Figure 8.1

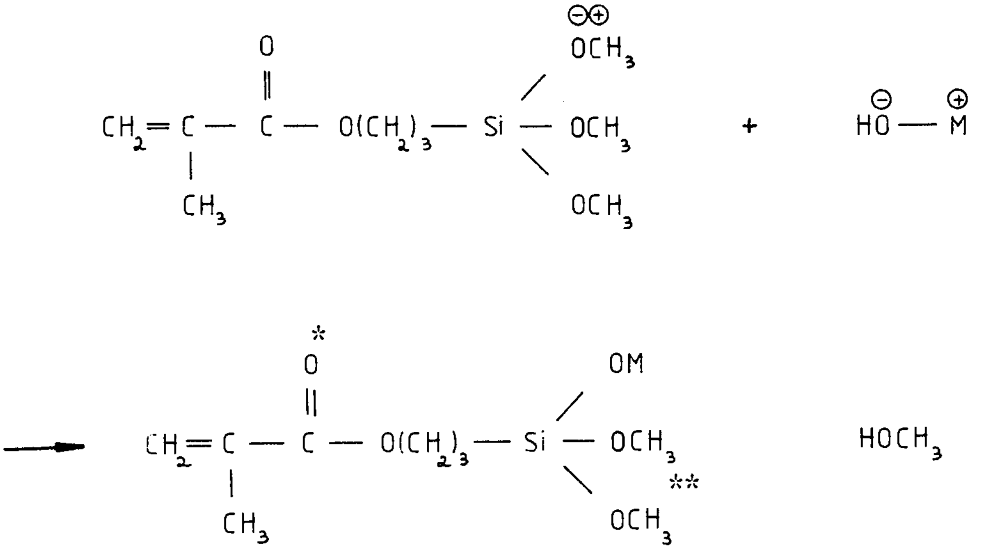
A Comparison of the Three Techniques for Evaluating Shrinkage Stress

		Shrinkage Stress (MN/m^2)		
Method / Shape Factor		Finite Element Analysis	Empirical Calculation	Experimental Method
2.0		1.552	0.848	0.869
4.0		5.862	2.979	2.800
6.0		$\simeq$10.5	6.248	-
Method / Rubber Hardness (IRHD)				
45		-	0.510	0.552
60		1.552	0.848	0.869
75		-	1.593	1.545

Figure 8.2

Examples of Reactions at the Bond Interface

1. Metal/Adhesive Interface (Silane with Hydrated Metal Oxide)



* Possible polymer reaction site

** 2 more sites for reaction with the metal

2. Rubber/Adhesive Interface (Natural Rubber Chains with p-dinitroso benzene)

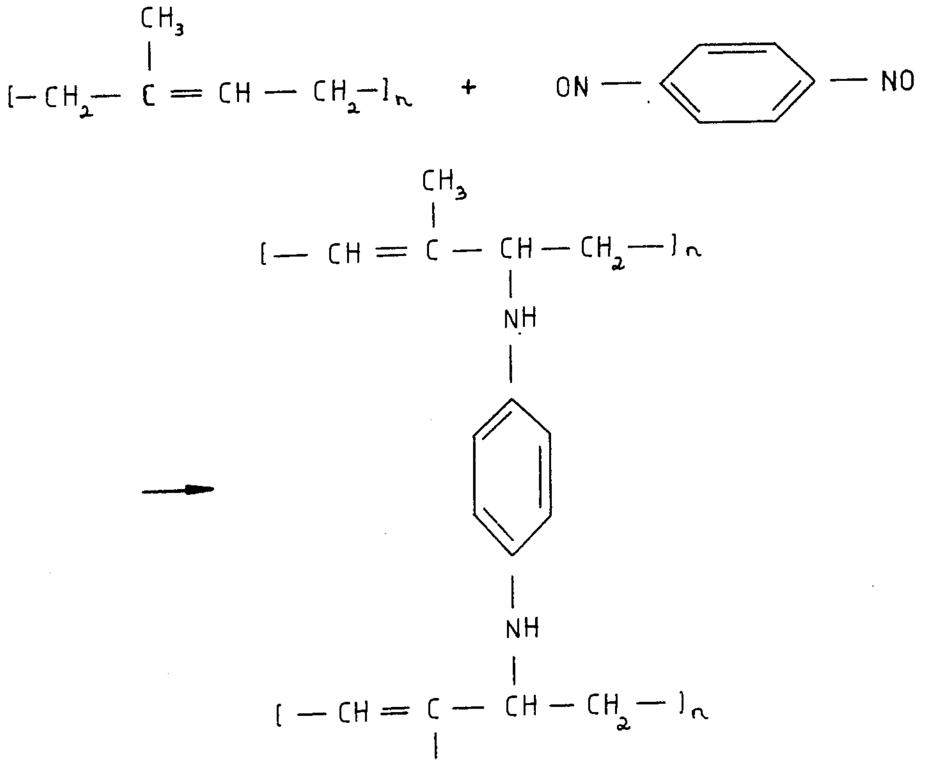


Figure 8.3

The Comparison of Metal Surface Variation with Adhesive Thickness

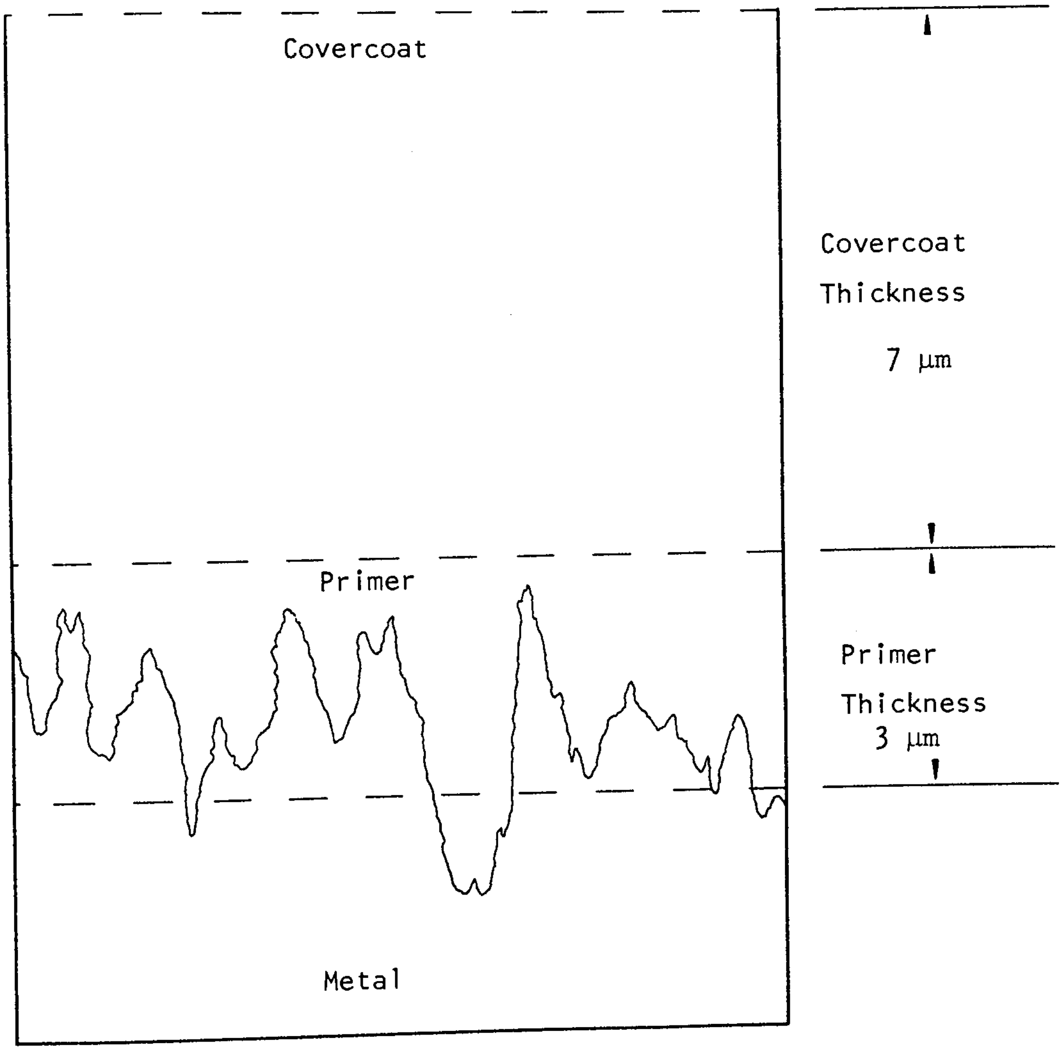
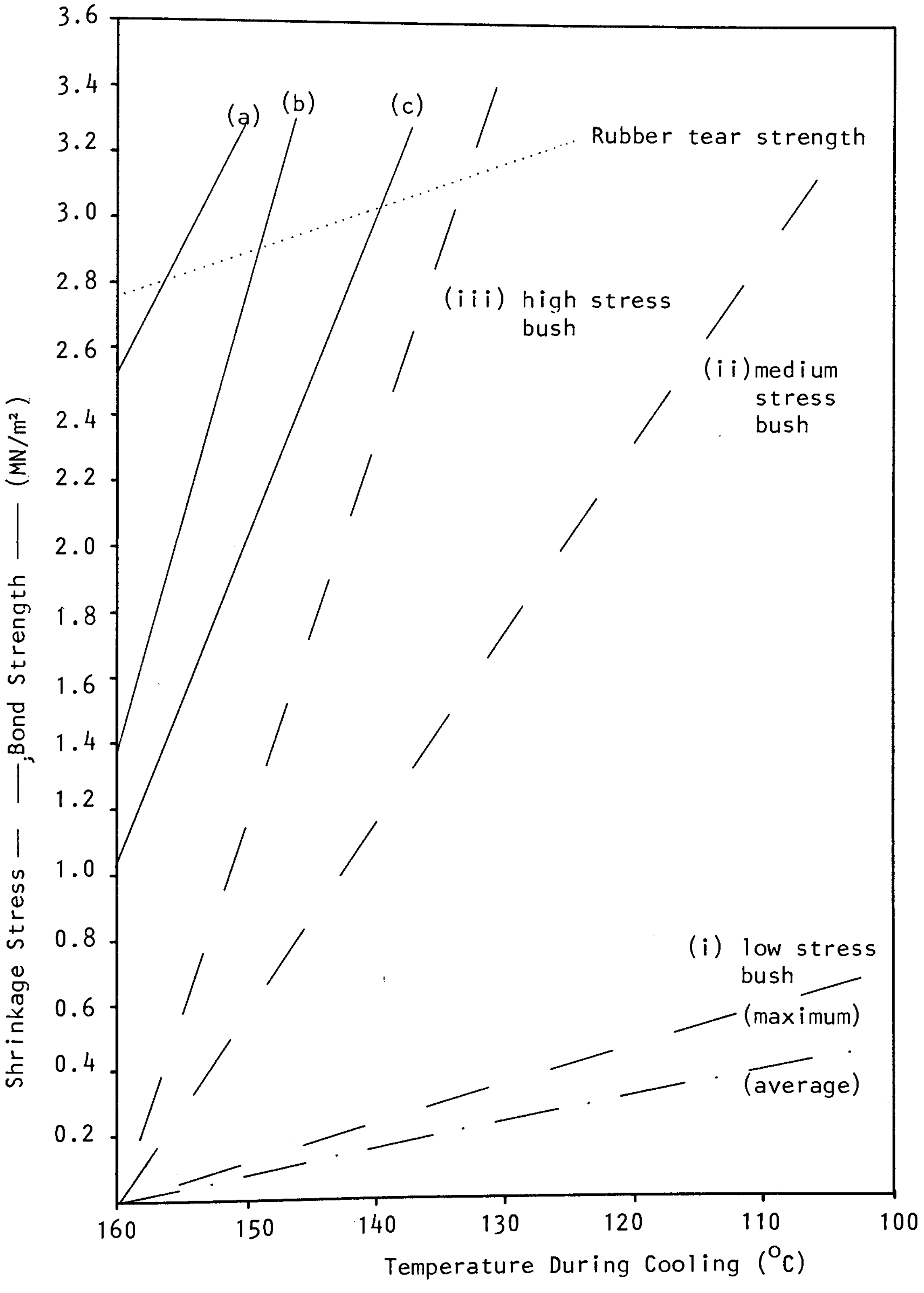


Figure 8.4

Shrinkage Stress/Bond Strength Relationships

Category No. 1 (Uniform Temperature)

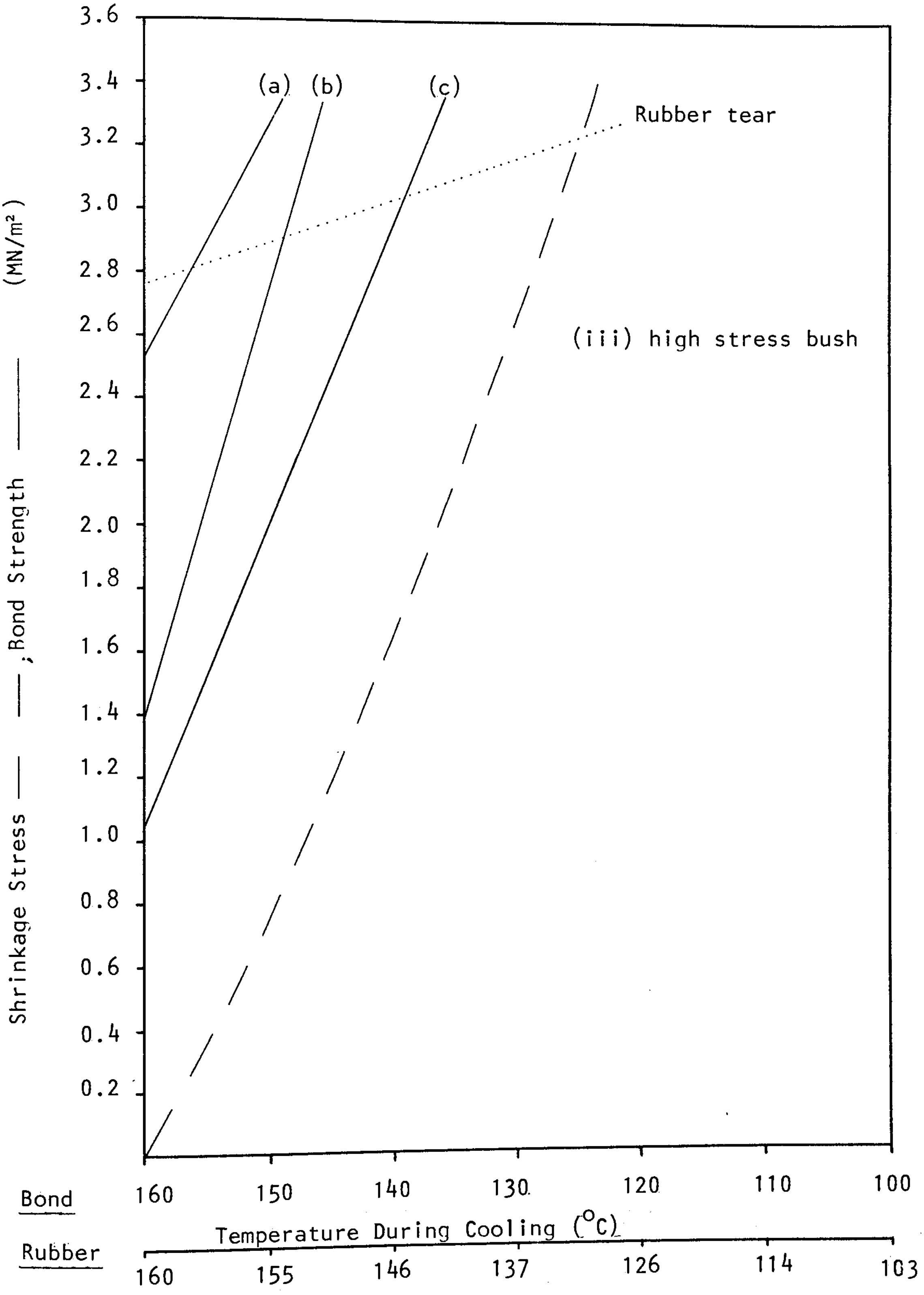


(a) C205/C252
(b) C205/C220/AP1559
(c) C205/220

Figure 8.5

Shrinkage Stress/Bond Strength Relationships

Category No. 2 (Thick Rubber)

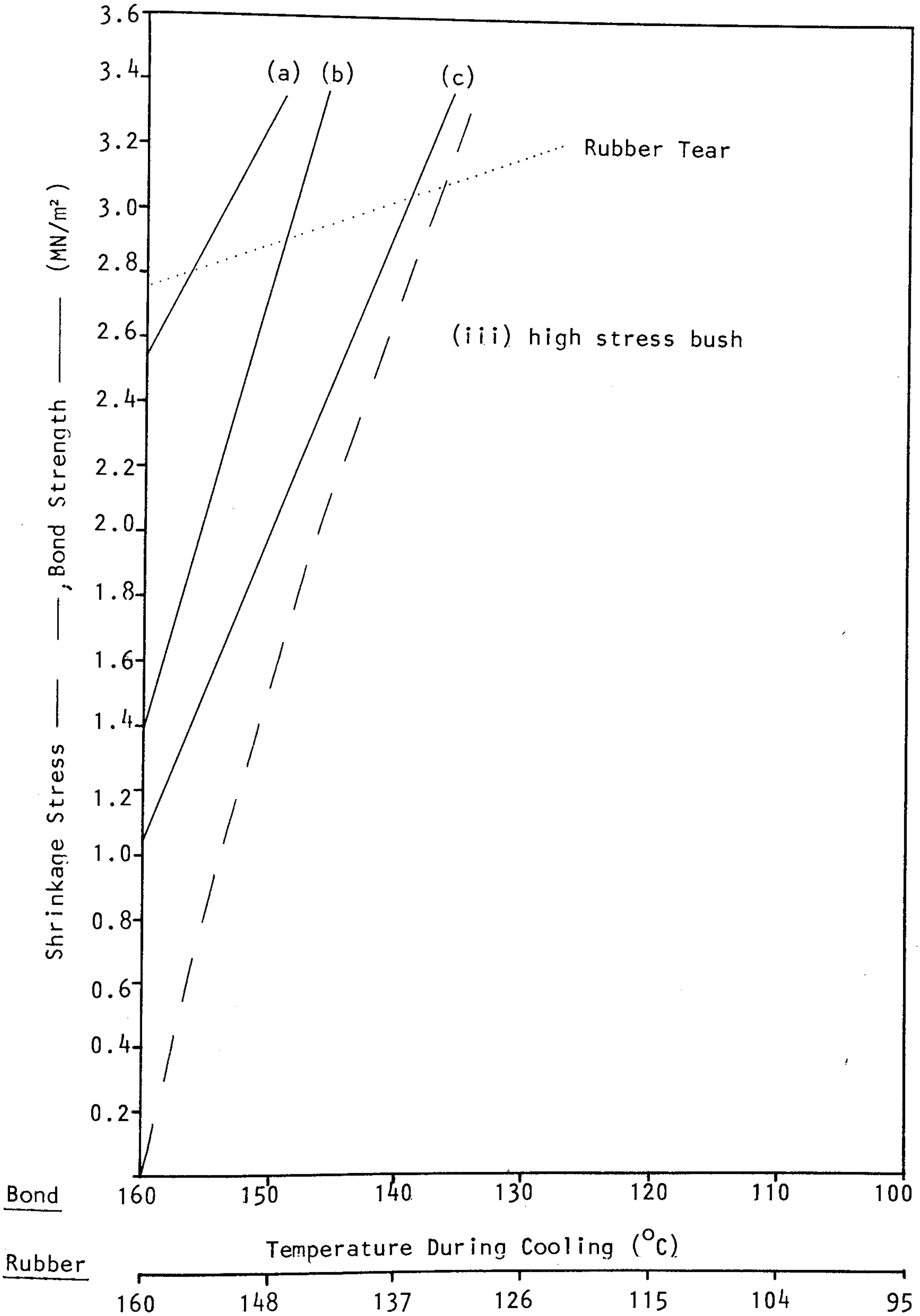


(a) C205/252; (b)C205/C220/AP1559; (c) C205/C220

Figure 8.6

Shrinkage Stress/Bond Strength Relationships Category No. 3

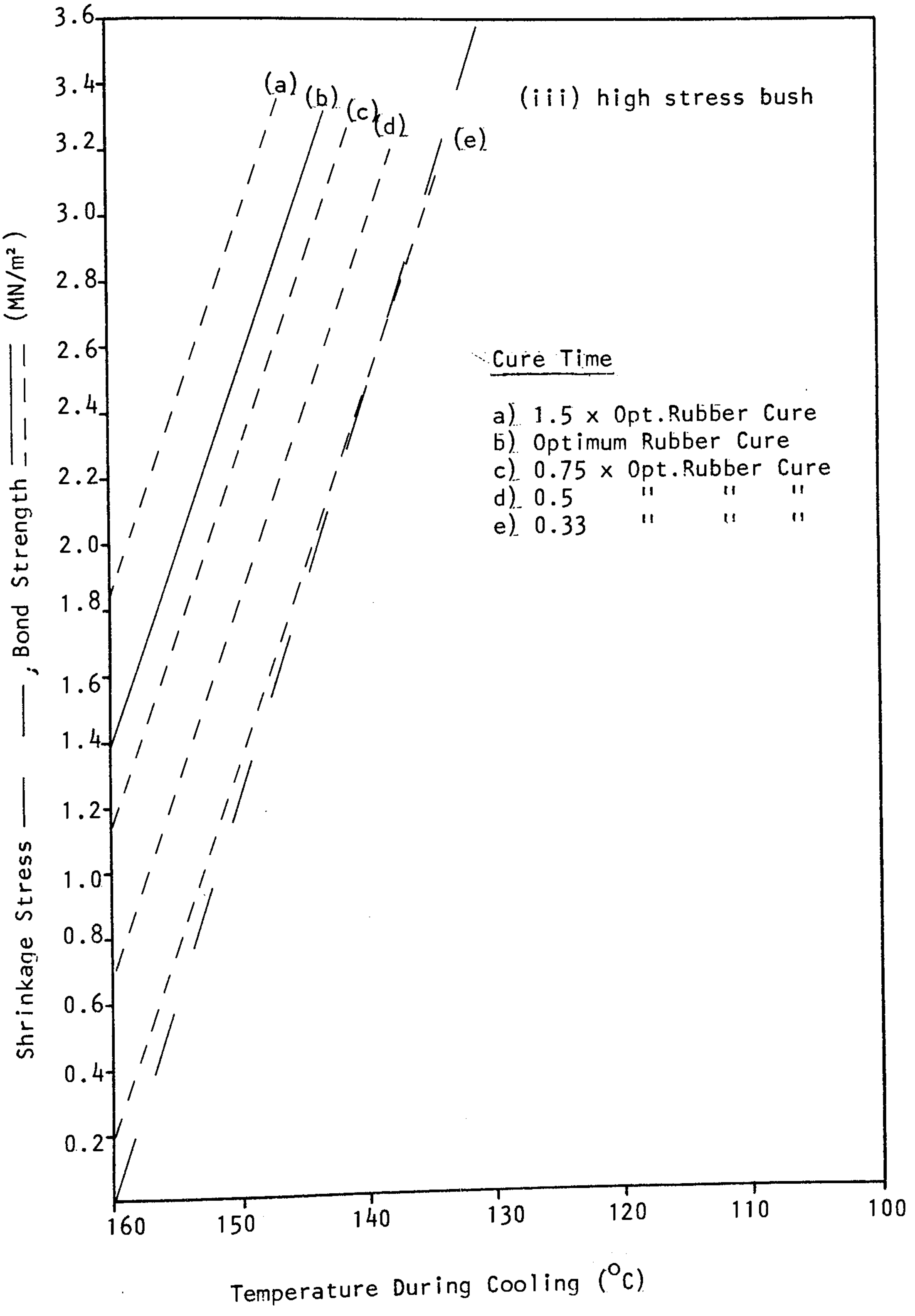
(Thick Inner Metal)



(a) C205/C252; (b) C205/C220/AP1559; (c) C205/C220

Figure 8.7

Shrinkage Stress/Bond Strength Relationships (Influence of Cure Time)



(C205/C220/AP1559)

Figure 8.8

Shrinkage Stress/Bond Strength Relationships

(Influence of Rubber Hardness)

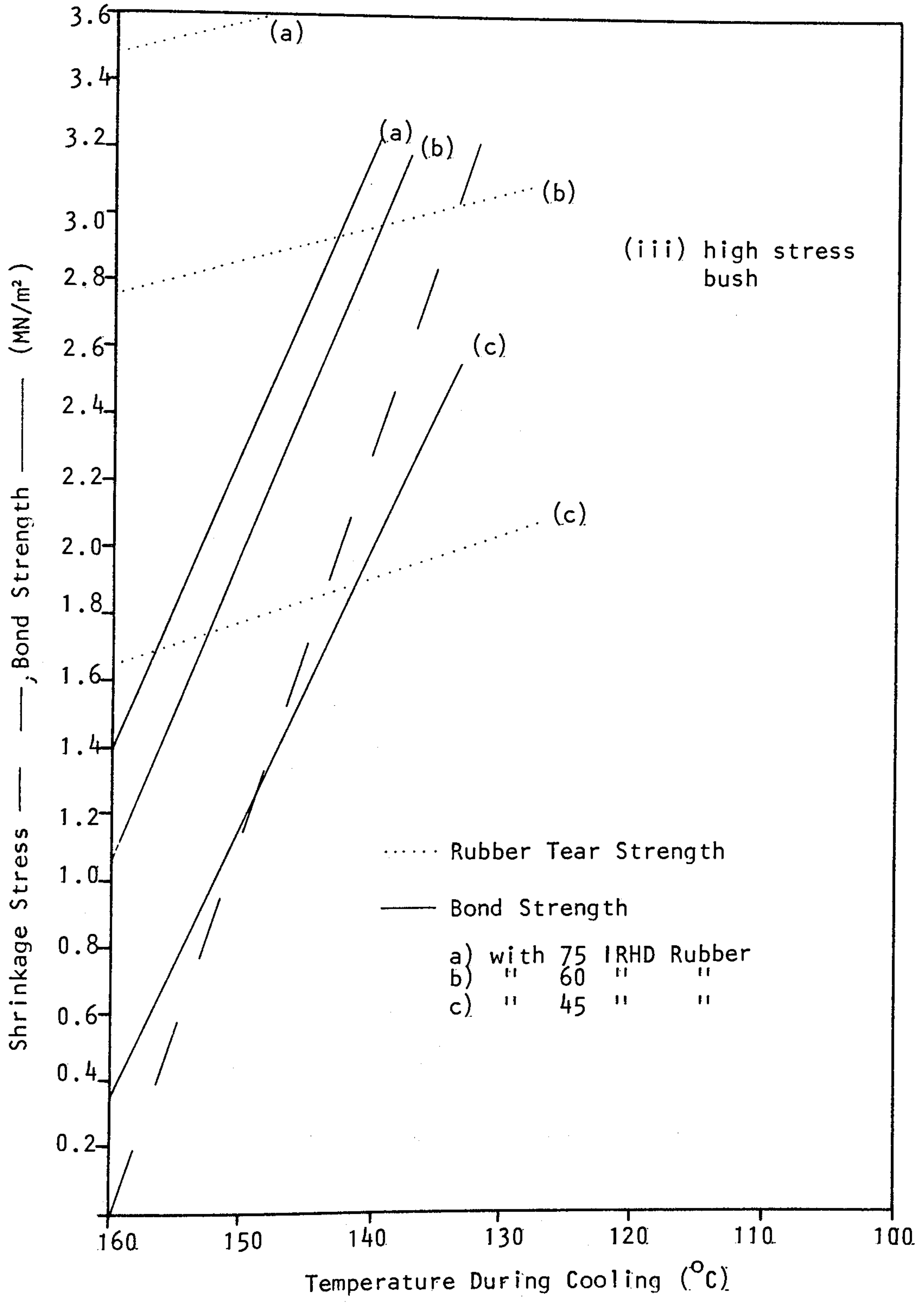


Figure 9.1

Heat Flow Through A Bush Transfer Mould

NB: Rubber areas indicated by shading. Arrows show the principle routes of heat flow.

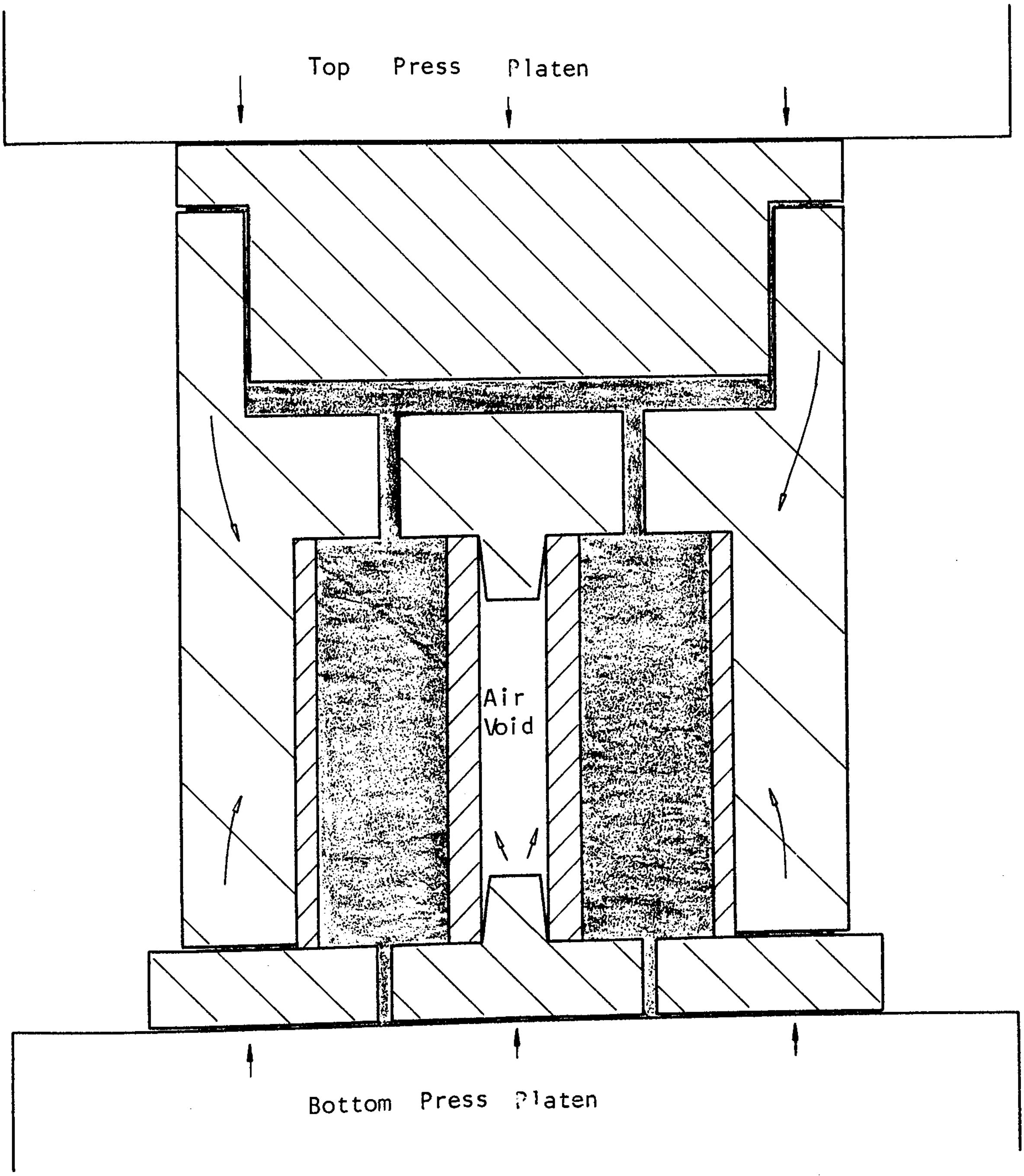


Figure 9.2

Heat Flow Through a Bush Hydramould

NB: Rubber Areas indicated by shading.
Arrows show principle routes of heat flow.

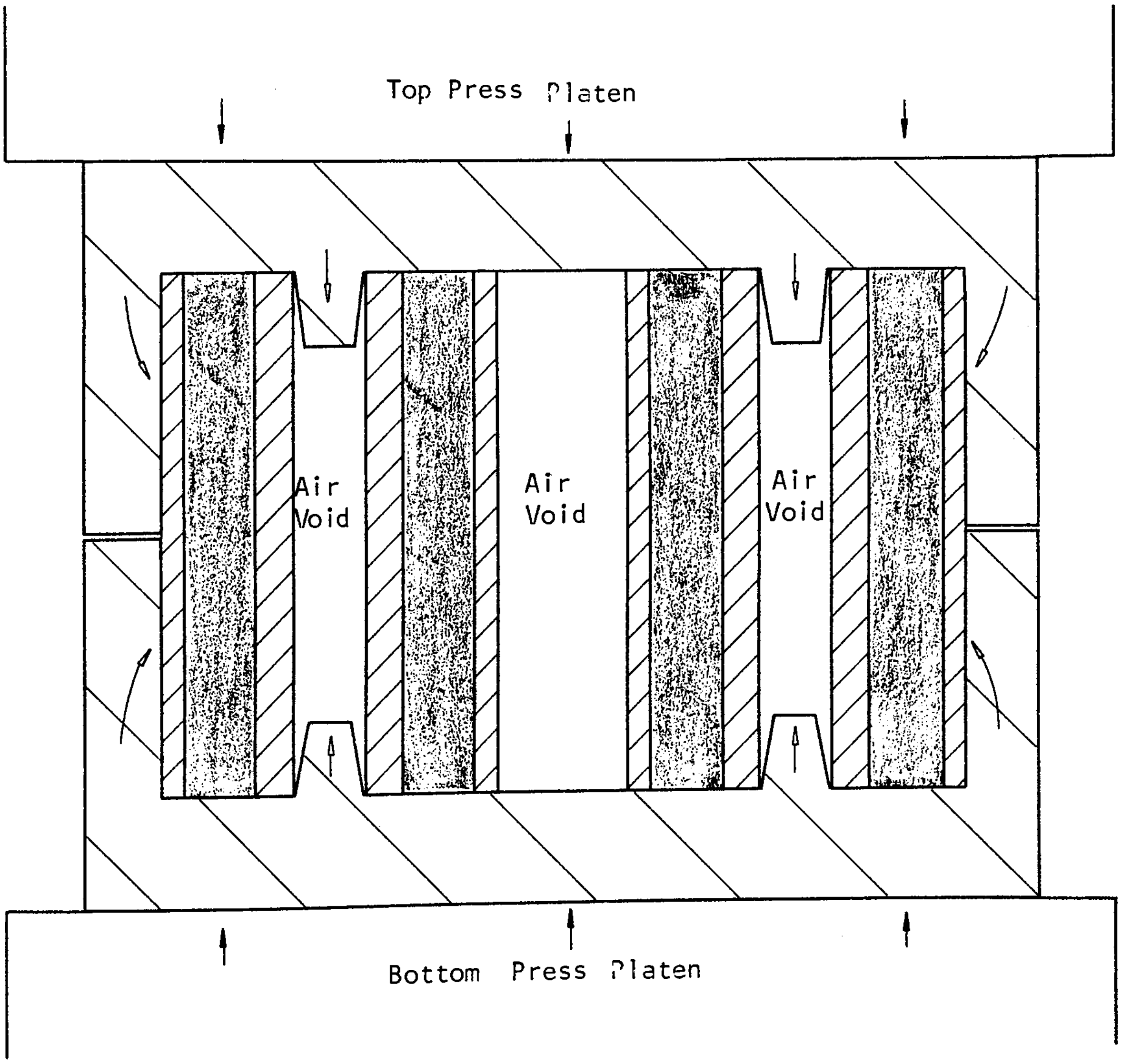


Figure 9.3

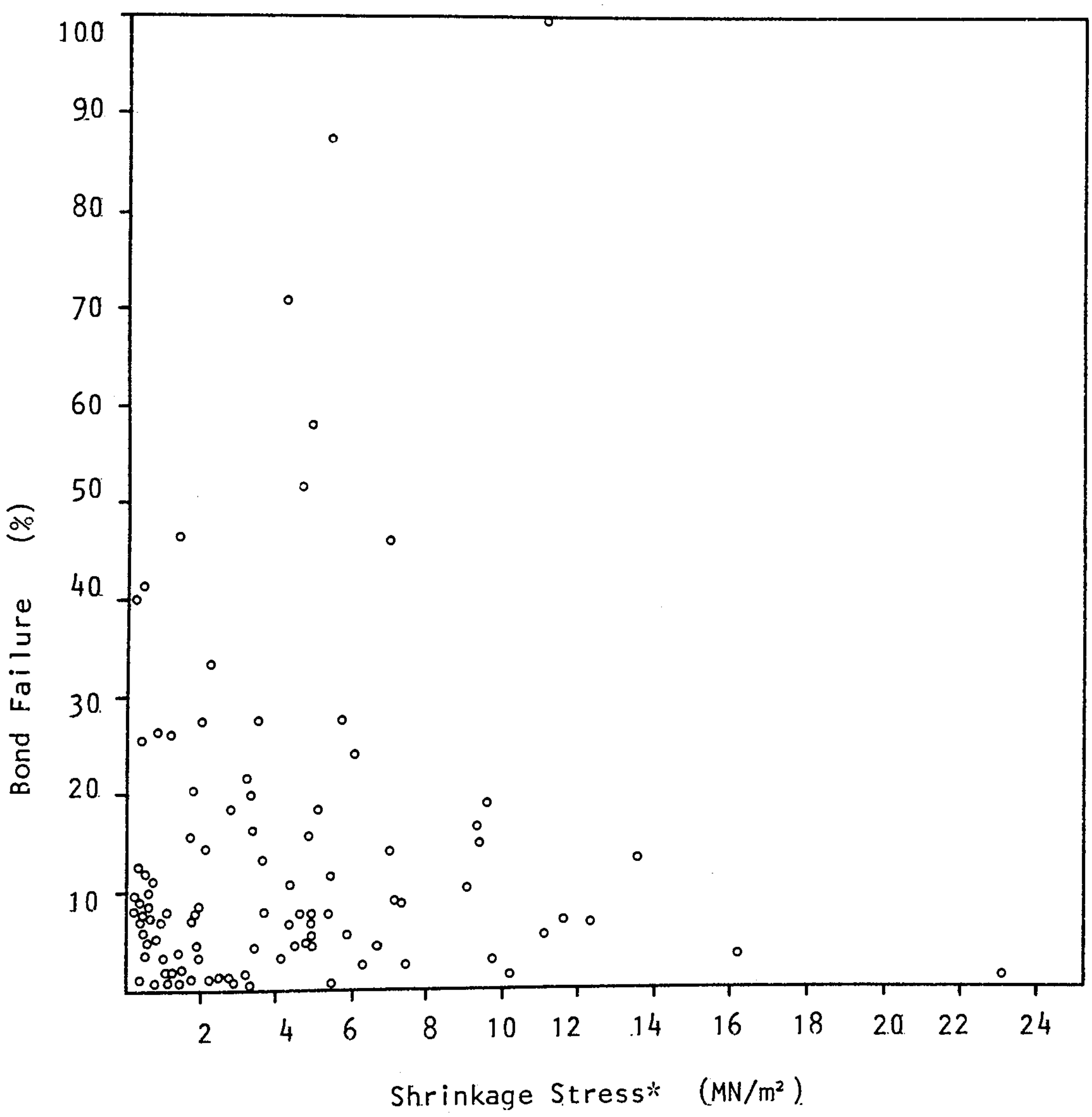
A Comparison of the Bush Population with the Data Sample

Criterion	Population	Data Sample
Number of Products	525	108
Mean Shrinkage Stress	3.045 MN/m²	4.132 MN/m²
Mean Inner Metal Length	50 mm	66 mm
Mean Rubber Hardness	59 IRHD	56 IRHD
Bond Failure Level *	7.0%	11.9%

* Bond failure values are not completely comparable as they relate to different periods.

Figure 9.4

Shrinkage Stress v s. % Bond Failure

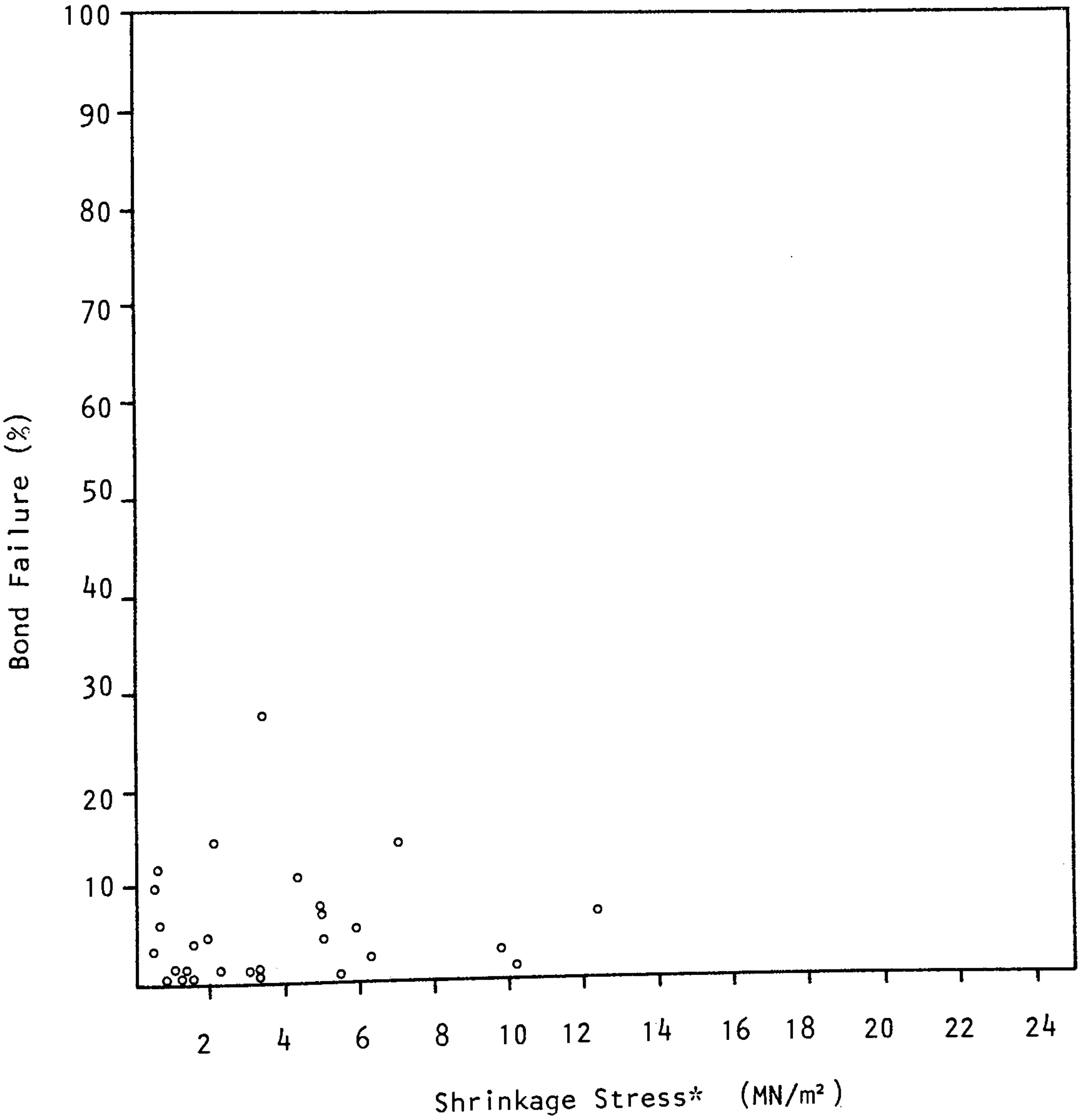


* For 130°C, Temperature Change

Figure 9.5

Shrinkage Stress v s. % Bond Failure

(one Moulding Area)



* For 130°C Temperature Change

Figure 9.6

Inner Metal Length v s. % Bond Failure

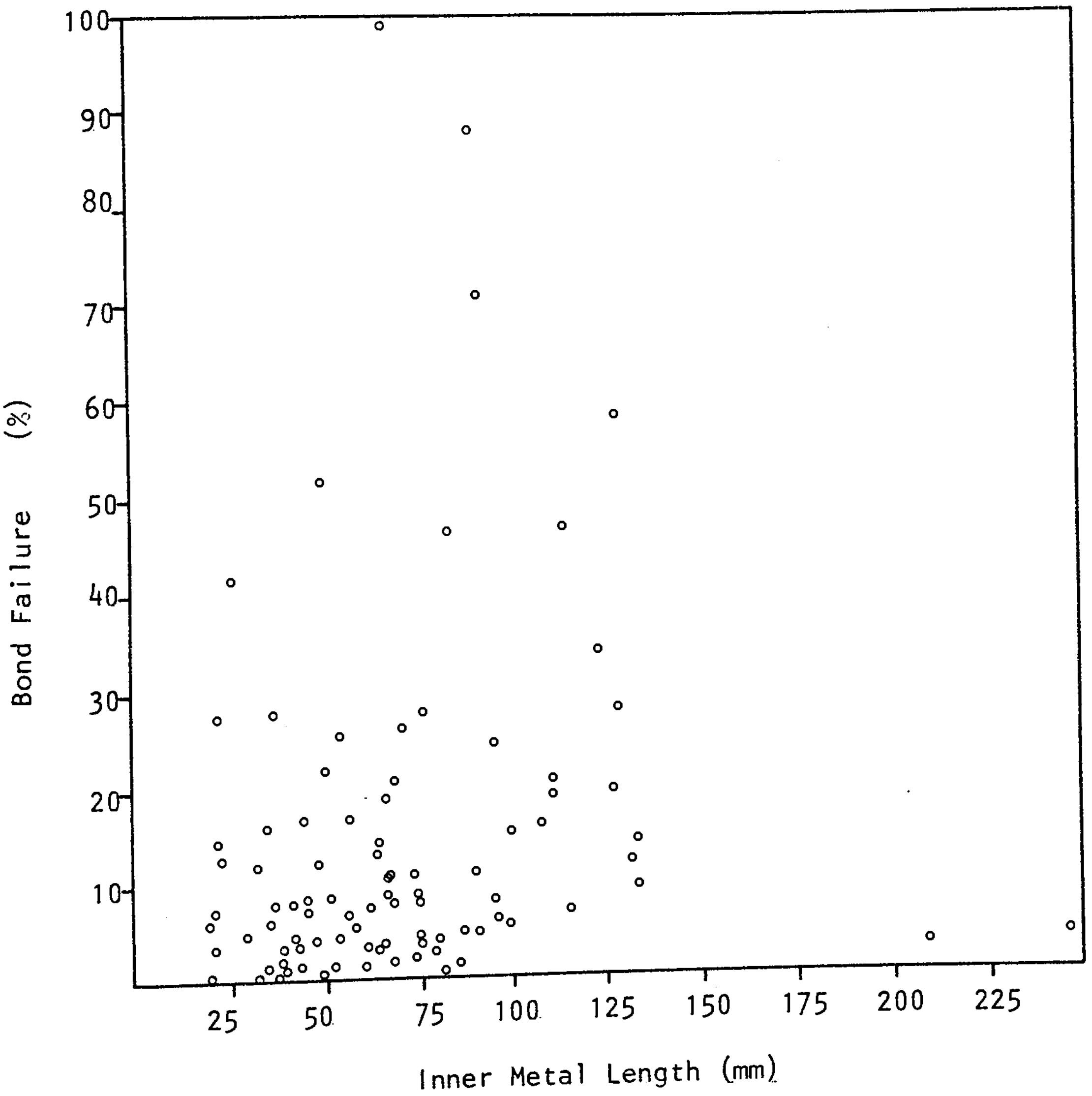


Figure 9.7

Rubber Hardness v s. % Bond Failure

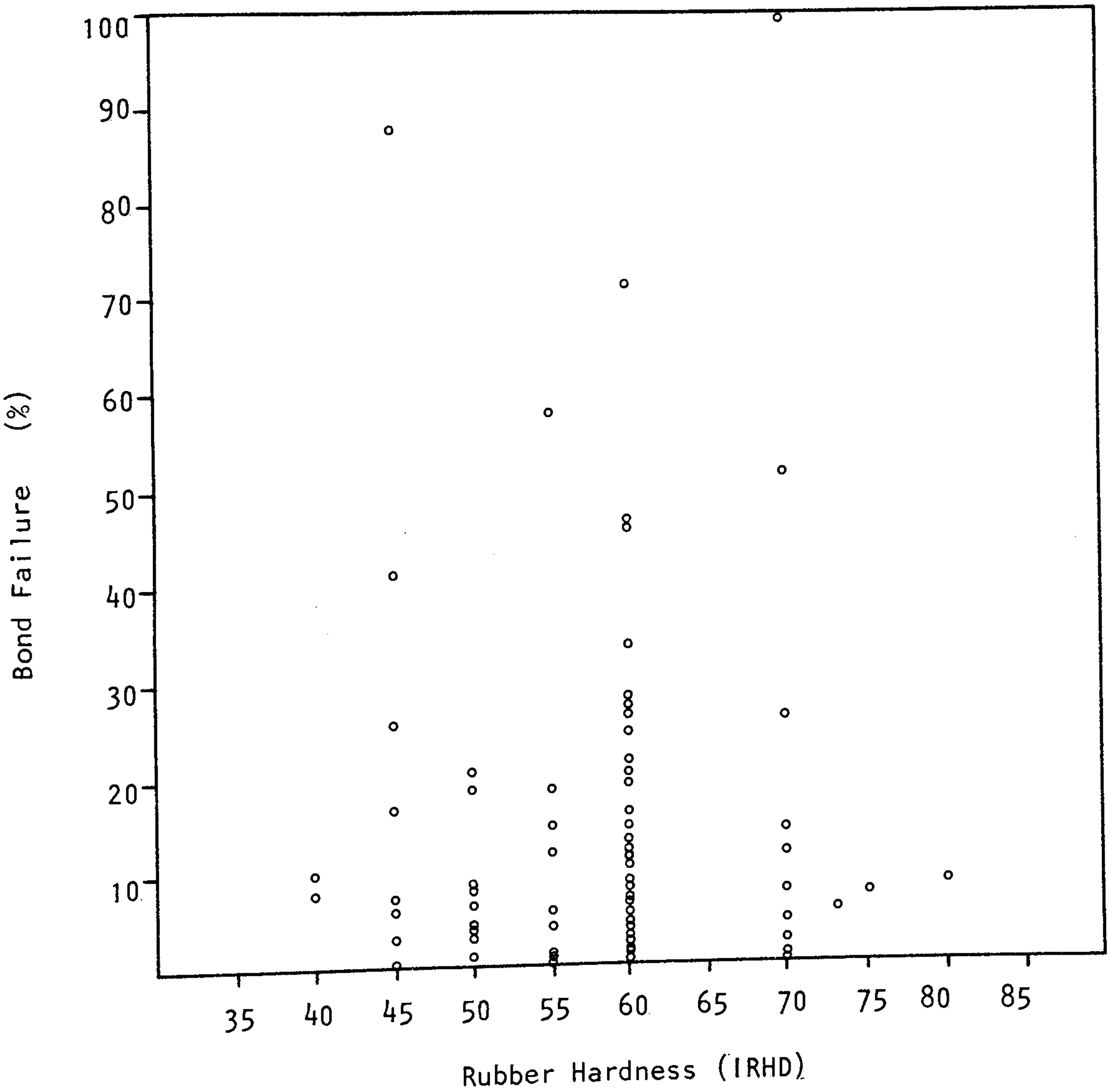


Figure 9.8

Bond Failure Rates for the Main Bush Moulding Areas

	Moulding Area (Shop)	No. of Products	Mean ($\bar{x}$) Batch Failure Level(%)	Variance from the Mean(s)	% Inner Metal Failures	Cure Time (mins)	Comments
CONVENTIONAL	Small Transfer Code 9001	19	17.6	595	68.6	15	Uncontrolled
	Small Transfer Code 9002	4	(9.5)	(19)	90.6	15	"
	Large Transfer Code 9004	25	18.9	316	61.4	20 15	"
	Large Transfer* Code 9024	11	20.6	650	90.8	45 30	"
	Multicavity Compression	4	(2.8)	(2)	55.1	20	Semi-Controlled
	Hydramould Code 9034	30	5.2	35	70.0	-	Controlled
	Misc.Remainder	15	8.3	55	92.4	-	-

(* Problem Products)

Figure 9.9

The Effect of Multicavity Moulds on Bond Failure Rates

Number of Mould Cavities	Mean ($\bar{x}$) Batch Bond Failure Level %	Variance from the Mean(s)
Single Cavity	19.9	566
2 - 9	14.3	142
10 - 50	5.2	24

Figure 10.1

An Evaluation of Selected Adhesive Systems

(Using Laboratory Moulded Bushes)

	Cure Conditions / Adhesive System	150°C				160°C		
		20'	15'	12'	9'	15'	12'	9'
BUSH A	252	-	2M	5M	4M	2M	5M	<1M
	205/252	-	100R	100R	trace RC	100R	100R	100R
	OSN-2	-	100R	100R	1 RC	100R	1 RC	trace RC
	P7/OSN-2	100R	5 CP	10 CP	-	trace M	5 CP	5 CP
	205/X2311	-	100R	100R	10RC	1M	5 RC	15 RC
	205/220 (control)	100R	10RC	20RC	-	2RC	1 RC	15 RC
BUSH B	252	-	1M	2M/5RC	4M/10RC	5M	5M	5M/10RC
	205/252	-	100R	5RC	20RC	trace RC	<2RC	20 RC
	OSN-2	-	100R	1RC	10RC	100R	-	-
	P7/OSN-2	100R	100R	5CP/RC	25CP/RC	-	-	-
	205/220 (Control)	1 RC	5 RC	30 RC	75RC	5 RC	25 RC	25 RC

NB: Values represent the percentage of failed bond area.
(Except 100R where no bond failure has occurred)

Bush (A) = 13/1914 (specified cure 15' @ 160)
" (B) = 13/1944 (specified cure 20' @ 160)

Figure 10.2

A Summary of Adhesive Performance Characteristics

Property / Bonding Agent System	Hot bond strength (Reactivity)	Environmental Resistance	Pre-bake Resistance	Versatility (Rubber compounds)	Other general bonding properties	Reliability and availability
Chemlok 252	A	C	B	A	A	A ?
Chemlok 205/252	A	B	B	A	A	A ?
Thixon OSN-2	A	D	B	B	B	C
Thixon P7/OSN-2	A	B	B	B	C	C
Chemlok 205/ Chemosil X2311	B	B	A	C	A	B

A = Good   B = Adequate   C = Marginal   D = Unacceptable

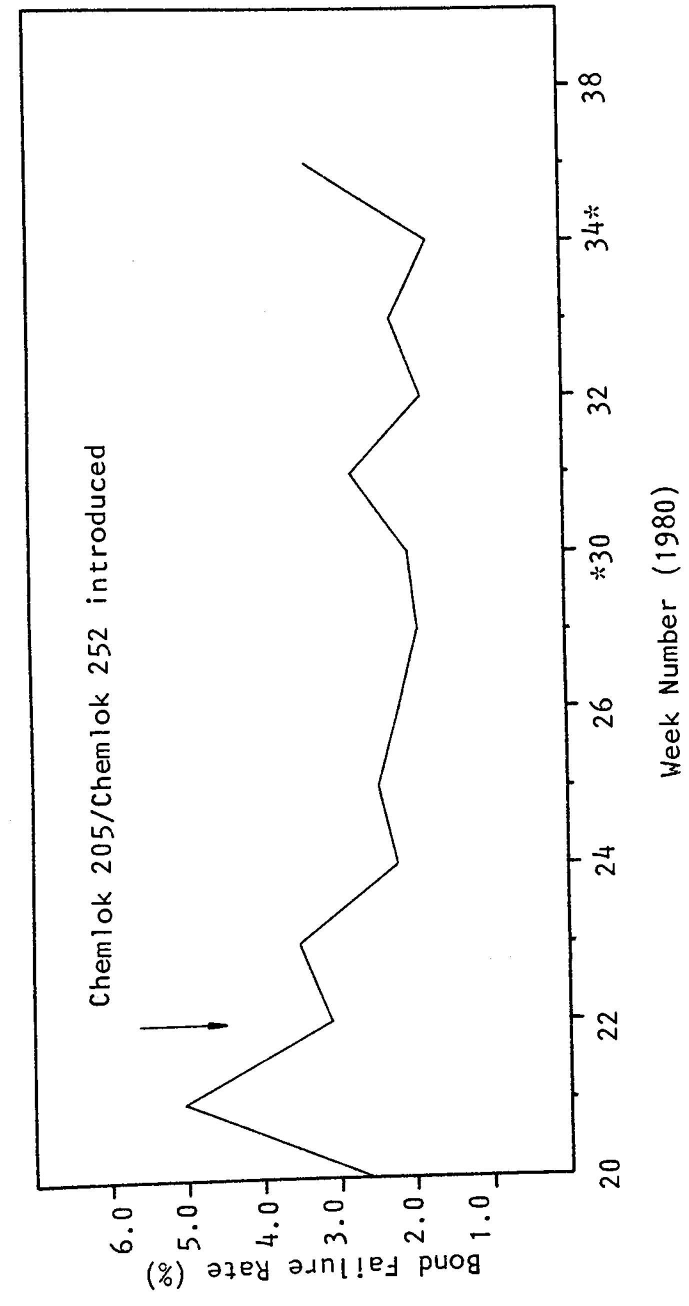
Figure 10.3

Results of the Large Scale Factory Trial Using Chemlok 205/Chemlok 252

	Week One		Week Two	
	205/252 prepared bushes	Corresponding 13 week data	205/252 prepared bushes	Corresponding 13 week data
Number of Products	43	43	49	49
Total Number of Parts "Tested"	82,131	516,340	92,148	499,200
Total Number of Parts Failed	2004	17,530	2040	19,029
Total Bond Failure Rate(%)	2.44	3.40	2.21	3.81
Mean Batch Bond Failure Rate (%)	3.99	8.43	2.99	10.75

Figure 10.4

Factory Bond Failure Rates



* Weeks 28,29,35 and 36 No production (Factory holiday)

Figure 11.1

Primary and Secondary Causes of Bond Failure Problems

Problem	Secondary Cause	Primary Cause
Bond-line contamination	Excessive mould lubricant	Wrong metal dimensions Mould damage Poor mould design
Inadequate heat input	Short cure time	Operator payment system Poor supervision Poor machine control
Inadequate heat input	Low cure temperature	Factory draughts Poor press maintenance Lengthy mould recharging period
Rubber lamination	Slow rubber transfer High adhesive reactivity	Low mould pressure Thick rubber blanks A need for shorter cure time
Adhesive/Metal separation	Oils retained in the metal surface Smooth metal surfaces	Metal fabrication process Insufficient etching of metal during chemical cleaning

Figure 11.2

Examples of Bond Failure Variation

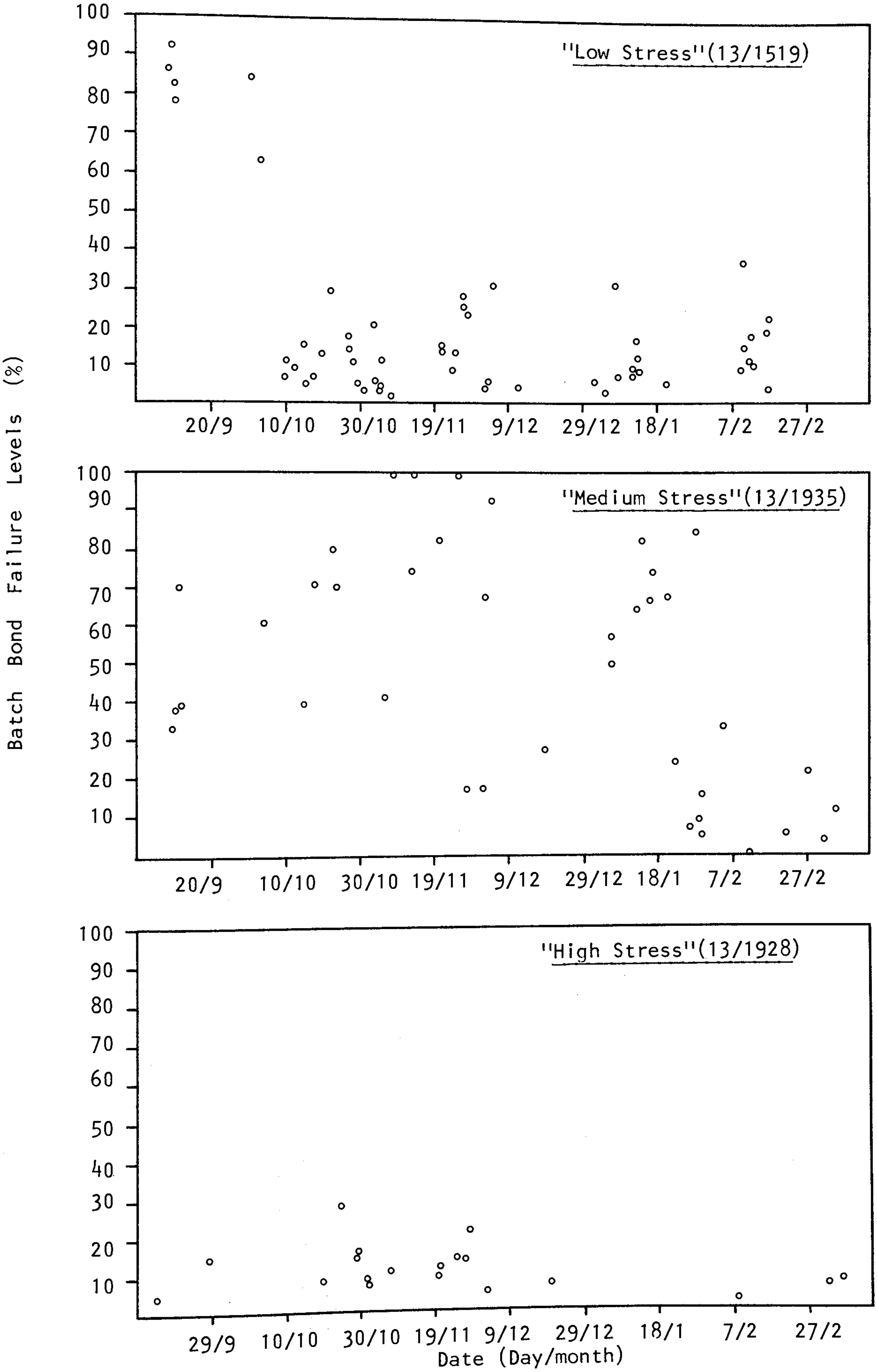


Figure 11.3

Shrinkage Stress/Hot Bond Strength - Batch Distribution

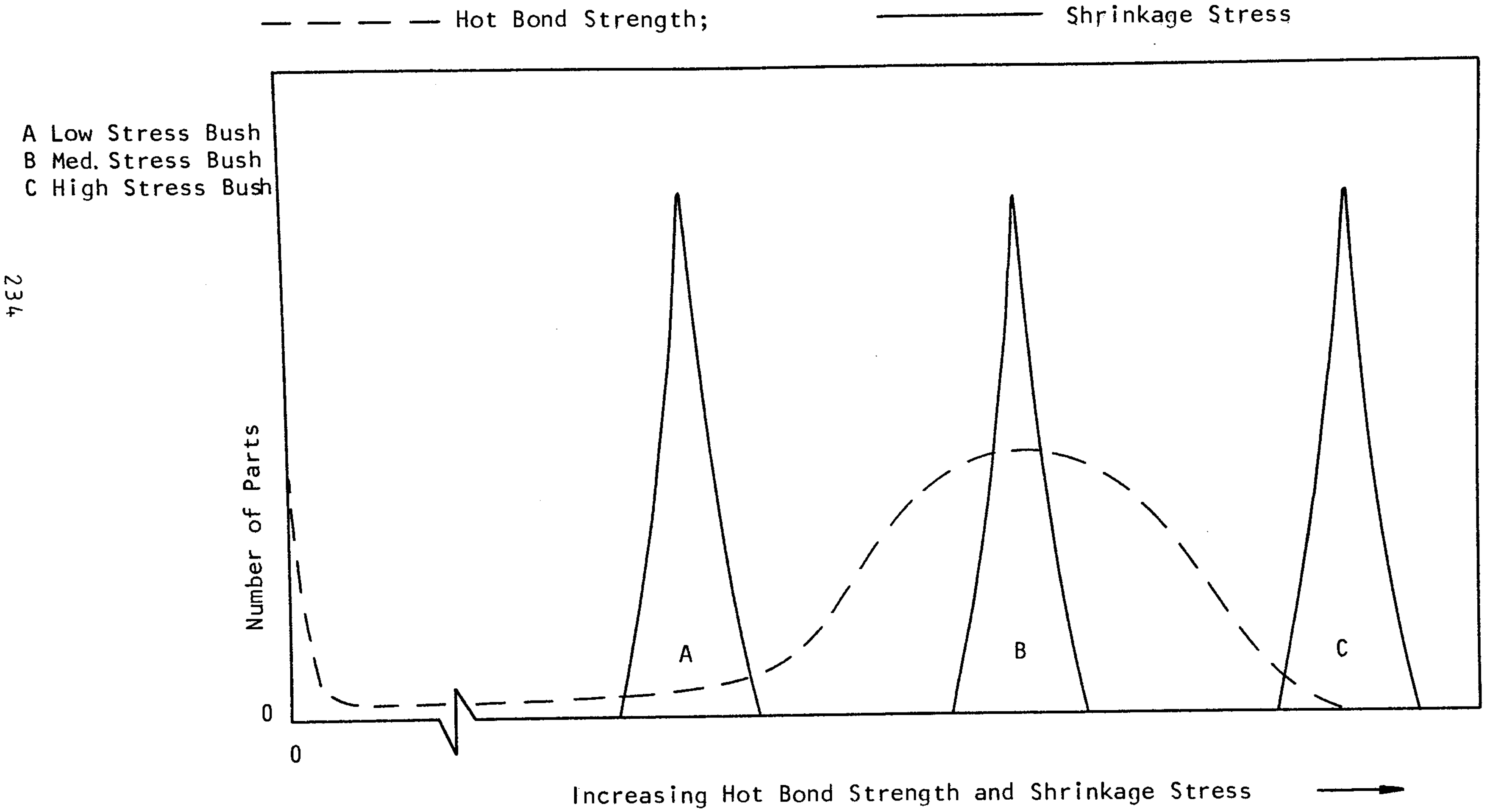
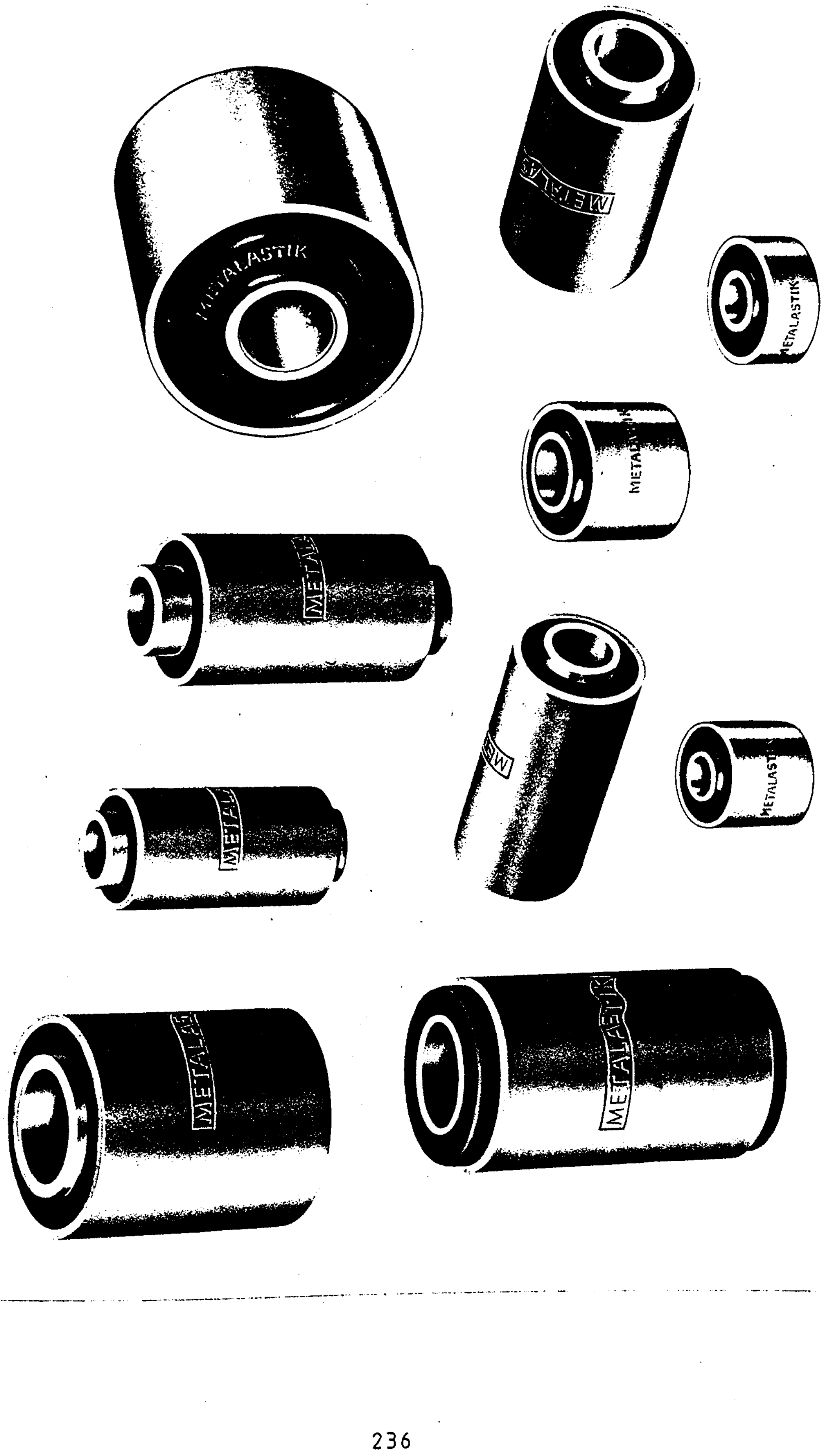


Figure 11.4

Links between Theoretical, Ideal and Actual Bond Failures

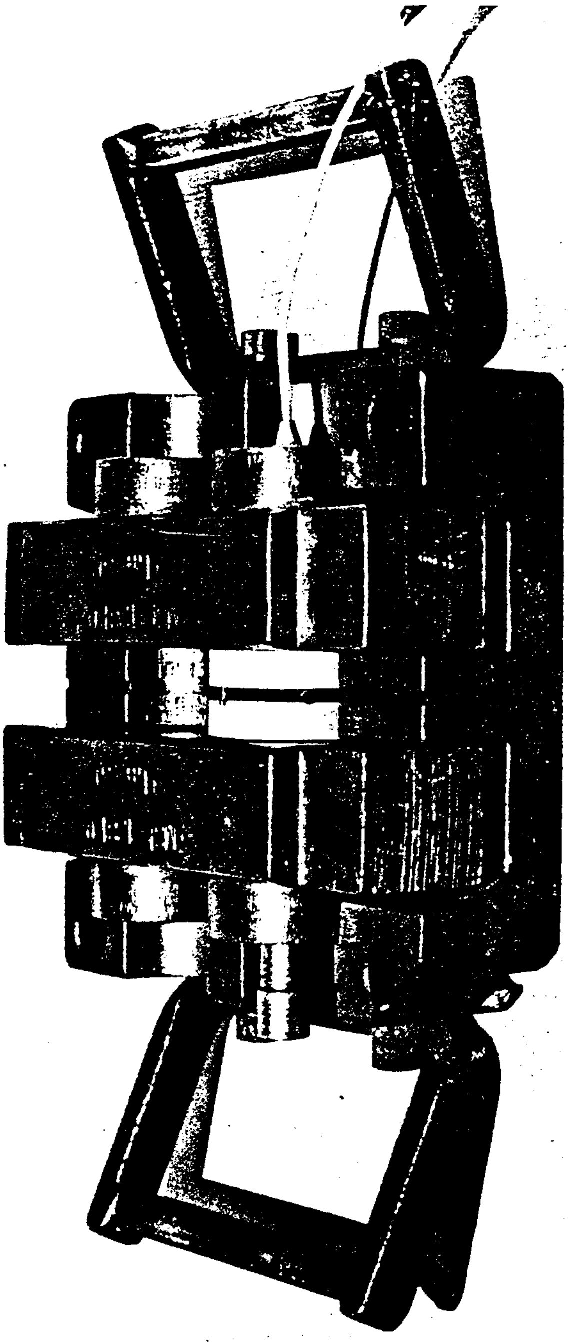
Bush Number	Predicted Outcome (see Appendix No. 6)	Failure in Laboratory Moulded Bushes (or in bushes moulded under supervision)	Approximate Production Failure Levels (%)
13/1914	Prob.Fail	Slight Failure	5
13/1944	Good Bond	No Failure	50
13/1920	Good Bond	" "	20
13/1895	Good Bond	" "	10
13/1935	Good Bond	Slight Failure	70
13/1916	Poss.Fail	Slight Failure	15

Plate 1



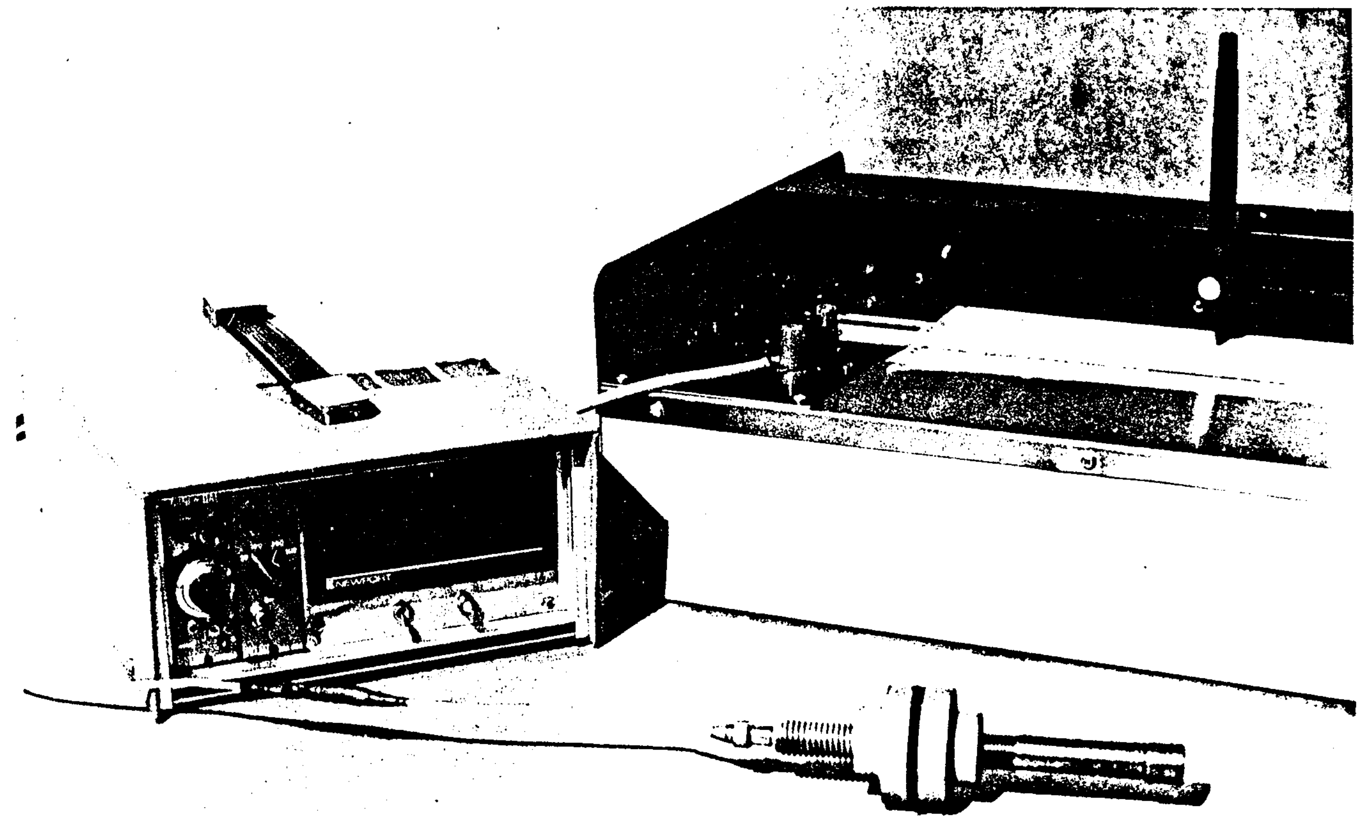
A Selection of Typical Concentric Bushes

Plate 2



Position of the Test-Piece in the Transfer Mould (mould Top omitted)

Plate 3



The Hot Bond Test Apparatus

Appendix No. 1

The U.K. Rubber to Metal Bonding Industry

The 12 Largest Companies (over 100 employees)

Long and Hambly Ltd.

Avon Industrial Polymers Ltd.

Dunlop (Polymer Engineering Division) Ltd.

Dunlop (Suspensions Division) Ltd.

Sutcliff Rubber Ltd.

*Andre Rubber Ltd.

British Vita Co.Ltd.

J.H.Fenner Ltd.

Firestone Tyre and Rubber Co.Ltd.

*Miles Redfern Ltd.

*Peradin Bonded Polymers Ltd.

Metzler Ltd.

(* part of the B.T.R. Group)

Appendix No. 2

The Scrap levels of Bushes for the period Week 29 to Week 51, 1979

The bushes listed below are those deemed "out of control" (i.e. exceeding the predetermined scrap level used for product costing purposes) by the Quality Control Department.

Although a number of reasons contribute towards the total scrap, for these products bond failures predominate.

The values given in the table refer to the 13 week average batch failure level (in percent).

Appendix No. 2

Bush No.	WEEK NUMBER (1979)																						
	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
13/1177/01	35.8	41.1	38.8	35.2	35.2		HOLIDAY PERIOD	16.4															
13/1284/01									71.3	74.0			77.5				73.4						90.7
13/1519/03	25.8	27.8	31.8	38.0	38.9	39.6		51.9	63.0		68.6	68.3	68.6	47.7	44.1	41.2	35.1		22.4	22.0	21.4	15.1	14.8
13/1684/00						19.8			22.6										33.7	31.1	35.1	34.4	37.3
13/1895/00	20.5	24.2	16.0	13.8	14.8					12.9			13.2				14.2	18.0	18.7	17.3	21.0	23.0	27.7
13/1920/02					27.0	29.0		36.3	35.1	22.9			12.3		14.0	16.6	15.1				18.5		
13/1928/00		60.4	65.0	62.7	50.0	46.5		41.5		10.0	18.9		16.1		11.2		13.2		14.1	15.3	15.5	18.9	18.4
13/1935/00	44.3	45.8	53.0						37.2		46.1			40.0	43.6	42.3	55.1	65.8	84.2	80.2	76.0	73.9	
13/2012/00	22.8	23.7		20.7	31.0	29.7		31.9				40.0	37.4	35.5		34.0	29.7	19.8	13.2				
13/2036/00						23.7			43.0						35.8		41.7			24.7	22.6		
13/2048/00									56.7	58.0		27.3	28.7		24.0	25.6	19.1		22.0	23.6	25.0	22.6	22.0
13/2050/00			16.8	18.4				33.1	47.9		64.0							62.9					
13/2053/00						42.1		19.7	22.8	24.1	24.1			30.3						18.4			

13 Week Cummulative Scrap Levels

Appendix No. 2

High Volume Bush Products which also exhibit high levels of Bond Failure

The following table refers to the period, Week 29 to Week 45, 1979 (the products listed accounted for 51% of factory bond failures).

Bush Product No.	No. of failed parts during period	Cummulative failures during period	Cummulative percentage of failures during period.
13/1519	11,598	11,598	16
13/2050	13,093	24,691	34.4
13/1895	3,150	27,841	38.7
13/1888	2,649	30,490	42.4
13/1960/01	2,502	32,992	45.9
13/1684	1,312	34,304	47.7
13/1935	1,264	35,568	49.5
13/1960/00	1,180	36,748	51.0 %

Appendix No. 2

Batch Bond Failure Levels for Bushes

Examples of the variation in percent bond failure levels between batches of parts.

(13/902)

Date Tested	Batch Size	% Bond failure
27/9/79	318	17.9
24/10/79	91	39.6
24/10/79	179	13.9
31/10/79	175	61.7
2/11/79	124	17.7
14/11/79	189	22.2
7/12/79	300	19.3
17/1/80	232	14.2
18/1/80	310	27.4
11/2/80	60	33.3

(13/1284)

Date Tested	Batch Size	% Bond failure
20/9/79	60	36.7
11/10/79	205	12.2
7/11/79	91	7.7
9/11/79	159	27.0
13/11/79	61	16.4
18/12/79	36	22.2
19/12/79	252	11.1
9/1/80	106	9.4
24/1/80	200	7.5
27/2/80	128	6.3

(13/1916)

Date Tested	Batch Size	% Bond failure
30/10/79	2177	10.2
30/11/79	879	19.2
5/12/79	710	17.6
11/1/80	880	12.3
25/1/80	621	6.4
19/2/80	810	21.2
19/2/80	425	21.9
20/2/80	950	13.7
20/2/80	850	18.6
21/2/80	865	3.7

(13/2036)

Date Tested	Batch Size	% Bond failure
18/9/79	74	100
25/10/79	16	31.2
13/11/79	54	18.5
15/11/79	81	16.1
19/11/79	214	9.8
20/11/79	62	25.8
27/11/79	183	9.3
30/11/79	94	20.2
20/2/80	132	7.6
22/2/80	54	9.3

Appendix No. 3.1

The Finite Element Method - Theoretical Considerations

The following details on the theoretical basis for the above technique are extracted from the S.D.R.C. Manual and relate to the SUPERB computer program.

Appendix No. 3.1

SUPERB USERS MANUAL

The SUPERB computer program is based on the finite element method (FEM) of structural analysis. This method embodies the concept of representing the distributed continuum of a physical structure by a model consisting of a finite number of idealized elements that are interconnected at a finite number of points. Known loads are applied to this model, a system of equations is solved, and desired results (e.g. unknown structural displacements, stresses, etc) are obtained. The behaviour of the model closely approximates the behaviour of the real structure.

Since its introduction in the early 1940's, the finite element method has emerged as the most powerful method of structural analysis having enjoyed very wide applicability and real-world verification of its accuracy and utility. As might be expected, much effort has been devoted toward improvement of the method and making it a convenient, user-oriented analytical design tool. The parallel development of high speed digital computers was indeed fortunate, since without such computational capabilities, the FEM would certainly be impractical for actual engineering problems and would have been doomed to academic curiosity.

The equations established and solved by SUPERB are based on the matrix displacement method of finite element analysis, which is ideally suited to the digital computer. The static problem may be expressed by the equation:

$$(F) = [K]\ (X)\ .$$

The stiffness matrix [K] must be generated from a description of the geometric and physical properties of the structure. Elements used in this description are rods, beams, membranes, plates, shells and solids. If the load vector (F) is known, the computer busies itself in determining the unknown displacement vector (X) ,from which stresses and other quantities of interest can be calculated. In the early days of computer-aided-design, the actual solution was the only thing for which the computer was used; the analyst was left with tedium of input data preparation and output data manipulation. It was soon discovered that, for most practical problems, the computer must be utilized to further unburden the user of these onerous tasks. If this were accomplished, dramatic reductions of time and cost would be possible, along with a vast extension in the range of practical analyses.

From the earliest days until the current time, however, simple element shapes with straight edges and a minimum number of degrees of freedom have been used almost exclusively. During this time, it has become apparent that, for a given total number of degrees of freedom in a structure, accuracy is increased with larger elements which contain a greater number of degrees of freedom per element. Furthermore, the convergence rates can be shown to increase with element complexity.

(Finite element people must always worry about convergence, since a fundamental premise in the FEM is that the mosaic of element displacement fields should converge to the exact solution based on linear theory of elasticity).

In view of these facts, the engineer may well have the opportunity to drastically reduce the number of elements required, thus reducing cost of both data preparation and equation solution.

The use of larger, more complex elements immediately introduces difficulties in representing the true geometrical configuration of a structure. This difficulty is overcome by allowing the large elements to have curved sides. Such a step forward has been achieved by the introduction of isoparametric element families.

Indeed, the SDRC SUPERB computer program takes full advantage of these advanced isoparametric elements. These elements are formulated by highly complex relationships (shape functions) and as a result can assume highly complex geometries and represent high order displacement variations. The number of elements required to describe the geometry of a particular structure is thus drastically reduced when compared to the number of simple of "conventional" elements. The cost of computer solution is also correspondingly reduced due to the abbreviation of structural definition. Numerical accuracy is also enhanced. SUPERB contains the fundamental elements of axisymmetric, plane stress, plane strain, flat plate, curved shell, and solid representations. Linear, parabolic, and cubic displacement functions are available, along with suitable combinations of same.

Wavefront Solution Method

SUPERB formulates structural problems using the stiffness method (or displacement method). With this method the stiffness characteristics of each element are first derived. The behaviour of the entire structure is then determined by considering the assemblege of elements subjected to a particular loading condition. To solve this resulting system of simultaneous linear equations, SUPERB uses the efficient wavefront solution method. The so-called "wave-front" is equal to the number of equations active at any point in the solution procedure. Each equation is associated with a particular degree of freedom in the structure (up to six degrees of freedom can be defined for each node). The wavefron at any point in the solution is then directly proportional to the number of active nodes at that point. An active equation is one which has been identified and previously used in the solution and is required again at a further point.

Equations (or nodes) are activated by the element to which they are connected as the solution progresses from element to element. The order in which the elements (and associated nodes) are processed in the solution is determined by the order in which the elements are defined in the data deck. As the solution wavefront progresses across a structure processing new elements, new nodes associated with these elements are activated. These nodes remain activated until every element which is connected to them is processed.

Finite Element Method

The exact governing equations for structural analysis are the three-dimensional equations of elasticity. For many problems these equations are intractable, however, due to the geometric complexity of the structure. To solve this class of problem, simplified, approximate representations of the structural characteristics must be derived. The most widely accepted method of approximating structural behaviour is the finite element method in which a structure is represented as an assemblage of discrete units called finite elements. The behaviour of the complex structure is approximated by summing the known effects of each finite element.

Finite elements are considered to be inter-connected at nodes to form the representation of a structure.
Simple algebraic functions called displacement functions are typically selected to approximate the actual displacement variation across each finite element. By applying a variational principle of mechanics such as the principle of minimum potential energy, the relationship between the forces and displacements at the nodes of the element may be obtained. The constants of proportionality may be represented as a stiffness matrix (k). By then combining the effects of all finite representing the structure, the relationship between force and displacement for every node may be obtained. The summation of elemental stiffnesses is known as the system stiffness matrix (K). The approximate unknown displacements, (X), caused by the external load (F) may be determined by standard matrix techniques.

The essence of the finite element method of structural representation is thus seen to be the approximate displacement variation assumed in each discrete element. Having assumed element displacement functions and determined the resulting elemental stiffness, the solution of the system displacements follows routinely.

Appendix No. 3.2

Input Values for the F.E.M. Stress Analysis

Analysis Property	Bush No. 13/1914	Bush No. 13/665	Modified Test Piece
Rubber Properties			
Hardness (I.R.H.D.)	60	75	60
Young's Modulus (MN/m^2)	4.365	7.210	4.365
Shear Modulus (MN/m^2)	1.039	1.700	1.039
Poisson's Ratio	0.499	0.499	0.499
Thermal Conductivity (W/mm/°C)	1.67×10^{-4}	1.59×10^{-4}	1.67×10^{-4}
Dimensions			
Rubber Length (mm)	38.06	63.50	13.93
Inner Metal (O.D.) (mm)	12.19	9.46	*3.303
Outer Metal (bore) (mm)	15.72	17.44	
Shape Factor	6.25	3.97	2.11
Temperature (Initial) (°C)	150	150	150
" (Ambient) (°C)	20	20	20

* Rubber Thickness

Appendix No. 3.2

```
[illegible]
ACCESS THROUGH HITCHIN WILL BE UNAVAILABLE 1100-1500GMT 16 MAR 78

[illegible]
[illegible]
[illegible]
[illegible]
[illegible] SYSTEM 'G' WILL BE UNAVAILABLE FROM 0900 UNTIL 1400 GMT 3/16/78

*** [illegible] VERSION III IS NOW AVAILABLE IN THE SDRC B072000 CATALOG   ***
*** TO OBTAIN A LIST OF SDRC'S 1978 SEMINARS, LIST THE FILE SEMINARS ***

[illegible]      .43 UNITS
[illegible] CARDS
[illegible]      CRU'S

[illegible]      .0382
[illegible]      .0004
[illegible]      .0269
[illegible]      .3318
               --------
TOTAL          0.3973

START
/JOB CARD

VERSN:  March 78

.

CARD [illegible]

[illegible] RETURNED
[illegible] SUBMITTED
 [illegible] FILES
 =NONE

[illegible]                  [illegible] 1
[illegible]                  [illegible] 2
[illegible]                  [illegible] 3
[illegible]                  [illegible] 4
[illegible]                  [illegible] 5
[illegible]                  [illegible] 6
[illegible]                  [illegible] 7
[illegible]
[illegible] > [illegible]
[illegible] > [illegible]
                                       DUNLOP PFD UD BUSH SHRINKAGE STRESSES
[illegible] > [illegible]
                                       DUNLOP PFD UD BUSH SHRINKAGE STRESSES


******************************************************************************
GEOMETRY PLOT NUMBER    1
XMIN,XMAX =     0.0      0.0        YMIN,YMAX =     0.0      0.0        ZMIN,ZMAX =     0.0      0.0
LABEL OPTION =  0   KSTART =      1   KSTOP =     20   SCAX =  0.35   SCAY =  3.40   ELEM.TYPE =    0
****************************************************************************
```

= £87.00

16/3/78

U.D. Bush. 13/1914

Run No 2 Results

Nodes 2-8 Constraint in Y direction

Bush No. 13/1914

Results (Displacements, Stresses and Von Mises)

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                               5729 DRAGON WAY       CINCINNATI,OHIO 45227       (513) 272-1100

                          DUNLOP PED HD BUSH SHRINKAGE STRESSES

  INITIAL SOLUTION
  ITERATION NUMBER                          1
  MAXIMUM WAVEFRONT                        31
  RMS WAVEFRONT                            22
  TOTAL DEGREES OF FREEDOM                111
  SOLUTION CONDITION NUMBER       2.4639D+03

  ****** DISPLACEMENT SOLUTION ******

   NODE       UX                UY                 UZ                ROTX              ROTY              ROTZ
     1     0.0              0.0                0.0                0.0               0.0               0.0
     2     0.716657D-02     0.0                0.0                0.0               0.0               0.0
     3     0.[illegible]D-01     0.0                0.0                0.0               0.0               0.0
```

```
 4    0.116652D-02   0.0             0.0         0.0         0.0         0.0
 5   -0.147496D-01   0.0             0.0         0.0         0.0         0.0
 6   -0.111733D-01   0.0             0.0         0.0         0.0         0.0
 7   -0.117608D-01   0.0             0.0         0.0         0.0         0.0
 8   -0.263998D-03   0.0             0.0         0.0         0.0         0.0
 9    0.0            0.0             0.0         0.0         0.0         0.0
10    0.0            0.0             0.0         0.0         0.0         0.0
11   -0.341357D-01  -0.205129D+00    0.0         0.0         0.0         0.0
12    0.110523D-01  -0.267192D+00    0.0         0.0         0.0         0.0
13    0.311912D-01  -0.197696D+00    0.0         0.0         0.0         0.0
14    0.0            0.0             0.0         0.0         0.0         0.0
15    0.0            0.0             0.0         0.0         0.0         0.0
16    0.647083D-02  -0.245201D+00    0.0         0.0         0.0         0.0
17    0.295319D-01  -0.416175D+00    0.0         0.0         0.0         0.0
18    0.408929D-02  -0.514628D+00    0.0         0.0         0.0         0.0
19   -0.136412D-01  -0.545674D+00    0.0         0.0         0.0         0.0
20   -0.909876D-02  -0.502695D+00    0.0         0.0         0.0         0.0
21   -0.985405D-02  -0.397273D+00    0.0         0.0         0.0         0.0
22    0.690518D-03  -0.229285D+00    0.0         0.0         0.0         0.0
23    0.0            0.0             0.0         0.0         0.0         0.0
24    0.0            0.0             0.0         0.0         0.0         0.0
25   -0.357490D-01  -0.586910D+00    0.0         0.0         0.0         0.0
26    0.105642D-01  -0.760724D+00    0.0         0.0         0.0         0.0
27    0.324941D-01  -0.554635D+00    0.0         0.0         0.0         0.0
28    0.0            0.0             0.0         0.0         0.0         0.0
29    0.0            0.0             0.0         0.0         0.0         0.0
30    0.479412D-02  -0.443692D+00    0.0         0.0         0.0         0.0
31    0.234668D-01  -0.753476D+00    0.0         0.0         0.0         0.0
32    0.199774D-02  -0.933044D+00    0.0         0.0         0.0         0.0
33   -0.162033D-01  -0.981113D+00    0.0         0.0         0.0         0.0
34   -0.111352D-01  -0.917667D+00    0.0         0.0         0.0         0.0
35   -0.103049D-01  -0.728192D+00    0.0         0.0         0.0         0.0
36    0.169395D-02  -0.419359D+00    0.0         0.0         0.0         0.0
37    0.0            0.0             0.0         0.0         0.0         0.0
38    0.0            0.0             0.0         0.0         0.0         0.0
39   -0.343998D-01  -0.879654D+00    0.0         0.0         0.0         0.0
40    0.172020D-01  -0.114844D+01    0.0         0.0         0.0         0.0
41    0.368274D-01  -0.844518D+00    0.0         0.0         0.0         0.0
42    0.0            0.0             0.0         0.0         0.0         0.0
43    0.0            0.0             0.0         0.0         0.0         0.0

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                        DUNLOP PFD UD BUSH SHRINKAGE STRESSES

NODE      UX              UY             UZ          ROTX        ROTY        ROTZ
44    0.294002D-02  -0.602799D+00    0.0         0.0         0.0         0.0
45    0.227951D-01  -0.101394D+01    0.0         0.0         0.0         0.0
46    0.474204D-02  -0.125418D+01    0.0         0.0         0.0         0.0
47   -0.507206D-02  -0.134262D+01    0.0         0.0         0.0         0.0
```

```
 [illegible]
 58    0.686275D-02  -0.601186D+00  0.0          0.0          0.0          0.0
 59    0.439284D-01  -0.121557D+01  0.0          0.0          0.0          0.0
 60    0.490066D-01  -0.157988D+01  0.0          0.0          0.0          0.0
 61    0.628631D-01  -0.162817D+01  0.0          0.0          0.0          0.0
 62    0.814369D-01  -0.146823D+01  0.0          0.0          0.0          0.0
 63    0.481015D-01  -0.955430D+00  0.0          0.0          0.0          0.0
 64    0.175086D-01  -0.436039D+00  0.0          0.0          0.0          0.0
 65    0.0            0.0           0.0          0.0          0.0          0.0
 66    0.0            0.0           0.0          0.0          0.0          0.0
 67   -0.262129D-01  -0.443243D+00  0.0          0.0          0.0          0.0
 68    0.113593D+00  -0.644978D+00  0.0          0.0          0.0          0.0
 69    0.0            0.0           0.0          0.0          0.0          0.0
 70    0.0            0.0           0.0          0.0          0.0          0.0
 71    0.961435D-02  -0.130759D+00  0.0          0.0          0.0          0.0
 72    0.563798D-02  -0.256252D+00  0.0          0.0          0.0          0.0
 73    0.151726D+00  -0.447127D+00  0.0          0.0          0.0          0.0
 74    0.299778D-01  -0.236132D+00  0.0          0.0          0.0          0.0
 75    0.0            0.0           0.0          0.0          0.0          0.0
 76    0.0            0.0           0.0          0.0          0.0          0.0
 77   -0.354789D-01   0.121054D+00  0.0          0.0          0.0          0.0
 78    0.107416D+00  -0.794211D-01  0.0          0.0          0.0          0.0
 79    0.0            0.0           0.0          0.0          0.0          0.0
 80    0.0            0.0           0.0          0.0          0.0          0.0
 81    0.222816D-01  -0.122860D+00  0.0          0.0          0.0          0.0
 82    0.576316D-01  -0.249548D+00  0.0          0.0          0.0          0.0
 83   -0.946986D-01  -0.159571D+00  0.0          0.0          0.0          0.0
 84   -0.254273D-01  -0.787039D-01  0.0          0.0          0.0          0.0
 85    0.0            0.0           0.0          0.0          0.0          0.0
```

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                            DUNLOP PED UD BUSH SHRINKAGE STRESSES

 AVERAGED STRESSES AT NODES OF 2-D,THICK SHELL AND SOLID ELEMENTS

 NODE *LOC* STRESS-X   STRESS-XY  STRESS-Y   STRESS-XZ  STRESS-YZ  STRESS-Z    *******PRINCIPAL STRESSES*******    VON
 STRS.
   1 [illegible]   13.70      0.06      13.81       0.0        0.0       13.82       13.82      13.70      13.81
```

[illegible] 6 G-STS	13.81	0.02	13.58	0.0	0.0	13.77	13.81	13.58	13.77
0.21 7 G-STS	13.84	0.03	13.66	0.0	0.0	13.83	13.85	13.66	13.83
0.18 8 G-STS	13.75	0.02	13.72	0.0	0.0	13.81	13.81	13.71	13.76
0.08 9 G-STS	13.66	-0.00	13.78	0.0	0.0	13.79	13.79	13.66	13.78
0.12 10 G-STS	12.79	-0.46	12.91	0.0	0.0	12.92	13.32	12.38	12.92
0.81 11 G-STS	12.85	-0.22	12.65	0.0	0.0	12.81	12.99	12.51	12.81
0.42 12 G-STS	12.80	0.01	12.60	0.0	0.0	12.81	12.89	12.50	12.81
0.27 13 G-STS	12.82	0.23	12.65	0.0	0.0	12.81	12.98	12.49	12.81
0.43 14 G-STS	12.80	0.43	12.93	0.0	0.0	12.94	13.30	12.43	12.94
0.76 15 G-STS	11.75	-0.93	11.87	0.0	0.0	11.88	12.74	10.87	11.88
1.62 16 G-STS	11.79	-0.69	11.74	0.0	0.0	11.83	12.46	11.08	11.83
1.20 17 G-STS	11.84	-0.45	11.63	0.0	0.0	11.80	12.20	11.28	11.80
0.60 18 G-STS	11.86	-0.22	11.60	0.0	0.0	11.80	11.99	11.48	11.80
0.44 19 G-STS	11.87	0.03	11.56	0.0	0.0	11.79	11.88	11.56	11.79
0.29 20 G-STS	11.85	0.25	11.60	0.0	0.0	11.80	12.00	11.45	11.80
0.49 21 G-STS	11.82	0.46	11.65	0.0	0.0	11.81	12.20	11.27	11.81
0.81 22 G-STS	11.77	0.66	11.75	0.0	0.0	11.83	12.42	11.10	11.83
1.14 23 G-STS	11.71	0.86	11.84	0.0	0.0	11.85	12.64	10.92	11.85
1.49 24 G-STS	9.65	-1.31	9.78	0.0	0.0	9.79	11.02	8.40	9.79
1.27 25 G-STS	9.77	-0.02	9.55	0.0	0.0	9.73	10.29	9.03	9.73
1.10 26 G-STS	9.75	0.03	9.43	0.0	0.0	9.67	9.75	9.43	9.67
0.28 27 G-STS	9.80	0.05	9.59	0.0	0.0	9.78	10.35	9.04	9.78
1.14 28 G-STS	9.65	1.21	9.78	0.0	0.0	9.70	10.92	8.50	9.79
2.10 29 G-STS	7.89	-1.69	8.02	0.0	0.0	8.03	9.64	6.26	8.03
2.93 30 G-STS	7.65	-1.25	7.60	0.0	0.0	7.70	5.88	6.38	7.70
2.17 31 G-STS	7.61	-0.82	7.38	0.0	0.0	7.56	8.32	6.66	7.56
1.43 32 G-STS	7.77	-0.37	7.49	0.0	0.0	7.71	8.03	7.23	7.71
0.76 33 G-STS	7.62	0.04	7.31	0.0	0.0	7.55	7.63	7.31	7.55
0.29 34 G-STS	7.72	0.42	7.46	0.0	0.0	7.67	8.03	7.15	7.67

Appendix No. 3.2

```
39 G-STS        5.68      -0.92       5.43       0.0        0.0         5.63          6.48       4.62        5.63
1.61
40 G-STS        5.78       0.06       5.40       0.0        0.0         5.68          5.79       5.39        5.68
0.30
41 G-STS        5.50       0.95       5.33       0.0        0.0         5.51          6.37       4.46        5.51
1.65
42 G-STS        5.31       1.83       5.45       0.0        0.0         5.46          7.21       3.55        5.46
3.18
43 G-STS        3.64      -2.31       3.90       0.0        0.0         3.85          6.08       1.46        3.85
4.46
44 G-STS        3.37      -1.73       3.41       0.0        0.0         3.47          5.12       1.67        3.47
2.59
45 G-STS        3.42      -1.15       3.15       0.0        0.0         3.36          4.45       2.13        3.36
2.61
46 G-STS        3.63      -0.57       3.37       0.0        0.0         3.68          4.21       2.98        3.68
1.07
47 G-STS        3.63       0.13       3.05       0.0        0.0         3.44          3.66       3.02        3.44
0.50
48 G-STS        3.61       0.72       3.19       0.0        0.0         3.50          4.15       2.65        3.50
1.50
49 G-STS        3.63       1.20       3.51       0.0        0.0         3.67          4.77       2.37        3.67
 2.08

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    5
                              5729 DRAGON WAY      CINCINNATI,OHIO 45227      (513) 272-1100

                          DUNLOP PSD OD BUSH SHRINKAGE STRESSES

NODE *STS* STRESS-X   STRESS-XY  STRESS-Y   STRESS-XZ  STRESS-YZ  STRESS-Z    *******PRINCIPAL STRESSES*******
SIGES
 50 G-STS       3.07       1.65       3.21       0.0        0.0         3.23          4.79       1.44        3.23
2.67
 51 G-STS       2.74       2.09       3.03       0.0        0.0         2.97          4.98       0.79        2.97
```

Appendix No. 3.2

										2.09
57 G-STS	4.21	-2.00	4.54	0.0	0.0	4.46	6.38	2.37	4.46	3.47
58 G-STS	2.06	-2.03	2.45	0.0	0.0	2.64	4.58	0.52	2.64	3.51
59 G-STS	1.06	-1.83	0.30	0.0	0.0	0.77	2.55	-1.19	0.77	3.24
60 G-STS	0.56	-0.52	-0.34	0.0	0.0	0.21	0.80	-0.58	0.21	1.20
61 G-STS	0.70	0.10	-0.37	0.0	0.0	0.29	0.71	-0.38	0.29	0.95
62 G-STS	1.06	0.93	0.62	0.0	0.0	0.97	1.79	-0.11	0.97	1.65
63 G-STS	2.62	2.00	3.05	0.0	0.0	2.95	4.85	0.82	2.95	3.49
64 G-STS	1.96	1.05	2.33	0.0	0.0	2.25	3.80	0.49	2.25	2.67
65 G-STS	0.42	1.29	0.64	0.0	0.0	0.62	1.82	-0.76	0.62	2.24
66 G-STS	-1.23	-2.02	-1.04	0.0	0.0	-1.04	0.89	-3.16	-1.04	3.50
67 G-STS	5.47	-2.00	5.52	0.0	0.0	5.57	7.55	3.44	5.57	3.50
68 G-STS	4.05	1.67	5.65	0.0	0.0	4.96	6.70	3.30	4.96	3.21
69 G-STS	-1.75	1.27	-1.88	0.0	0.0	-1.72	-0.54	-3.09	-1.72	2.21
70 G-STS	-4.03	-1.07	-3.87	0.0	0.0	-3.85	-2.88	-5.02	-3.85	1.85
71 G-STS	0.30	-0.97	1.11	0.0	0.0	0.80	1.76	-0.34	0.80	1.82
72 G-STS	4.63	-0.87	6.10	0.0	0.0	5.44	6.50	4.23	5.44	1.97
73 G-STS	-0.10	0.75	2.91	0.0	0.0	1.54	3.09	-0.27	1.54	2.91
74 G-STS	0.47	0.94	1.95	0.0	0.0	1.32	2.40	0.02	1.32	2.07
75 G-STS	1.03	1.12	0.99	0.0	0.0	1.10	2.14	-0.11	1.10	1.95
76 G-STS	0.41	-0.04	0.60	0.0	0.0	0.59	0.60	0.40	0.59	0.20
77 G-STS	-0.40	-0.00	-0.20	0.0	0.0	-0.21	-0.20	-0.40	-0.21	0.19
78 G-STS	-0.30	0.13	0.51	0.0	0.0	0.18	0.53	-0.41	0.18	0.82
79 G-STS	0.64	0.50	0.84	0.0	0.0	0.83	1.25	0.23	0.83	0.88
80 G-STS	-0.81	0.05	-0.61	0.0	0.0	-0.62	-0.60	-0.82	-0.62	0.21
81 G-STS	-0.00	0.04	-0.57	0.0	0.0	-0.19	-0.00	-0.57	-0.19	0.50
82 G-STS	0.80	0.02	-0.53	0.0	0.0	0.24	0.80	-0.53	0.24	1.16
83 G-STS	0.79	-0.31	-0.53	0.0	0.0	0.22	0.86	-0.60	0.22	1.27
84 G-STS	-0.03	-0.13	-0.58	0.0	0.0	-0.21	0.00	-0.61	-0.21	0.54
85 G-STS	-0.85	0.05	-0.63	0.0	0.0	-0.64	-0.62	-0.86	-0.64	0.23

Appendix No. 3.2

```
Cmd:EDIT 4
Cmd > [illegible] 118
Cmd > L/DD.LOPZ
                                        DUNLOP PED UD BUSH SHRINKAGE STRESSES 4
Cmd > [-*
                                        DUNLOP PED UD BUSH SHRINKAGE STRESSES 4


**********************************************************************
GEOMETRY PLOT NUMBER    1
XMIN,XMAX =     0.0      0.0        YMIN,YMAX =     0.0      0.0        ZMIN,ZMAX =     0.0      0.0
LABEL OPTION =   0   KSTART =      1   KSTOP =      16   SCAX =  0.28   SCAY =  1.50   ELEM.TYPE =    0
**********************************************************************
```

Bush No 13/665

Results (Displacements, Stresses and Von Mises)

9th May 1978

UDBUSH

Run No 4 13/665 bush

Results.

Appendix No. 3.2

```
VERSION IV                      SDRC SUPERB--STRUCTURAL DYNAMICS RESEARCH CORPORATION          05/08/78  PAGE
   2
                           5729 DRAGON WAY       CINCINNATI,OHIO 45227       (513) 272-1100

                         DUNLOP PED UD BUSH SHRINKAGE STRESSES 4


INITIAL SOLUTION
ITERATION NUMBER                   1
MAXIMUM WAVEFRONT                 27
RMS WAVEFRONT                     21
TOTAL DEGREES OF FREEDOM          87
SOLUTION CONDITION NUMBER  2.1880D+02


****** DISPLACEMENT SOLUTION ******

NODE        UX               UY              UZ              ROTX            ROTY            ROTZ
  1     0.0              0.0             0.0             0.0             0.0             0.0
  2     0.251959D-01     0.0             0.0             0.0             0.0             0.0
  3     0.627085D-01     0.0             0.0             0.0             0.0             0.0
  4     0.461067D-01     0.0             0.0             0.0             0.0             0.0
  5     0.141724D-01     0.0             0.0             0.0             0.0             0.0
  6    -0.234759D-01     0.0             0.0             0.0             0.0             0.0
  7    -0.713858D-01     0.0             0.0             0.0             0.0             0.0
  8    -0.223266D-01     0.0             0.0             0.0             0.0             0.0
  9     0.0              0.0             0.0             0.0             0.0             0.0
```

```
  10    0.0              0.0              0.0          0.0          0.0          0.0
 112   -0084101787H601  -00399000DH800    0000         0000         0000         10000
  13    0.105232D+00    -0.356223D+00     0.0          0.0          0.0          0.0
  14    0.0              0.0              0.0          0.0          0.0          0.0
  15    0.0              0.0              0.0          0.0          0.0          0.0
  16    0.235900D-01    -0.475648D+00     0.0          0.0          0.0          0.0
  17    0.791573D-01    -0.786084D+00     0.0          0.0          0.0          0.0
  18    0.423540D-01    -0.961529D+00     0.0          0.0          0.0          0.0
  19   -0.145860D-01    -0.100423D+01     0.0          0.0          0.0          0.0
  20   -0.191450D-01    -0.914770D+00     0.0          0.0          0.0          0.0
  21   -0.276424D-01    -0.710445D+00     0.0          0.0          0.0          0.0
  22   -0.207474D-01    -0.407821D+00     0.0          0.0          0.0          0.0
  23    0.0              0.0              0.0          0.0          0.0          0.0
  24    0.0              0.0              0.0          0.0          0.0          0.0
  25   -0.845423D-01    -0.109497D+01     0.0          0.0          0.0          0.0
  26    0.171783D-01    -0.139285D+01     0.0          0.0          0.0          0.0
  27    0.106690D+00    -0.965894D+00     0.0          0.0          0.0          0.0
  28    0.0              0.0              0.0          0.0          0.0          0.0
  29    0.0              0.0              0.0          0.0          0.0          0.0
  30    0.232212D-01    -0.855429D+00     0.0          0.0          0.0          0.0
  31    0.637795D-01    -0.142736D+01     0.0          0.0          0.0          0.0
  32    0.489407D-01    -0.171475D+01     0.0          0.0          0.0          0.0
  33    0.137792D-01    -0.176351D+01     0.0          0.0          0.0          0.0
  34   -0.259210D-01    -0.162673D+01     0.0          0.0          0.0          0.0
  35   -0.720977D-01    -0.126627D+01     0.0          0.0          0.0          0.0
  36   -0.203791D-01    -0.734277D+00     0.0          0.0          0.0          0.0
  37    0.0              0.0              0.0          0.0          0.0          0.0
  38    0.0              0.0              0.0          0.0          0.0          0.0
  39   -0.940474D-01    -0.164425D+01     0.0          0.0          0.0          0.0
  40    0.223925D-01    -0.205085D+01     0.0          0.0          0.0          0.0
  41    0.122347D+00    -0.147610D+01     0.0          0.0          0.0          0.0
  42    0.0              0.0              0.0          0.0          0.0          0.0
  43    0.0              0.0              0.0          0.0          0.0          0.0

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                            5729 DRAGON WAY      CINCINNATI,OHIO 45227      (513) 272-1100

                          DUNLOP PFD HD BUSH SHRINKAGE STRESSES 4

NODE        UX               UY            UZ           ROTX          ROTY         ROTZ
  44    0.173586D-01    -0.109866D+01     0.0          0.0          0.0          0.0
  45    0.637267D-01    -0.183286D+01     0.0          0.0          0.0          0.0
  46    0.261939D-01    -0.227420D+01     0.0          0.0          0.0          0.0
  47    0.229166D-01    -0.241819D+01     0.0          0.0          0.0          0.0
  48    0.113665D-01    -0.215914D+01     0.0          0.0          0.0          0.0
  49   -0.455647D-01    -0.163041D+01     0.0          0.0          0.0          0.0
  50   -0.135000D-01    -0.928717D+00     0.0          0.0          0.0          0.0
  51    0.0              0.0              0.0          0.0          0.0          0.0
  52    0.0              0.0              0.0          0.0          0.0          0.0
  53   -0.628720D-01    -0.194244D+01     0.0          0.0          0.0          0.0
  54   -0.704632D-02    -0.252976D+01     0.0          0.0          0.0          0.0
```

Appendix No. 3.2

```
VERSION IV                        SDRC SUPERB--STRUCTURAL DYNAMICS RESEARCH CORPORATION          05/08/78  PAGE
    4
                                5729 DRAGON WAY     CINCINNATI,OHIO 45227      (513) 272-1100
                                  DUNLOP PED UD BUSH SHRINKAGE STRESSES 4

AVERAGED STRESSES AT NODES OF 2-D,THICK SHELL AND SOLID ELEMENTS

NODE *SYS* STRESS-X   STRESS-XY  STRESS-Y   STRESS-XZ  STRESS-YZ  STRESS-Z   *******PRINCIPAL STRESSES*******    VON
MISES
  1 G-STS      12.51     -0.00     12.71      0.0        0.0      12.73       12.73     12.51     12.71
 0.21
  2 G-STS      12.61     -0.06     12.50      0.0        0.0      12.66       12.66     12.47     12.64
 0.18
  3 G-STS      12.78     -0.12     12.37      0.0        0.0      12.68       12.81     12.34     12.68
 0.42
  4 G-STS      12.75     -0.05     12.30      0.0        0.0      12.64       12.75     12.29     12.64
 0.42
  5 G-STS      12.63      0.00     12.13      0.0        0.0      12.52       12.63     12.13     12.52
 0.45
  6 G-STS      12.71      0.06     12.31      0.0        0.0      12.65       12.72     12.30     12.65
 0.39
  7 G-STS      12.75      0.13     12.44      0.0        0.0      12.74       12.80     12.40     12.74
 0.38
  8 G-STS      12.57      0.07     12.53      0.0        0.0      12.69       12.69     12.48     12.62
 0.18
```

Appendix No. 3.2

9 G-STS	12.44	0.00	✓12.67	0.0	0.0	12.68	12.68	12.44	12.67
0.23									
10 G-STS	11.65	-0.67	✓11.85	0.0	0.0	11.87	12.42	11.07	11.87
1.16									
11 G-STS	11.75	-0.28	11.35	0.0	0.0	11.66	11.90	11.21	11.66
0.60									
12 G-STS	11.85	0.03	11.31	0.0	0.0	11.72	11.85	11.31	11.72
0.48									
13 G-STS	11.69	0.31	11.40	0.0	0.0	11.70	11.89	11.20	11.70
0.61									
14 G-STS	11.67	0.55	✓11.89	0.0	0.0	11.91	12.34	11.21	11.91
0.59									
15 G-STS	10.62	-1.34	✓10.83	0.0	0.0	10.84	12.06	9.30	10.94
2.32									
16 G-STS	10.64	-0.95	10.55	0.0	0.0	10.71	11.55	9.64	10.71
1.60									
17 G-STS	10.74	-0.59	10.35	0.0	0.0	10.65	11.17	9.93	10.65
1.06									
18 G-STS	10.83	-0.28	10.35	0.0	0.0	10.71	10.95	10.22	10.71
0.64									
19 G-STS	10.79	0.07	10.22	0.0	0.0	10.64	10.80	10.21	10.64
0.53									
20 G-STS	10.79	0.37	10.36	0.0	0.0	10.73	11.00	10.15	10.73
0.75									
21 G-STS	10.74	0.64	10.45	0.0	0.0	10.75	11.25	9.93	10.75
1.15									
22 G-STS	10.59	0.86	10.57	0.0	0.0	10.72	11.44	9.71	10.72
1.50									
23 G-STS	10.56	1.10	✓10.79	0.0	0.0	10.81	11.78	9.57	10.81
1.92									
24 G-STS	8.53	-1.86	✓8.74	0.0	0.0	8.76	10.50	6.77	8.76
3.23									
25 G-STS	8.64	-0.79	8.40	0.0	0.0	8.73	9.44	7.86	8.73
1.42									
26 G-STS	8.67	0.10	8.14	0.0	0.0	8.54	8.68	8.12	8.54
0.51									
27 G-STS	8.76	0.86	8.43	0.0	0.0	8.75	9.47	7.72	8.75
1.53									
28 G-STS	8.50	1.53	✓8.74	0.0	0.0	8.76	10.16	7.09	8.76
2.60									
29 G-STS	6.22	-2.40	✓6.45	0.0	0.0	6.46	8.74	3.93	6.46
4.10									
30 G-STS	6.44	-1.74	6.31	0.0	0.0	6.50	8.12	4.64	6.50
3.02									
31 G-STS	6.83	-1.05	6.35	0.0	0.0	6.70	7.66	5.52	6.70
1.80									
32 G-STS	6.82	-0.41	6.34	0.0	0.0	6.71	7.06	6.10	6.71
0.84									
33 G-STS	6.54	0.13	6.05	0.0	0.0	6.44	6.57	6.02	6.44
0.50									
34 G-STS	6.75	0.59	6.32	0.0	0.0	6.69	7.16	5.91	6.69
1.10									
35 G-STS	6.88	1.14	6.51	0.0	0.0	6.86	7.85	5.54	6.86
2.01									
36 G-STS	6.38	1.58	6.32	0.0	0.0	6.50	7.93	4.77	6.50
2.74									
37 G-STS	6.06	1.98	✓6.31	0.0	0.0	6.33	8.17	4.29	6.33

Appendix No. 3.2

```
   42 G-STS       5.04       2.25     x5.30       0.0        0.0        5.31        7.43       2.92       5.31
   3.91
 • 43 G-STS       0.36      -3.08     ✓0.58       0.0        0.0        0.61        3.55      -2.61       0.61
   5.33
   44 G-STS       1.68      -2.25      1.63       0.0        0.0        1.78        3.90      -0.60       1.78
   3.90
   45 G-STS       3.24      -1.48      2.94       0.0        0.0        3.20        4.58       1.60       3.20
   2.59
   46 G-STS       3.03      -0.78      2.39       0.0        0.0        2.84        3.55       1.87       2.84
   1.46
   47 G-STS       2.52       0.14      1.54       0.0        0.0        2.20        2.54       1.52       2.20
   0.96
   48 G-STS       2.93       1.00      2.40       0.0        0.0        2.84        3.69       1.63       2.84
   1.79
   49 G-STS       3.32       1.00      3.21       0.0        0.0        3.45        4.87       1.66       3.45
   2.78


 VERSION IV                    SDRC SUPERB--STRUCTURAL DYNAMICS RESEARCH CORPORATION          05/08/78   PAGE
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                           5729 DRAGON WAY        CINCINNATI,OHIO 45227       (513) 272-1100

                         DUNLOP PFG UD BUSH SHRINKAGE STRESSES 4

 NODE *STS* STRESS-X   STRESS-XY  STRESS-Y   STRESS-XZ  STRESS-YZ  STRESS-Z     *******PRINCIPAL STRESSES*******     VON
 MISES
    50 G-STS       1.76       2.00      1.82       0.0        0.0        1.96        3.79      -0.21       1.96
    3.47
    51 G-STS       0.27       2.49     x0.51       0.0        0.0        0.54        2.88      -2.10       0.54
    4.32
    52 G-STS       2.05      -3.36     ✓2.23       0.0        0.0        2.28        5.50      -1.21       2.28
    5.62
    53 G-STS       1.79      -1.14      1.13       0.0        0.0        1.60        2.84       0.58       1.60
    2.46
    54 G-STS       0.44       0.11      0.55       0.0        0.0        0.64        0.64       0.38       0.61
    [illegible]
```

Appendix No. 3.2

1.70									
60 G-STS	-0.98	-0.25	-0.88	0.0	0.0	-0.76	-0.67	-1.18	-0.76
0.47									
61 G-STS	-0.27	0.08	0.92	0.0	0.0	0.44	0.92	-0.28	0.44
1.04									
62 G-STS	-0.60	0.29	-0.74	0.0	0.0	-0.57	-0.37	-0.97	-0.57
0.52									
63 G-STS	-0.77	0.84	-2.26	0.0	0.0	-1.40	-0.39	-2.63	-1.40
1.94									
64 G-STS	3.70	2.01	3.04	0.0	0.0	3.51	5.41	1.33	3.51
3.53									
65 G-STS	7.77	3.11	7.94	0.0	0.0	8.00	10.97	4.74	8.00
5.40									

BUSHSTR - LIST   Appendix No. 3.3

```
10    DIM Bush$(526)[80]
20    INTEGER I,I0,I1,I2
30    ASSIGN #1 TO "Data:T15"                ! MAIN DATA FILE
40 Heading: PRINT PAGE,LIN(3)                ! HEADINGS
41   PRINT "         SHRINKAGE STRESS IN U.D.BUSHES  (PRODUCT GROUPS 1,2,3,4,5,
6,17,19)",LIN(2)
50  PRINT "          BUSH No.","        HARDNESS";"      SHAPE FACTOR ";"
    STRESS"
60  PRINT "             ","         (IRHD) ","     ";"          ";"
 (MN/M^2)"
70  IMAGE "          ", 66("=")
80  PRINT USING 70
90  I=0
100   IF I2>0 THEN 980
110 ON END #1 GOTO 150
120 I=I+1
130 READ #1;Bush$(I)                         !READ DATA
140 GOTO 120
150   Z=I=I-1
160   FOR I1=1 TO I
170   Bush$(I1)[1]=Bush$(I1)[7]
180   NEXT I1
190   CALL Stringsort_q(Bush$(*),1,Z,80,1)    ! CALL SORT ROUTINE
200   FOR I1=1 TO I
210   NEXT I1
220   FOR I2=1 TO I
230   CALL Unpack(Bush$(I2),C$,Group,D1,D2,L1,D3,D4,L2,V,R)
231                                           ! CALL DATA UNPACK
240 D5=D1+D2*2
250 D6=D3-D4*2
260 Thick=(D6-D5)/2
270 Sfactr=L2/(2*Thick)
280 GOSUB 410                                 ! FOR CONSTANTS
290 A=1.5*Sfactr*T2/(1+.75*Sfactr)            ! SHRINKAGE CALC'N
300 B=A+1
310 C=B*(1+T2)
320 P=(C-1)*100                               ! P=% SHRINKAGE
330 X=P*Thick/100
340 J=1+K1*Sfactr^2                           ! STRESS CALC'N
350 L=G1*J*X*4/(3*Thick)
360 Lunits=L*9.810
370 Stress=M=L*1422.4
380 IMAGE 8X,15A,8X,DD,12X,DD.DD,12X,6X,DD.DDD
390 PRINT USING 380;C$,R,Sfactr,Lunits        ! RESULTS
400 GOTO 950
410 IF R=35 THEN 520                          ! MATERIAL PROPERTY CONSTANTS
420 IF R=40 THEN 560
430 IF R=60 THEN 720
440 IF R=45 THEN 600
450 IF R=50 THEN 640
460 IF R=55 THEN 680
470 IF R=65 THEN 760
480 IF R=70 THEN 800
490 IF R=73 THEN 840
500 IF R=75 THEN 840
510 IF R=80 THEN 880
520 T1=340
530 G=11.8
540 K=89
550 GOTO 910
560 T1=320
570 G=15
580 K=85
590 GOTO 910
600 T1=258
610 G=18
620 K=80
```

```
630 GOTO 910
640 T1=237
650 G=22
660 K=73
670 GOTO 910
680 T1=225
690 G=32.5
700 K=64
710 GOTO 910
720 T1=217
730 G=44.5
740 K=57
750 GOTO 910
760 T1=211
770 G=58.5
780 K=54
790 GOTO 910
800 T1=207
810 G=73.5
820 K=53
830 GOTO 910
840 T1=205
850 K=52
860 G=94.5
870 GOTO 910
880 T1=205
890  G=94.5
900  K=52
910  T2=T1/10000
920  G1=G/100
930  K1=K/100
940  RETURN
950  Num=Num+1                                     !NUMBER OF BUSHES
960  IF FRACT(Num/50)>0 THEN 980
961  Page=Page+1
970  PRINT LIN(3),"          Temperture change = 130 C",LIN(2),"          For shri
nkage stress per  C divide by 130",LIN(-3)!,"PAGE";Page
971  GOTO Heading
980  NEXT I2
990   GOTO 1020
1000 Error:PRINT "ERROR ERRN=";ERRN;" ERRL=";ERRL
1010  RETURN
1020 PRINT "END OF DATA"
1030  OFF ERROR
1040 ASSIGN #1 TO *
1050 END
1060 SUB Stringsort_q(A$(*),I1,J1,Length,Incdec)  ! SUB ROUTINES
1070     N=J1+1-I1
1080     Logtwo=INT(LGT(N)/LGT(2))+1
1090     CALL Qsort(A$(*),Logtwo,I1,J1,Length,Incdec)
1100 SUBEXIT
1110 SUB Qsort(A$(*),Log,I1,J1,Length,Incdec)
1120 OPTION BASE 1
1130 DIM L(Log),U(Log),T$[Length],T1$[Length]
                                         ! Set stack pointer.
1140     M=1                             ! Set lower endpoint.
1150     I=I1                            ! Set upper endpoint.
1160     J=J1
1170 Start1:IF I>=J THEN Nextgroup
1180 Start2:K=I                          ! Determine the midpoint of a segment.
1190         I2=INT((J+I)/2)
1200         T$=A$(I2)
1210         IF Incdec=0 THEN D1
1220 I1:     IF A$(I)<=T$ THEN Lowmiddle1
1230         GOTO 1250                     ! Check to see if lower endpoint and
1240 D1:     IF A$(I)>=T$ THEN Lowmiddle1  !  midpoint are in order.  If not,
1250         A$(I2)=A$(I)                  !  switch them.
1260         A$(I)=T$                      ! Reset midpoint.
1270         T$=A$(I2)                      ! Set upper endpoint.
1280 Lowmiddle1: L=J
1290                IF Incdec=0 THEN D2
```

Appendix No. 3.3

```
1300 I2:          IF A$(J))=T$ THEN Middlehigh
1310              GOTO 1330
1320 D2:          IF A$(J)<=T$ THEN Middlehigh ! Check to see if the midpoint and
1330              A$(I2)=A$(J)                 ! the upper endpoint are in order.
1340              A$(J)=T$                     ! If not, switch them.
1350              T$=A$(I2)
1360              IF Incdec=0 THEN D3
1370 I3:          IF A$(I)<=T$ THEN Middlehigh
1380              GOTO 1400
1390 D3:          IF A$(I)>=T$ THEN Middlehigh  ! Check to see if the switch left
1400              A$(I2)=A$(I)                  !  the lower endpoint and the mid
-
1410              A$(I)=T$                      !  point in order.
1420              T$=A$(I2)                     ! If not, switch them.
1430 Middlehigh: L=L-1                          ! Decrement the upper endpoint.
1440              IF Incdec=0 THEN D4
1450 I4:          IF A$(L)>T$ THEN Middlehigh
1460              GOTO 1480
1470 D4:          IF A$(L)<T$ THEN Middlehigh   ! Check to see if the new upper
1480              T1$=A$(L)                     !  endpoint is in order.
1490 Stepup: K=K+1                     ! If not, save the upper endpoint and
1500          IF Incdec=0 THEN D5
1510 I5:      IF A$(K)<T$ THEN Stepup  !  increment the lower endpoint.  Now
1520          GOTO 1540
1530 D5:      IF A$(K)>T$ THEN Stepup
1540          IF K>L THEN Passed       !  check if the lower endpoint is less
1550          A$(L)=A$(K)              !  than the midpoint.  If not, then switch
1560          A$(K)=T1$                !  the upper and lower endpoints.
1570          GOTO Middlehigh
1580 Passed: IF L-I<=J-K THEN Storehigh   ! Sort the shortest segment first.
1590          L(M)=I                      ! Store the lower
1600          U(M)=L                      !  endpoints.
1610          I=K                         ! Set the new lower endpoint.
1620          M=M+1                       ! Push the stack
1630          GOTO 1680
1640 Storehigh: L(M)=K                    ! Store the upper
1650             U(M)=J                   !  endpoints
1660             J=L                      ! Set the new upper endpoint.
1670             M=M+1                    ! Push the stack
1680             IF J-I>=11 THEN Start2
1690             IF I=I1 THEN Start1
1700             I=I-1
1710 Inc: I=I+1                      ! Increment lower endpoint.
1720      IF I=J THEN Nextgroup      ! If the current segment is sorted, then
1730      T$=A$(I+1)                 !  sort the next segment.
1740      IF Incdec=0 THEN D6
1750 I6:  IF A$(I)<=T$ THEN Inc
1760      GOTO 1780
1770 D6:  IF A$(I)>=T$ THEN Inc      ! Check to see if next element is in order.
1780      K=I                        ! Insert element in otherwise sorted list.
1790 Copy: A$(K+1)=A$(K)             ! This section bumps the array up.
1800       K=K-1                     ! Prepare to bump next element.
1810       IF Incdec=0 THEN D7
1820 I7:   IF T$<A$(K) THEN Copy
1830       GOTO 1850                   ! Check to see if insertion is here.
1840 D7:   IF T$>A$(K) THEN Copy       ! If so, then insert.
1850       A$(K+1)=T$
1860       GOTO Inc
1870 Nextgroup: M=M-1                ! Pop the stack.
1880            IF M=0 THEN Out      ! Check for end conditions.
1890            I=L(M)               ! Restore the
1900            J=U(M)               !  previous endpoints.
1910            GOTO 1680
1920 Out: SUBEXIT
1930 SUB Unpack(A$,C$,Group,D1,D2,L1,D3,D4,L2,V,R)
1940  INTEGER N,I,J
1950  N=0
1960  J=1
1970  GOSUB Unpac
1980  C$=A$[1,J]
```

```
1990  GOSUB Unpac
2000  Group=B=VAL(A$[K,J])
2010  GOSUB Unpac
2020  D1=C=VAL(A$[K,J])
2030  GOSUB Unpac
2040  D2=D=VAL(A$[K,J])
2050  GOSUB Unpac
2060  L1=E=VAL(A$[K,J])
2070  GOSUB Unpac
2080  D3=F=VAL(A$[K,J])
2090  GOSUB Unpac
2100  D4=G=VAL(A$[K,J])
2110  GOSUB Unpac
2120  L2=X=VAL(A$[K,J])
2130  GOSUB Unpac
2140  V=Y=VAL(A$[K,J])
2150  GOSUB Unpac
2160  R=Z=VAL(A$[K,J])
2170  N=N+1
2180  GOTO 2250
2190 Unpac: K=J+2
2200  FOR I=K TO 160
2210  IF A$[I;1]="," THEN 2230
2220  NEXT I
2230  J=I-1
2240  RETURN
2250  SUBEND
```

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/0648/00	40	1.62	.434
13/0648/01	45	1.62	.402
13/0648/02	55	1.62	.546
13/0648/03	60	1.62	.671
13/0648/05	70	1.62	1.013
13/0657/00	60	3.30	2.240
13/0657/01	60	3.30	2.240
13/0660/00	35	6.23	5.036
13/0660/01	45	6.23	5.230
13/0660/02	55	6.23	6.626
13/0660/03	60	6.23	7.826
13/0660/04	70	6.23	11.496
13/0663/00	45	3.78	1.900
13/0663/01	55	3.78	2.437
13/0663/02	60	3.78	2.899
13/0663/03	70	3.78	4.280
13/0663/04	60	3.78	2.899
13/0665/00	60	3.98	3.200
13/0665/01	65	3.98	3.895
13/0665/02	70	3.98	4.720
13/0665/03	45	3.98	2.103
13/0669/00	45	5.71	4.378
13/0669/01	60	5.71	6.566
13/0687/00	60	8.74	15.583
13/0697/00	60	3.18	2.079
13/0697/02	60	3.18	2.079
13/0714/00	60	2.30	1.167
13/0714/01	60	2.30	1.167
13/0714/02	60	2.30	1.167
13/0714/03	60	2.30	1.167
13/0714/04	70	2.30	1.741
13/0718/00	35	3.95	1.993
13/0718/01	45	3.95	2.079
13/0718/02	60	3.95	3.165
13/0718/03	65	3.95	3.853
13/0718/05	60	3.95	3.165
13/0718/06	50	3.95	2.143
13/0728/01	60	4.16	3.489
13/0728/02	70	4.16	5.144
13/0728/03	60	4.16	3.489
13/0728/04	65	4.16	4.245
13/0731/00	60	4.54	4.153
13/0736/00	55	.88	.258
13/0742/01	60	4.28	3.690
13/0742/03	45	4.28	2.434
13/0742/07	55	4.28	3.109
13/0742/08	60	4.28	3.690
13/0754/00	55	2.95	1.514
13/0754/01	73	2.95	3.368
13/0754/02	73	2.95	3.368

Temperture change = 130°C

For shrinkage stress per °C divide by 130

Appendix No. 3.3

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/0754/03	73	2.95	3.368
13/0754/04	60	2.95	1.813
13/0754/06	70	2.95	2.687
13/0754/07	45	2.95	1.167
13/0754/08	60	2.95	1.813
13/0754/10	70	2.95	2.687
13/0754/11	60	2.95	1.813
13/0756/00	60	4.78	4.608
13/0756/01	60	4.78	4.608
13/0756/02	45	4.78	3.054
13/0767/00	45	6.11	5.034
13/0767/01	55	6.11	6.379
13/0767/02	60	6.11	7.536
13/0767/03	70	6.11	11.071
13/0767/04	80	6.11	13.841
13/0767/05	60	6.11	7.536
13/0767/06	45	6.11	5.034
13/0771/00	40	2.27	.777
13/0771/01	60	2.27	1.137
13/0779/00	60	5.44	5.962
13/0780/00	60	2.40	1.247
13/0785/00	60	4.55	4.180
13/0785/01	70	4.55	6.156
13/0785/02	60	4.55	4.180
13/0790/00	60	4.07	3.355
13/0790/01	70	4.07	4.948
13/0791/00	45	1.69	.428
13/0791/01	55	1.69	.579
13/0791/02	60	1.69	.711
13/0791/03	70	1.69	1.070
13/0791/04	75	1.69	1.347
13/0791/05	50	1.69	.451
13/0797/00	70	5.36	8.514
13/0797/01	73	5.36	10.647
13/0797/02	73	5.36	10.647
13/0797/03	73	5.36	10.647
13/0797/04	60	5.36	5.790
13/0797/05	60	5.36	5.790
13/0801/00	73	3.15	3.801
13/0801/01	73	3.15	3.801
13/0801/02	73	3.15	3.801
13/0801/03	70	3.15	3.034
13/0801/04	60	3.15	2.049
13/0801/05	60	3.15	2.049
13/0802/00	60	2.63	1.474
13/0803/00	60	2.26	1.127
13/0803/01	60	2.26	1.127
13/0812/00	45	3.93	2.051
13/0812/01	60	3.93	3.124
13/0815/01	60	5.32	5.710

Temperture change = 130 °C

For shrinkage stress per °C divide by 130

Appendix No. 3.3

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/0830/00	60	3.18	2.081
13/0830/01	65	3.18	2.540
13/0830/02	75	3.18	3.861
13/0832/00	35	1.02	.191
13/0832/01	60	1.02	.379
13/0832/02	60	1.02	.379
13/0838/00	60	3.95	3.153
13/0865/00	50	1.05	.233
13/0865/01	60	1.05	.389
13/0865/02	65	1.05	.487
13/0865/04	65	1.05	.487
13/0872/00	45	1.23	.266
13/0872/01	55	1.23	.373
13/0872/02	60	1.23	.466
13/0872/03	70	1.23	.709
13/0872/04	55	1.23	.373
13/0877/00	60	1.82	.796
13/0878/00	60	1.35	.524
13/0878/01	70	1.35	.795
13/0878/02	75	1.35	1.003
13/0886/00	55	6.11	6.379
13/0888/00	75	3.39	4.363
13/0888/01	60	3.39	2.356
13/0890/00	60	.76	.293
13/0890/01	70	.76	.454
13/0890/02	55	.76	.229
13/0890/03	55	.76	.229
13/0890/04	70	.76	.454
13/0890/05	55	.76	.229
13/0897/00	45	2.61	.925
13/0897/01	60	2.61	1.453
13/0897/02	60	2.61	1.453
13/0897/03	50	2.61	.961
13/0898/00	60	5.95	7.133
13/0898/01	70	5.95	10.481
13/0901/00	60	2.74	1.588
13/0901/01	70	2.74	2.358
13/0902/00	35	2.10	.587
13/0902/01	60	1.77	.760
13/0902/02	73	2.10	1.881
13/0902/03	73	1.77	1.437
13/0902/04	70	1.77	1.142
13/0902/06	70	1.77	1.142
13/0902/07	45	1.77	.461
13/0902/08	40	1.77	.499
13/0902/10	60	1.77	.760
13/0912/00	55	1.27	.390
13/0912/01	55	1.27	.390
13/0917/00	60	3.56	2.582
13/0917/01	60	3.56	2.582

Temperture change = 130 °C

For shrinkage stress per °C divide by 130

Appendix No. 3.3

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/0917/02	45	3.56	1.686
13/0917/03	60	3.56	2.582
13/0922/00	60	2.82	1.668
13/0922/01	70	2.82	2.475
13/0922/02	45	2.82	1.070
13/0923/03	40	8.74	11.540
13/0927/00	50	4.87	3.254
13/0927/01	60	4.87	4.772
13/0937/00	40	6.53	6.339
13/0937/01	60	6.53	8.610
13/0937/02	70	6.53	12.643
13/0937/03	60	6.53	8.610
13/0941/00	60	1.44	.567
13/0941/01	60	1.44	.567
13/0941/02	60	1.44	.567
13/0941/03	60	1.44	.567
13/0948/00	60	4.86	4.755
13/0948/01	60	4.86	4.755
13/0949/00	45	3.99	2.116
13/0949/01	60	3.99	3.219
13/0949/02	60	3.99	3.219
13/0949/03	60	3.99	3.219
13/0949/04	60	3.99	3.219
13/0949/05	60	3.99	3.219
13/0949/06	60	3.99	3.219
13/0950/00	70	9.19	25.342
13/0957/00	45	2.90	1.132
13/0957/01	60	2.90	1.760
13/0957/02	45	2.90	1.132
13/0957/03	60	2.90	1.760
13/0960/00	45	2.42	.803
13/0960/01	60	2.42	1.272
13/0968/00	60	3.31	2.245
13/0970/00	60	4.52	4.114
13/0971/00	60	2.94	1.805
13/0971/01	60	2.94	1.805
13/0975/00	40	5.00	3.681
13/0975/01	60	5.00	5.043
13/0975/03	75	5.00	9.282
13/0975/05	60	5.00	5.043
13/0985/00	60	2.98	1.841
13/0985/01	40	2.98	1.298
13/0985/02	70	2.98	2.729
13/0989/00	60	4.78	4.604
13/0989/01	70	4.78	6.777
13/0994/00	45	1.62	.401
13/0994/01	55	1.62	.545
13/0994/02	60	1.62	.670
13/0994/04	70	1.62	1.010
13/0995/00	60	1.56	.632

Temperture change = 130°C

For shrinkage stress per °C divide by 130

Appendix No. 3.3

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/0995/01	60	1.56	.632
13/0995/02	70	1.56	.954
13/0995/03	60	1.56	.632
13/0995/04	60	1.56	.632
13/0998/00	55	2.29	.954
13/0998/01	60	2.29	1.153
13/1004/00	50	1.72	.465
13/1004/01	60	1.72	.731
13/1004/02	65	1.72	.904
13/1004/03	45	1.72	.442
13/1004/04	70	1.72	1.101
13/1004/06	60	1.72	.731
13/1009/00	60	6.65	8.942
13/1012/00	60	5.68	6.501
13/1012/01	60	5.68	6.501
13/1013/00	60	1.76	.755
13/1013/01	45	1.76	.457
13/1014/00	60	.99	.368
13/1016/00	60	2.60	1.436
13/1025/00	50	3.40	1.589
13/1025/01	60	3.40	2.363
13/1027/00	60	1.43	.561
13/1027/01	70	1.43	.850
13/1027/02	60	1.43	.561
13/1027/03	60	1.43	.561
13/1032/00	60	2.95	1.807
13/1036/00	35	1.31	.268
13/1038/00	55	3.47	2.059
13/1038/01	60	3.47	2.455
13/1039/00	40	5.20	3.980
13/1039/01	55	5.20	4.601
13/1039/02	60	5.20	5.445
13/1039/03	65	5.20	6.614
13/1040/00	45	1.80	.476
13/1040/01	60	1.80	.783
13/1055/00	70	3.53	3.763
13/1055/01	65	3.53	3.104
13/1055/02	60	3.53	2.546
13/1062/00	60	1.90	.848
13/1076/00	60	4.96	4.957
13/1076/01	60	4.96	4.957
13/1079/00	35	1.11	.214
13/1079/01	45	1.11	.234
13/1079/02	55	1.11	.331
13/1080/01DUAL	60	4.28	3.700
13/1080/01DUAL	60	4.63	4.315
13/1080/03DUAL	60	4.28	3.700
13/1080/03DUAL	60	4.63	4.315
13/1090/00	35	2.94	1.108
13/1090/01	60	2.94	1.805

Temperture change = 130 °C

For shrinkage stress per °C divide by 130

Appendix No. 3.3

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/1110/00	60	5.32	5.710
13/1110/01	70	5.32	8.397
13/1132/00	60	5.40	5.882
13/1132/01	60	5.40	5.882
13/1136/00	55	1.49	.483
13/1136/01	60	1.49	.596
13/1136/02	55	1.49	.483
13/1136/03	60	1.49	.596
13/1141/00	45	2.60	.920
13/1155/00	60	3.67	2.732
13/1162/00	45	.83	.169
13/1162/01	45	.83	.169
13/1162/02	55	.83	.247
13/1164/00	60	1.32	.507
13/1177/00	40	5.53	4.507
13/1177/01	60	5.53	6.153
13/1184/00	60	2.21	1.084
13/1184/01	60	2.21	1.084
13/1189/00	70	4.15	5.140
13/1205/01	60	4.69	4.432
13/1230/00	55	1.65	.560
13/1230/01	70	1.65	1.036
13/1231/00	60	5.86	6.934
13/1232/00	60	2.11	1.003
13/1232/01	60	2.11	1.003
13/1258/01	60	6.93	9.715
13/1258/02	60	6.93	9.715
13/1263/00	60	2.36	1.217
13/1265/00	60	1.64	.681
13/1265/01	60	1.64	.681
13/1266/00	60	1.59	.653
13/1266/01	60	1.59	.653
13/1266/02	60	1.59	.653
13/1267/00	60	1.99	.912
13/1267/01	70	1.99	1.367
13/1267/02	60	1.99	.912
13/1273/00	50	3.95	2.143
13/1273/01	60	3.95	3.165
13/1273/02	60	3.95	3.165
13/1273/03	60	3.95	3.165
13/1273/04	70	3.95	4.669
13/1274/00	60	2.09	.990
13/1274/01	60	2.09	.990
13/1274/02	60	2.09	.990
13/1280/00	60	3.74	2.847
13/1284/03	55	3.47	2.059
13/1284/04	60	3.47	2.455
13/1287/02	60	2.11	1.007
13/1287/03	60	2.11	1.007
13/1288/00	55	7.21	8.933

Temperture change = 130 °C

For shrinkage stress per °C divide by 130

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/1288/01	60	7.21	10.539
13/1288/02	70	7.21	15.468
13/1296/00	55	1.26	.385
13/1296/01	55	1.26	.385
13/1296/02	55	1.26	.385
13/1302/00	60	4.40	3.912
13/1302/01	65	4.40	4.758
13/1302/03	45	4.40	2.584
13/1305/00	60	1.69	.711
13/1308/00	60	3.18	2.081
13/1317/02	55	4.28	3.119
13/1317/03	60	4.28	3.702
13/1317/04	60	4.28	3.702
13/1322/00	70	5.39	8.593
13/1324/00	60	1.09	.406
13/1326/00	60	3.09	1.975
13/1326/01	60	3.09	1.975
13/1326/02	60	3.09	1.975
13/1345/00	60	4.33	3.790
13/1349/00	50	5.87	4.755
13/1349/01	60	5.87	6.942
13/1362/00	45	1.23	.266
13/1363/01DUAL	60	4.08	3.372
13/1363/01DUAL	60	3.53	2.547
13/1363/02DUAL	60	4.08	3.372
13/1363/02DUAL	60	3.53	2.547
13/1386/00	60	6.63	8.878
13/1389/00	60	3.34	2.290
13/1411/00	60	6.78	9.295
13/1414/01	70	4.89	7.081
13/1415/00	60	6.70	9.081
13/1415/02	60	6.70	9.081
13/1416/00	60	5.60	6.318
13/1416/01	60	5.60	6.318
13/1423/00	60	3.18	2.081
13/1433/00	45	1.28	.280
13/1433/01	60	1.28	.486
13/1433/02	45	1.28	.280
13/1433/04	50	1.28	.298
13/1442/00	70	4.16	5.144
13/1459/00	35	2.03	.551
13/1459/01	50	2.03	.611
13/1459/02	60	2.03	.945
13/1459/03	60	2.03	.945
13/1459/05	70	2.03	1.415
13/1459/06	60	2.03	.945
13/1460/00	60	2.33	1.185
13/1460/01	65	2.33	1.454
13/1460/02	70	2.33	1.767
13/1460/03	50	2.33	.776

Temperture change = 130 °C

For shrinkage stress per °C divide by 130

Appendix No. 3.3

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/1460/04	75	2.33	2.219
13/1469/00DUAL	55	4.41	3.299
13/1469/00DUAL	55	2.92	1.487
13/1469/01DUAL	60	4.41	3.914
13/1469/01DUAL	60	2.92	1.782
13/1469/04DUAL	60	4.41	3.914
13/1469/04DUAL	60	2.92	1.782
13/1472/07	50	3.88	2.066
13/1472/08	55	3.88	2.569
13/1472/09	55	3.88	2.569
13/1472/10	60	3.88	3.054
13/1472/11	70	3.88	4.507
13/1480/00	60	6.24	7.872
13/1493/00	50	1.21	.277
13/1498/00	60	1.89	.844
13/1511/00	60	2.36	1.215
13/1519/03	40	1.59	.420
13/1519/05	60	1.59	.652
13/1531/00	60	4.78	4.608
13/1536/00	55	1.62	.544
13/1547/00	60	1.72	.731
13/1548/00	50	4.49	2.758
13/1548/01	55	4.49	3.419
13/1548/02	60	4.49	4.055
13/1548/03	70	4.49	5.973
13/1548/04	60	4.49	4.055
13/1567/00	60	4.06	3.326
13/1570/00	60	2.82	1.668
13/1585/00	70	1.52	.925
13/1594/00	50	.73	.164
13/1594/01	50	.73	.164
13/1606/00	60	7.42	11.188
13/1609/00	60	3.18	2.081
13/1612/00	45	6.54	5.784
13/1612/01	60	6.54	8.646
13/1612/02	70	6.54	12.697
13/1613/03	60	1.80	.784
13/1620/00	60	2.50	1.348
13/1620/01	60	2.50	1.348
13/1620/02	55	2.50	1.119
13/1620/03	55	2.50	1.119
13/1620/04	70	2.50	2.006
13/1623/00	55	1.38	.434
13/1624/00	50	3.27	1.477
13/1624/01	60	3.27	2.201
13/1630/00	60	5.55	6.205
13/1633/00	50	2.29	.756
13/1644/00	60	1.03	.381
13/1644/01	60	1.03	.381
13/1657/00	60	2.26	1.132

Temperture change = 130°C

For shrinkage stress per °C divide by 130

Appendix No. 3.3

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/1657/01	60	2.26	1.132
13/1657/02	60	2.26	1.132
13/1667/00	55	3.49	2.082
13/1667/01	60	3.49	2.482
13/1667/02	75	3.49	4.594
13/1667/03	60	3.49	2.482
13/1667/04	60	3.49	2.482
13/1667/05	55	3.49	2.082
13/1667/06	55	3.49	2.082
13/1667/07	65	3.49	3.026
13/1684/00	60	.68	.270
13/1698/03	60	1.57	.641
13/1698/04	70	1.57	.969
13/1708/00	60	5.68	6.505
13/1709/00	60	5.43	5.940
13/1718/00	45	2.21	.681
13/1718/01	60	2.21	1.089
13/1729/00	65	.96	.447
13/1730/00	60	3.01	1.880
13/1733/00	60	1.70	.715
13/1736/00	60	3.52	2.527
13/1740/00	73	3.33	4.221
13/1740/01	73	3.33	4.221
13/1740/02	73	3.33	4.221
13/1740/04	70	3.33	3.370
13/1740/05	60	3.33	2.278
13/1740/06	70	3.33	3.370
13/1741/00	60	1.88	.837
13/1741/01	60	1.88	.837
13/1761/00	60	4.02	3.269
13/1762/00	55	1.35	.421
13/1763/00	60	1.38	.537
13/1782/00	35	1.30	.264
13/1782/01	45	1.30	.286
13/1782/02	55	1.30	.398
13/1782/03	60	1.30	.496
13/1782/04	65	1.30	.617
13/1782/05	50	1.30	.305
13/1783/00	60	.84	.316
13/1783/01	55	.84	.248
13/1786/00	60	1.85	.813
13/1786/01	45	1.85	.496
13/1811/00	60	4.75	4.538
13/1812/00	50	1.48	.369
13/1817/00	60	2.86	1.717
13/1817/02	70	2.86	2.548
13/1817/03	75	2.86	3.194
13/1817/04	60	2.86	1.717
13/1817/05	73	2.86	3.194
13/1817/06	73	2.86	3.194

Temperture change = 130 °C

For shrinkage stress per °C divide by 130

Appendix No. 3.3

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/1817/07	73	2.86	3.194
13/1817/08	60	2.86	1.717
13/1817/10	60	2.86	1.717
13/1817/11	60	2.86	1.717
13/1817/14	60	2.86	1.717
13/1817/15	45	2.86	1.103
13/1817/16	70	2.86	2.548
13/1817/17	60	2.86	1.717
13/1823/00	60	3.15	2.047
13/1827/00DUAL	60	7.62	11.810
13/1827/00DUAL	60	4.83	4.693
13/1828/00DUAL	60	3.72	2.817
13/1828/00DUAL	60	2.50	1.349
13/1829/00	60	4.40	3.905
13/1839/00	50	4.93	3.334
13/1840/00DUAL	55	4.39	3.278
13/1840/00DUAL	55	3.09	1.653
13/1849/00	60	6.93	9.715
13/1849/01	60	6.93	9.715
13/1864/00	50	5.57	4.278
13/1872/00	60	4.02	3.270
13/1874/00	60	2.92	1.783
13/1880/01	45	1.10	.231
13/1880/02	60	1.10	.412
13/1891/00	55	2.44	1.065
13/1895/00	50	.63	.146
13/1897/01	55	2.65	1.243
13/1897/02	70	2.65	2.221
13/1905/00	50	4.26	2.492
13/1908/00	45	1.55	.372
13/1910/00	45	1.42	.327
13/1912/00	65	1.82	.983
13/1912/01	60	1.82	.796
13/1914/00	75	6.26	14.543
13/1914/01	75	6.26	14.543
13/1916/00DUAL	45	8.07	8.894
13/1916/00DUAL	45	4.83	3.120
13/1920/02	70	4.72	6.605
13/1923/01	50	1.38	.331
13/1928/00	70	8.61	22.205
13/1935/00	60	4.50	4.076
13/1940/00	60	9.01	16.613
13/1944/00	65	5.32	6.913
13/1949/00	60	5.25	5.556
13/1956/00	65	2.30	1.425
13/1957/00	60	5.76	6.693
13/1958/00	60	9.00	16.552
13/1959/00	55	1.46	.467
13/1961/00DUAL	40	5.88	5.113
13/1961/00DUAL	40	4.83	3.428

Temperture change = 130 °C

For shrinkage stress per °C divide by 130

SHRINKAGE STRESS IN U.D.BUSHES (PRODUCT GROUPS 1,2,3,4,5,6,17,19)

BUSH No.	HARDNESS (IRHD)	SHAPE FACTOR	STRESS (MN/M^2)
13/1981/00	45	3.20	1.370
13/1983/00	50	2.00	.596
13/1983/01	80	2.00	1.737
13/1994/00	70	4.33	5.563
13/2001/00	50	1.11	.251
13/2003/00	60	2.69	1.533
13/2004/00DUAL	40	13.73	29.165
13/2004/00DUAL	40	4.66	3.187
13/2005/00	55	.84	.248
13/2005/01	60	.84	.317
13/2011/00	60	3.78	2.899
13/2013/00	60	3.85	3.011
13/2020/01	50	3.17	1.387
13/2020/01	65	3.17	2.527
13/2027/00	60	1.10	.412
13/2030/00DUAL	40	3.35	1.643
13/2030/00DUAL	40	2.57	.980
13/2036/00	60	3.99	3.225
13/2044/00	50	6.26	5.429
13/2045/00	60	3.70	2.781
13/2048/00	60	5.79	6.757
13/2053/00	60	8.00	13.032
13/2056/00	60	2.66	1.499
13/2056/01	65	2.66	1.835
13/2070/00	45	1.81	.478

The Shrinkage Stress/Hot Bond Strength Test-Piece

Details are given of the shrinkage stress test-piece described in section 5.4.3.1. and the 'modified' test-piece described in section 6.4.1.

NB. In essence the same apparatus is used for both tests, only the test methods (reported in the thesis text) differ.

The Test Apparatus

For a cross-sectional diagram of the test-piece refer to figure 5.14 and for a picture of the complete apparatus assembly refer to Plate 3.

Bobbin Metals:- Made of mild steel, turned from solid bars. The drawing for the bobbin metal is given below. The metal with a U.N.C. threaded hole receives the load cell bolt while the UNF holed bobbin receives the Cap-head bolt.

Load Cell Bolt:- A threaded, internally gaged stud was employed as the load cell bolt. A full description of this stud appears here.

Length = 3"

Width = 0.5"

Thread : ½" U.N.C.

Connector type : C (four pin separable connector)

Service Temperature : 153°C max

Excitation Circuit : 350 ohm Full Bridge

Gage Material (Factor) : Metal Foil (2.00)

Optional extras utilised : Full temperature change compensation circuit.

Supplied by : A.J.B. Associates, Wells, Somerset.

The load stud was modified for the test-piece by removing the threaded end (0.75 inch from end opposite to the connector).

Bridge Circuit and Amplifier Module:-

A complete module, for both exciting and receiving the signal from the load cell and amplifying it to a digital readout, was used. This was the Fylde FE 492 BBS, supplied by Fylde Electronic Laboraties Ltd.

The range switch was set at 200 and the load cell and bridge calibrated using a Howden (Machine 1899) test-bench.
Calibration was carried out before each programme of tests (normally once a week). Any "drift" on the amplifier was corrected prior to each test.

The Chart Recorder*:-

A standard J.J. Instruments C.R. 500 single channel chart recorder was used

The main settings were

i) chart speed = 10 mm/min

ii) chart range = ± 1.0 v

iii) zero point = normally at the centre of the chart

The Mould and Press:-

A 2 cavity transfer mould was utilized (Dunlop P.E.D. Mould No. 13/1200/6). Removable inserts (Variant No. 3) held the test bobbins.
A 33g rubber blank weight was used for all tests.

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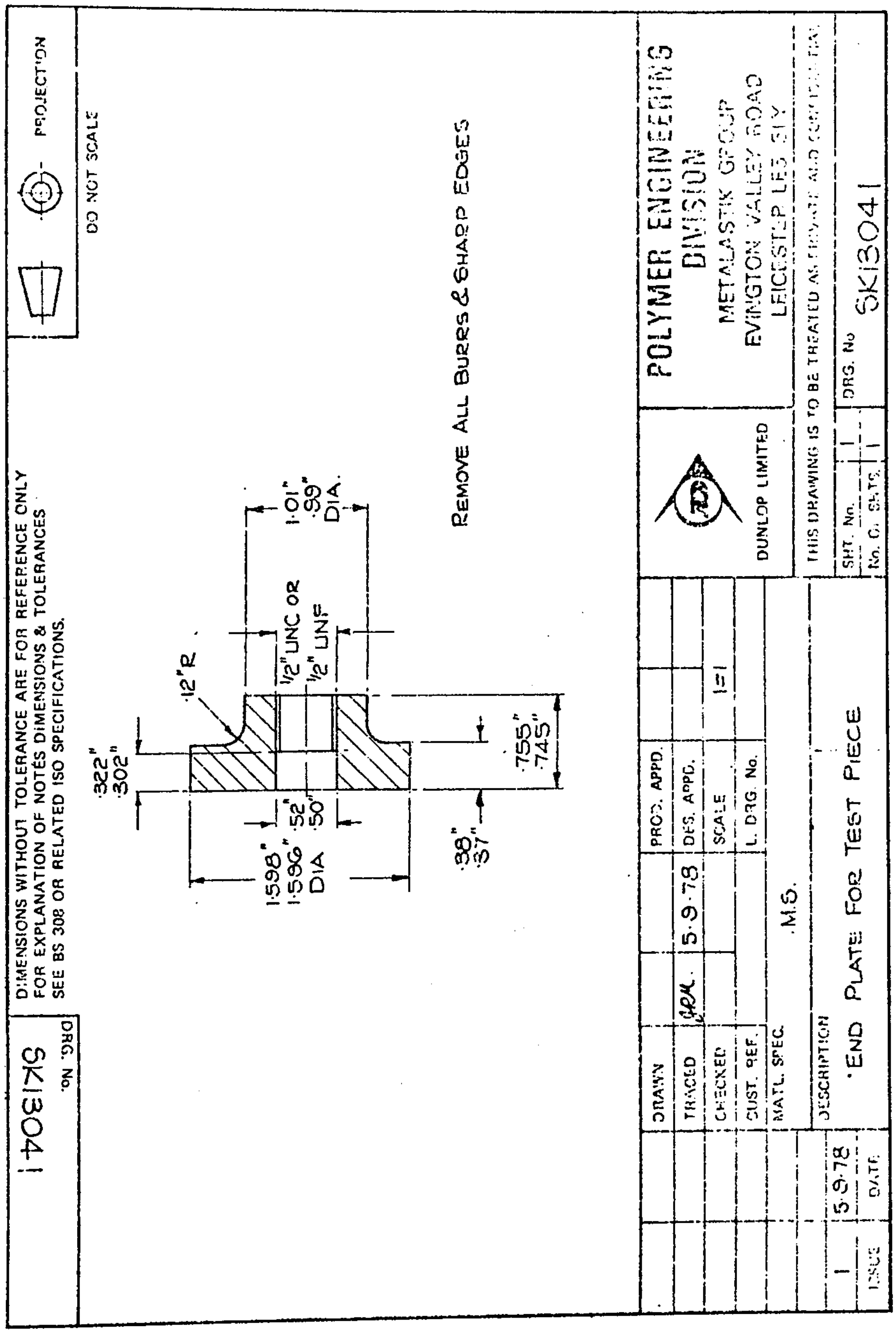
* only used in the hot bond strength measurements.

The electrically heated laboratory press was set at the required pressure for this mould (1200 P.S.I.) Only the bottom section of the press, i.e. between the lower and middle platens, could accommodate the test-piece mould.

Test-Piece Jig or Clamp

A clamp was engaged for the hot bond test so that the test-piece could be held while the stress was applied. The clamp was pre-heated on the press platen and only had limited contact with the test-bobbin during the stressing operation. Occasionally the clamp proved cumbersome, e.g. when the stress was applied immediately after moulding, and thus was replaced by a pair of "mole-grips" for this operation.


SK13041
DRG. No.
DIMENSIONS WITHOUT TOLERANCE ARE FOR REFERENCE ONLY
FOR EXPLANATION OF NOTES DIMENSIONS & TOLERANCES
SEE BS 308 OR RELATED ISO SPECIFICATIONS.
PROJECTION
DO NOT SCALE
REMOVE ALL BURRS & SHARP EDGES
1·598" 1·596" DIA
·52" ·50" DIA
·322" ·302"
·12"R
1/2" UNC OR 1/2" UNF
1·01" ·99" DIA.
·755" ·745"
·38" ·37"
POLYMER ENGINEERING DIVISION
METALASTIK GROUP
EVINGTON VALLEY ROAD
LEICESTER LE5 5LY
DUNLOP LIMITED
THIS DRAWING IS TO BE TREATED AS PRIVATE AND CONFIDENTIAL
SHT. No. 1
No. OF SHTS 1
DRG. No SK13041
DRAWN
TRACED
5·9·78
CHECKED
CUST. REF.
MATL. SPEC. M.S.
DESCRIPTION
END PLATE FOR TEST PIECE
PROD. APPD.
DES. APPD.
SCALE 1=1
L. DRG. No.
1
5·9·78
ISSUE
DATE

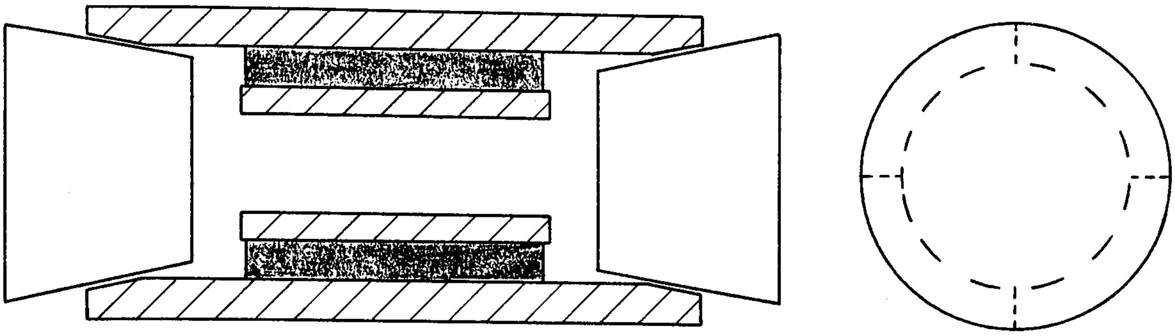
Appendix No. 3.5

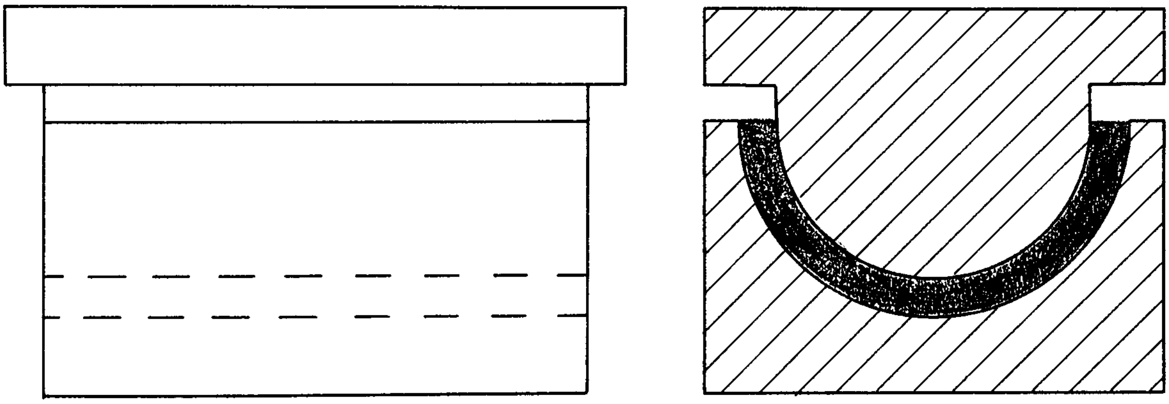
Detailed Results of the Experimental Method (Shape Factor = 2.11)

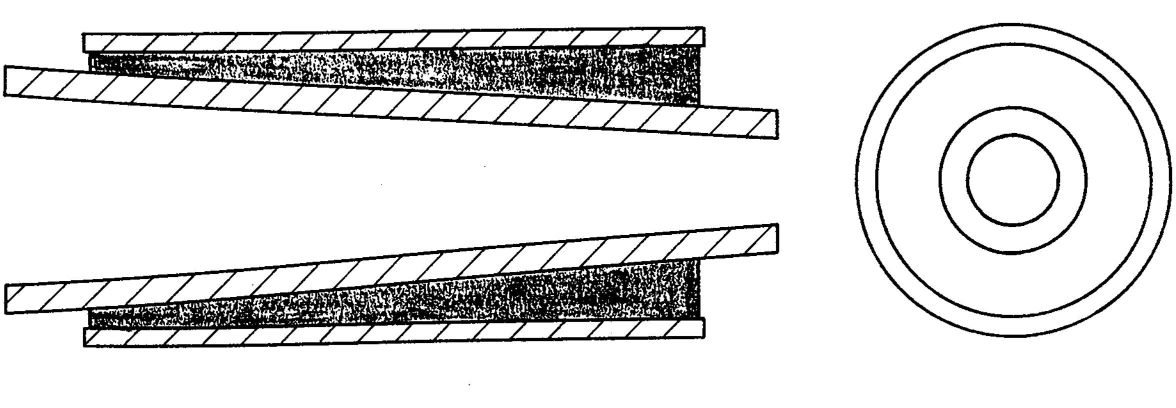
Sample No.	1	2	3	4	5	6	7	8	9	10	11
Load Cell reading prior to cooling (lbs)	-165	-180	-140	-120	-120	-160	-170	-150	-198	-168	-120
Maximum Load Cell reading at ambient temperature (lbs)	+199	+301	+212	+200	+244	+248	+161	+216	+283	+270	+270
Load Cell readings after shrinkage stress released (lbs)	+ 9	+ 55	- 27	- 17	- 20	- 25	- 16	- 2	+ 41	+ 18	+ 9
Force on Load cell due to shrinkage stress (lbs/Force)	190	246	239	217	264	273	177	218	242	252	261
Average Direct stress PSI	105	136	132	120	146	151	98	121	134	139	144
MN/m²	0.723	0.937	0.909	0.826	1.005	1.040	0.675	0.833	0.923	0.958	0.992

Appendix No. 4.1

Conceptual Ideas for a Hot Bond Strength Test-Piece (To represent the Bush Situation)







Rubber areas are shaded.

Metal areas are blank or hatched.

Appendix No. 4.2

Adhesive Suppliers

Supplier	Country	Adhesive Brand Name
Hughson Chemicals	U.S.A.	Chemlok*, Typly+
Dayton Chemicals	U.S.A.	Thixon*
Borg-Warner Corp.	U.S.A.	Typly*
Durham Raw Materials Ltd.	U.K.	Chemlok+, Chemosil+
Compounding Ingredients Ltd.	U.K.	Thixon+
Anchor Chemicals Ltd.	U.K.	Typly+
Henkel G.M.B.H.	F.D.R.	Chemosil*
Metallgesellschaft A.G.	F.D.R.	Megum*
Bayer A.G.	F.D.R.	Desmodur*
-	U.S.S.R.	Lekonite
Industrial Adhesives Ltd. (Agents)	Japan	Indesol*

* Patent Holders

\+ Licencies

BP = British Patent
USP = United States of America Patent
GP = German Patent (F.D.R.)

Patent No.	Date Filed	Assignee	Comments
BP806,449	24.4.56	Lord Corporation	Chemlok 205 (as USP 2,900,292)
BP822,725	24.4.56	Lord Corporation	Chemlok 220 (as USP 3,258,388/9)
BP873,358	6.10.58	Borg-Warner Corporation	Typly Q(or W?) (as USP 3053,712)
BP873,359	24.10.58	Borg-Warner Corporation	Modification of BP873,358 for Butyl Rubber (as USP 3053,712)
BP877,053	10.10.58	Borg-Warner Corporation	Similar to BP873,358 but using cheaper materials
BP877,923	13.10.58	Borg-Warner Corporation	Similar to BP873,358 but using different curing system.
BP943,156	11.8.61	Metallgesellschaft A.G.	-
BP971,356	1.11.62	Henkel and Cie GMBH	Mainly for post-cure bonding
BP1,048,673	16.11.63	Farbenfabriken Bayer A.G.	2 coat adhesive system (as GP 1,266,490)
BP1,055,928	9.3.64	Dunlop Rubber Co.Ltd.	-
BP1,079,346	5.10.65	Fabenfabriken Bayer A.G.	-
BP1,108,788	3.4.65	Dunlop Holdings Ltd.	Direct Bonding
BP1,131,845	8.12.65	General Tire and Rubber Co.	Post-vulcanisation adhesive for bushes
BP1,144,704	10.3.69	Deutsche Gold under Silber Scheideanstalt	-

Appendix No. 4.2

Patent No.	Date Filed	Assignee	Comments
BP 1,162,873	26.5.65	Farbenfabriken Bayer A.G.	Direct Bonding
BP 1,166,433	?.10.68	" " "	-
BP 1,183,353	8.3.67	Borg-Warner Corporation	-
BP 1,211,553	22.8.67	T.R.W. Incorporated	Post-vulcanisation bonding agent
BP 1,213,691	4.1.68	Lord Corporation	Chemlok 250 (as USP 3,542,639)
BP 1,223,727	12.7.68	Pyrene	-
BP 1,230,310	25.7.69	W.R.Grace and Co.Ltd.	-
BP 1,255,777	23.2.68	Dunlop	Direct bonding for tyre cords
BP 1,317,166	10.7.70	Vyzkummy Ustov Gumarenski A Plastikarske Technologie	Mostly for bonding rubber to fabrics
BP 1,329,210	19.8.70	Henkel and Cie GMBH	Single coat adhesive
BP 1,332,230	12.11.71	Whittaker Corporation	Basis of OSN-1 (as USP 3,640,941)
BP 1,338,930	10.12.71	Bridgestown Tire Co.Ltd	Direct bonding to copper, brass and bronze
BP 1,354,750	17.11.71	Battelle Memorial Institute	Direct bonding (as USP 3,809,635)
BP 1,389,800	4.9.73	Yokohama Rubber Co.Ltd.	Direct bonding

Appendix No. 4.2

Patent No.	Date Filed	Assignee	Comments
BP 1,416,586	7.6.73	Henkel and Cie GMBH	Basis of Chemosil X2311
BP 1,402,418	12.9.72	Anchor Chemical Co.Ltd.	Typly Experimental Adhesive No. 1471, Single Coat.
BP 1,423,578	21.3.73	Lord Corporation	Chemlok 230 series (as USP 3,840,784)
BP 1,463,014	9.10.74	Ciba-Geigy A.G.	Direct bonding technique (use in tyre production)
USA 2,900,292	29.4.55	Lord Corporation	Chemlok 205 (as BP 806,449)
USA 3,053,712	10.10.57	Borg-Warner Corporation	Typly Q (or W ?) (as BP 873,358)
USA 3,065,122	14.8.56	" " "	
USA 3,099,632	2.12.59	Lord Corporation	Single coat adhesive for bonding polar rubbers
USA 3,258,388	20.11.59	" "	Chemlok 220 (as BP 822,725)
USA 3,258,389	20.11.59	" "	Chemlok 220 includes dichlorobutadiene (as BP 822,725)
USA 3,282,883	2.12.63	" "	Chemlok 230 series
USA 3,445,318	7.2.64	Whittaker Corporation	For bonding EPDM rubber to metal
USA 3,528,943	5.9.67	Lord Corporation	For bonding EPDM rubbers
USA 3,542,639	26.1.67	" "	Chemlok 250 (as BP 1,213,691)

Appendix No. 4.2

Patent No.	Date Filed	Assignee	Comments
USP 3,586,568	26.7.67	Hooker Chemicals Corporation	
USP 3,640,941	8.5.70	Whittaker Corporation	Basis of OSN-1 (and 19605 experimental adhesive)
USP 3,809,635	4.11.71	Battelle	
USP 3,830,784	22.3.72	Lord Corporation	Chemlok 230 series (as BP 1,423,578)
USP 3,879,337	18.9.74	Lord Corporation	" "
GP 1,278,658	1.12.64	Henkel and Cie GMBH	Similar to Chemlok 230 adhesives
GP 1,266,490	12.7.62	Farbenfabriken Bayer A.G.	- (as BP 1,048,673)
GP 1,229,718	24.12.64	Henkel and Cie GMBH	-

Appendix No. 4.2

Bonding Agent Ingredients

Key

1. Base Polymer(s)
2. Main Curing System
3. Secondary Curing System
4. Other ingredients (Main)
5. Solvent System (Main)

Chemlok 205

1	Chlorinated Neoprene + Chlorinated N.R.
2	Zinc oxide or Magnesium oxide
4	Phenol-formaldehyde resin or amine-aldehyde resin condensate
5	Mixture of Toluene and Methyl Ethyl Ketone

Chemlok 220

1	Brominated 2,3,-dichlorobutadiene -1,3,-polymer + chlorinated Neoprene or chlorinated N.R.
2	p-dinitroso-benzene
4	Carbon black
5	Toluene

Chemlok 250

1 Chlorosulphonated polyethylene + chlorinated ethylene-propylene terpolymer

2 p-dinitrosobenzene

3 dianisidine diisocyanate (3,3'-dimethoxy-4,4'biphenylene diisocyanate)

4 Gamma-methacryloxypropyltrimethoxysilane + Carbon black + Zinc oxide

5 Xylene or Toluene

Chemlok 234

1 Chlorosulphonated Polyethylene

2 Polymethylene polyphenylisocyanate (P.A.P.I.)

3 P-dinitrosobenzene

4 Carbon black

5 Xylene or Toluene

Chemlok 252

1 Chlorosulphonated Polyethylene + Chlorinated N.R.

2 p-dinitrosobenzene

3 maleic-anhydride ? (+ a Silane ?)

4 Carbon black

5 Trichloro-ethane

The Basis of Thixon OSN-1 and Thixon OSN-2

1 Chlorinated Polybutadiene/hexachlorocyclo-pentadiene adduct
2 Resorcinol
4 Dibasic Lead Phosphite + Silica + Carbon black + Hexamethylene Tetramine
5 Xylene or Toluene or Petroleum Spirit

Chemosil X2311

1 Chlorosulphonated Polyethylene
2 Dianisidine diisocyanate ?
3 p-dinitroso-benzene
4 Resole Resin + Carbon black + Zinc oxide
5 Xylene

Typly Q

1 Chlorinated NR + Chlorinated Neoprene + Chlorinated SBR.
2 p-dinitrosobenzene
4 Dibasic Lead Phosphite + Wax + Victoria Blue Dye + Carbon black
5 Xylene

App No. 4.2

General Comments on Adhesive Ingredients

a) The above information has been gleaned mainly from the patent literature and can only be taken as the probable composition of bonding agents. Furthermore it is impossible to accurately state the proportion of each material contained in the mixture.

b) The actual conditions are further complicated in that some reactants may themselves be generated "in situ", e.g. addition of p-benzoquinone dioxime and potassium ferricyanide (an oxidising agent) to the original formulation will produce p-dinitrosobenzene when heat is applied during curing.

c) The formulation of the given adhesive may alter over a period of time due to the need to replace an ingredient for health or financial reasons, e.g. the change in isocyanate in the Chemlok 230 series from Dianisidine diisocyanate to Polymethylene polyphenylisocyanate.

d) The general trend is towards faster reacting bonding agents by formulating a higher concentration of active curing ingredient, e.g. Chemlok 252 contains $\simeq 3$ times more p-dinitrosobenzene than Chemlok 220. The base polymer of the newer adhesives tends to be chlorosulphonated polyethylene.

e) A range of solvents can be employed although Toluene, Xylene and Methyl Ethyl Ketone are by far the most common. Due to fire regulations now in force in the U.S.A. Chemlok 252 and future adhesives will be based on halogenated solvent systems. Water based adhesives are in their infancy but will probably replace conventional solvent bonding agents in the next decade.

Appendix No. 5

Heat Transfer Characteristics

Theoretical Considerations of the Finite Element Method

The following details are extracted from the A.N.S.Y.S. program manual and only relate to this particular program.

Appendix No. 5

ANSYS USER'S MANUAL - ABSTRACT

The ANSYS computer program is a large scale general purpose computer program for the solution of several classes of Engineering Analysis problems. Analysis capabilities include static and dynamic; plastic, creep and swelling; small and large deflections; steady state and transient heat transfer and steady state fluid flow.

The ANSYS program uses the wave front (or "frontal") direct solution method for the system of simultaneous linear equations developed by the matrix displacement method, and gives results of high accuracy in a minimum of computer time. The program has the capability of solving large structures. There is no limit on the number of elements used in a problem. The number of nodes can be in excess of 2500 for three dimensional problems, and 5000 for two dimensional problems. There is no "brand width" limitation in the problem definition; however, there is a "wave front" restriction. The "wave front" restriction depends on the amount of core storage available for a given problem. Up to 576 degrees of freedom on the wave front can be handled in a large core. The wave front limitation tends to be restrictive only for analysis of arbitrary three dimensional solids or in the use of ANSYS on a small computer.

Heat Transfer

Transient and steady state heat transfer problems can be solved by finite element techniques analogous to those used for structural analyses. In this case the basic equilibrium equation is:

$$[\bar{C}]\ (\dot{T}) \quad + \quad [\bar{K}]\ (\dot{T}) \qquad (Q)$$

where $[\bar{K}]$ is the thermal conductivity matrix

(Q) is the heat flow vector

$(\dot{T})$ is the vector of the nodal point temperatures

$[\bar{C}]$ is the specific heat matrix

This equation is identical to the non-linear dynamic equation except that the mass term does not exist. The solution technique is the same as for the dynamic analysis except that linear and quadratic options are available for this approximation function.

This equation is solved in ANSYS at each time point in the heat transfer transient. Material properties (and convection coefficients) can be a function of temperature. In a steady-state analysis the properties are evaluated at the temperature of the previous iteration. In a transient analysis the properties are evaluated at a temperature extrapolated from the previously calculated temperatures.

STIF 55 ISOPARAMETRIC QUADRILATERAL TEMPERATURE ELEMENT

The isoparametric quadrilateral temperature element can be used as a biaxial plane element or as an axisymmetric ring element with a two-dimensional thermal conduction capability. The element has four nodal points with a single degree of freedom, temperature, at each node. The isoparametric temperature element is a higher-order version of the two-dimensional linear temperature element (STIF35). The advantage of isoparametric temperature elements over linear temperature elements is that, for a given accuracy, the number of degrees of freedom necessary to describe the structure may be reduced. Accordingly, the data preparation time and the computer wave front solution time are also reduced.

The isoparametric temperature element is applicable to a two-dimensional, steady-state or transient, Therman (K20 = -1) analysis. If the model containing the isoparametric temperature element is also to be analysed structurally, the element should be replaced by an equivalent structural element. The nodal temperatures determined from the isoparametric temperature element are applied to the corresponding structural nodal points.

Theory

The theory on which the isoparametric temperature element is based as described for the STIF35 element* except for the temperature function. The temperature function in this element is not a linear polynomial but includes additional incompatible temperature modes. The theory for this thermal element is analogous to the given in Reference 12. A 3 x 3 lattice of integration points is used for the numerical (Gaussian) integration procedure.

Assumption and Restrictions

The isoparametric quadrilateral temperature element must not have a negative or a zero area. The element must lie in an X-Y plane and the X-axis must be the radial direction for axisymmetric problems. Also, axisymmetric structures should be modeled in the +X quadrants.

A triangular element may be formed by defining duplicate K and L node numbers. The extra mode shapes and automatically deleted for triangular elements so that a linear temperature element results. Face 3 should not be defined as a convection surface if nodes K and L are coincident.

* Theory (STIF35)

The temperature distribution for this element is obtained from the numerical solution of the following equation (for the plane analysis):

$$pC_p \frac{\partial T}{\partial t} = K_{xxx} \frac{\partial^2 T}{\partial x^2} + K_{yy} \frac{\partial^2 T}{\partial y^2} + \dddot{q}$$

where p = density (Weight (or Mass)/Volume)

C_p = specific heat (Heat/Weight(or Mass)*Deg)

K = thermal conductivity (Heat/Length*Time*Deg)

$\dddot{q}$ = internal heat generation rate (Heat/Volume*Time)

For the axisymmetric analaysis the equation is of the form:

$$p C_p \frac{\partial T}{\partial t} = K_{xx} \left\{ \frac{1}{x} \frac{\partial T}{\partial x} + \frac{\partial^2 T}{\partial x^2} \right\} + K_{yy} \frac{\partial^2 T}{\partial y^2} + \dddot{q}$$

where the x-axis is in the radial direction and the y-axis is in the axial direction.

The temperature function is a linear polynomial in the plane of the element, given by:

$$T(x,y) = C_1 + C_2 x + C_3 y$$

and is constant in the circumferential direction at any given point. The element coordinate system (x,y) is oriented parallel to the global coordinate system (X,Y).

An Example of the Inputs and Results of the F.E.M. Program

```
***          BACKGROUND PROGRAMS, EFFECTIVE FEBRUARY 12, 1979.         ***

USED       .44 UNITS
/JOB R803

versn:  April 79


R803 DONE

00045 RETURNED
00004 SUBMITTED
 SUBMITTED/PURGED FILES
 -NONE
 SYSOUT REPORTS
 R80301SS-RET'D     # 1
 R8030101-RET'D     # 2
 R8030201-RET'D     # 3
 R8030301-RET'D     # 4
 R80300AA-RET'D     # 5
 R80301*A-RET'D     # 6
 C80:FIL  T 4
 CSD > ATTACH 118
 CSD > L/L6.TOP/
  DUNLOP PLD HEAT TRANSFERIN NEW TEST-PIECE (RUN TWO)                        4:31:28    8/ 1/79
 CSD > I-*
  DUNLOP PLD HEAT TRANSFERIN NEW TEST-PIECE (RUN TWO)                        4:31:28    8/ 1/79
                                                                      ELAPSED TIME =   0.121 SEC.


 THE REGION SPECIFIED FOR THIS RUN YIELDS A WORKSPACE  OF     70324 WORDS


 ***** ANALYST = RPRIGGS


          ***** ANALYSIS OPTIONS (CARDS C1 AND C2) *****

                                    VALUE         VARIABLE    COLUMNS
                                                    NAME

 NUMBER OF LOAD STEPS  . . . . .      1            NSTEPS       1-4
 ANALYSIS TYPE . . . . . . . . .     -1            K20          5-7
 BOUNDARY CONDITION KEY. . . . .      1            K17          18
 POST-RUN PROCESS KEY  . . . . .     -4            KYPOST       27-28
 KAY( 2) . . . . . . . . . . . .      1            KAY( 2)      32
 MATERIAL TABLE ENTRIES. . . . .     10            KPROP        71-75
 COORD. SYSTEM ROTATION KEY  . .      1            K18          77

 REFERENCE TEMPERATURE . . . . .     0.0           TREF         1-12
 UNIFORM TEMPERATURE . . . . . .   150.00          TUNIF        13-24
 PLOT DEVICE TYPE. . . . . . . .      7            KPDV         79-80

 BLOCK SIZES . . . . . . . . . .    1000    1000    3000    500    500    500    0    0
 WORK SPACE REQUESTED(DECIMAL)      70324
```

1 August

Test-Piece Run 2

Output & ANSYS normal solution

Results OK

Appendix No. 5

```
                ***** ELEMENT DEFINITIONS (CARD F) *****

 ELEMENT     NODES                                              MAT   TYPE               ELEMENT REAL CONSTANTS

     1     1     2     9     8                                   1     1
     2     8     9    16    15                                   1     1
     3    15    16    23    22                                   1     1
     4    22    23    30    29                                   1     1
     5    29    30    37    36                                   1     1
     6    36    37    44    43                                   1     1
     7    16    17    24    23                                   1     1
     8    17    18    25    24                                   1     1
     9    23    24    31    30                                   1     1
    10    24    25    32    31                                   1     1
    11    18    19    26    25                                   1     1
    12    19    20    27    26                                   1     1
    13    20    21    28    27                                   1     1
    14     2     3    10     9                                   2     1
    15     3     4    11    10                                   2     1
    16     4     5    12    11                                   2     1
    17     5     6    13    12                                   2     1
    18     6     7    14    13                                   2     1
    19     9    10    17    16                                   2     1
    20    10    11    18    17                                   2     1
    21    11    12    19    18                                   2     1
    22    12    13    20    19                                   2     1
    23    13    14    21    20                                   2     1
 NUMBER OF ELEMENTS =     23     MAXIMUM NODE POINT USED =     44


              *** ELEMENT STIFFNESS FORMULATION TIME ESTIMATE IBM 370/165

 TYPE        STIF      NUMBER    TIME(EACH)    TIME(ALL)

   1          55          23       0.0288        0.662
                           TOTAL TIME =          0.662 SECONDS.
```

```
                                                                                   JAN 1,1972
          SWANSON ANALYSIS SYSTEMS, INC.     HOUSTON, PENNSYLVANIA  15342   PHONE (412) 746-3304

DUNLOP PFD HEAT TRANSFERIN NEW TEST-PIFCE (RUN TWO)                                  4:31:29    8/ 1/79
                                                                             ELAPSED TIME =   0.483 SEC.



          ***** NODE DEFINITIONS (CARD F) *****

                   LOCATION           ROTATION (DEGREES)

  NODE          X            Y           THXY
              (OR R)     (OR THETA)     (OR RT)

     1        .0           .0           .0
     2       6.3500        .0           .0
     3       9.8300        .0           .0
     4      13.320         .0           .0
     5      16.800         .0           .0
     6      19.410         .0           .0
     7      20.280         .0           .0
     8        .0          .82500        .0
     9       6.3500       .82500        .0
    10       9.8300       .82500        .0
    11      13.320        .82500        .0
    12      16.800        .82500        .0
    13      19.410        .82500        .0
    14      20.280        .82500        .0
    15        .0         1.6500         .0
    16       6.3500      1.6500         .0
    17       9.8300      1.6500         .0
    18      13.320       1.6500         .0
    19      16.800       1.6500         .0
    20      19.410       1.6500         .0
    21      20.280       1.6500         .0
```

```
  30       6.3500        20.700       .0
  31       9.8300        20.700       .0
  32      12.700         20.700       .0
  36        .0           28.000       .0
  37       6.3500        28.000       .0
  43        .0           30.000       .0
  44       6.3500        30.000       .0
XMIN=  .0        XMAX=  20.28      YMIN=  .0         YMAX=  30.00      ZMIN=  .0         ZMAX=  .0


         ***** MATERIAL PROPERTIES (CARD H) *****
MATERIAL   1

 KXX  PROPERTY TABLE (LINEAR INTERPOLATION)
TEMP     KXX        TEMP     KXX       TEMP     KXX        TEMP     KXX        TEMP     KXX        TEMP     KXX

 0. 0.4800E-01   100. 0.4600E-01   300. 0.4200E-01    0. 0.0             0. 0.0             0. 0.0
 0. 0.0             0. 0.0            0. 0.0          0. 0.0
MATERIAL   2

 KXX  PROPERTY TABLE (LINEAR INTERPOLATION)
TEMP     KXX        TEMP     KXX       TEMP     KXX        TEMP     KXX        TEMP     KXX        TEMP     KXX

 20. 0.2340E-03  150. 0.2340E-03     0. 0.0          0. 0.0             0. 0.0             0. 0.0
  0. 0.0            0. 0.0           0. 0.0          0. 0.0
MATERIAL   1

 C    PROPERTY TABLE (LINEAR INTERPOLATION)
TEMP     C          TEMP     C         TEMP     C          TEMP     C          TEMP     C          TEMP     C

 20. 0.4870E+00  150. 0.4870E+00     0. 0.0          0. 0.0             0. 0.0             0. 0.0
  0. 0.0            0. 0.0           0. 0.0          0. 0.0
MATERIAL   2

 C    PROPERTY TABLE (LINEAR INTERPOLATION)
TEMP     C          TEMP     C         TEMP     C          TEMP     C          TEMP     C          TEMP     C

 20. 0.2010E+01  150. 0.2010E+01     0. 0.0          0. 0.0             0. 0.0             0. 0.0
  0. 0.0            0. 0.0           0. 0.0          0. 0.0
MATERIAL   1

 DENS PROPERTY TABLE (LINEAR INTERPOLATION)
TEMP     DENS       TEMP     DENS      TEMP     DENS       TEMP     DENS       TEMP     DENS       TEMP     DENS

 20. 0.7800E-02  150. 0.7800E-02     0. 0.0          0. 0.0             0. 0.0             0. 0.0
```

```
0. 0.0             0. 0.0             0. 0.0             0. 0.0





                                                     O STON   PENNSYLVANIA  15342    PHONE (412) 746-3304
DUNLOP PFD. HEAT TRANSFER IN NEW TEST-PIECE (RUN TWO)                                     4:31:30    8/ 1/79
                                                                                  ELAPSED TIME =    1.001 SEC.
LOAD STEP NUMBER =    1

           ***** LOAD STEP OPTIONS (CARDS L AND M) *****

                                       VALUE        VARIABLE    COLUMNS
                                                      NAME

LOAD STEP KEY . . . . . . . . .          1          KDIS         2-3
HEAT GENERATION KEY . . . . .            0          KTEMP        4-6
NUMBER OF ITERATIONS. . . . .          -30          NITTER       7-9
HEAT PRINTOUT FREQUENCY . . .            5          NPRINT      10-12
TIME AT END OF LOAD STEP. . .       3600.0          TIME        13-24
TEMP. PRINTOUT FREQUENCY. . .            2          NDPRNT      71-72 (CARD M)

CONVERGENCE CRITERIA    TRANSIENT=  5.0000


           ***** CONVECTION BOUNDARY CONDITIONS (CARD P) *****

   NO.      ELEMENT    FACE         FILM COEF.          TBULK

    1         18         2        .25000E-04         30.000
    2         23         2        .25000E-04         30.000
    3         13         2        .16000E-04         30.000
    4         10         2        .16000E-04         30.000
    5          5         2        .16000E-04         30.000
    6          6         2        .16000E-04         30.000
    7         10         3        .16000E-04         30.000
    8         11         3        .16000E-04         30.000
    9         12         3        .16000E-04         30.000
   10         13         3        .16000E-04         30.000
   11          6         3        .16000E-04         30.000
   12          9         3        .16000E-04         30.000
```

```
WORK AREA REQUIRED              7120

TIMES AT START OF BACK SUBSTITUTION  CP=      2.067   PP=      0.0   STEP=    1   ITERATION=  1

    1380 WORDS WRITTEN TO BLOCKS 1 AND 2
    1113 WORDS WRITTEN TO BLOCK 3
      36 ACTIVE DEGREES OF FREEDOM
     7.7 R.M.S. WAVEFRONT

MATRIX SOLUTION TIME ESTIMATEIBM 370/165 =    0.06 SECONDS.


STEADY CONVERGENCE VALUE =  0.0     TRANSIENT OPTIMIZATION VALUE =   18.6729  STEP =   1  ITER =   1




                                                  , PENNSYLVANIA  15342    PHONE (412) 746-3304
 DUNLOP PED HEAT TRANSFERIN NEW TEST-PIECE (RUN TWO)                              4:31:35    8/ 1/79
                                                                           ELAPSED TIME =   3.587 SEC.


  ***** TEMPERATURE  SOLUTION *****      TIME =     240.00      LOAD STEP=   1  ITERATION=  2  CUM. ITER.=   2

      NODE     TEMP           NODE     TEMP           NODE     TEMP           NODE     TEMP           NODE     TEMP

        1    133.74             2    133.71             3    134.94             4    134.72             5    134.66
        6    129.00             7    122.11             8    133.74             9    133.71            10    134.61
       11    134.42            12    134.32            13    130.25            14    123.81            15    133.75
       16    133.69            17    133.61            18    133.51            19    122.36            20    133.23
       21    133.18            22    133.57            23    133.51            24    133.43            25    133.22
       26    133.21            27    133.14            28    133.11            29    133.16            30    133.11
       31    133.09            32    133.01            33    .0                34    .0                35    .0
       36    132.77            37    132.62            38    .0                39    .0                40    .0
       41    .0                42    .0                43    132.60            44    132.59


 STEADY CONVERGENCE VALUE =  0.0     TRANSIENT OPTIMIZATION VALUE =    0.4548  STEP =   1  ITER =   2
 STEADY CONVERGENCE VALUE =  0.0     TRANSIENT OPTIMIZATION VALUE =    1.0621  STEP =   1  ITER =   3
```

Appendix No. 5

```
          Ol ANALYSIS SYSTEMS, INC.    HOUSTON, PENNSYLVANIA  15342    PHONE (412) 746-3304

   DUNLOP PED HEAT TRANSFERIN NEW TEST-PIECE (RUN TWO)                           4:31:41     8/ 1/79
                                                                          ELAPSED TIME =   6.500 SEC.


   ***** TEMPERATURE  SOLUTION *****      TIME =    900.00      LOAD STEP=   1  ITERATION=  4  CUM. ITER.=   4

        NODE     TEMP             NODE     TEMP             NODE     TEMP             NODE     TEMP             NODE     TEMP

          1    90.703              2    90.680              3    91.384              4    91.262              5    91.233
          6    88.017              7    84.012              8    90.705              9    90.686             10    91.199
         11    91.091             12    91.037             13    88.786             14    84.977             15    90.711
         16    90.675             17    90.630             18    90.572             19    90.491             20    90.414
         21    90.390             22    90.610             23    90.573             24    90.528             25    90.469
         26    90.405             27    90.361             28    90.346             29    90.378             30    90.347
         31    90.336             32    90.293             33    .0                 34    .0                 35    .0
         36    90.161             37    90.076             38    .0                 39    .0                 40    .0
         41    .0                 42    .0                 43    90.064             44    90.055


    STEADY CONVERGENCE VALUE =  0.0     TRANSIENT OPTIMIZATION VALUE =   13.7760  STEP =    1  ITER =    4
   ELEMENT     5  NODES=    30    37  FACE= 2  AREA=  46.36         TAVE.TBULK =    68.    30.    HEAT FLOW=  .2808E-01
   ELEMENT     6  NODES=    37    44  FACE= 2  AREA=  12.70         TAVE.TBULK =    68.    30.    HEAT FLOW=  .7674E-02
   ELEMENT     6  NODES=    44    43  FACE= 3  AREA=  20.16         TAVE.TBULK =    68.    30.    HEAT FLOW=  .1218E-01
   ELEMENT     9  NODES=    31    30  FACE= 3  AREA=  28.15         TAVE.TBULK =    68.    30.    HEAT FLOW=  .1709E-01
   ELEMENT    10  NODES=    25    32  FACE= 2  AREA=  124.1         TAVE.TBULK =    68.    30.    HEAT FLOW=  .7559E-01
   ELEMENT    10  NODES=    32    31  FACE= 3  AREA=  32.23         TAVE.TBULK =    68.    30.    HEAT FLOW=  .1962E-01
   ELEMENT    11  NODES=    26    25  FACE= 3  AREA=  52.41         TAVE.TBULK =    68.    30.    HEAT FLOW=  .3106E-01
   ELEMENT    12  NODES=    27    26  FACE= 3  AREA=  47.25         TAVE.TBULK =    68.    30.    HEAT FLOW=  .2870E-01
   ELEMENT    13  NODES=    21    28  FACE= 2  AREA=  193.3         TAVE.TBULK =    69.    30.    HEAT FLOW=  .1174
   ELEMENT    13  NODES=    28    27  FACE= 3  AREA=  17.27         TAVE.TBULK =    68.    30.    HEAT FLOW=  .1018E-01
   ELEMENT    16  NODES=     7    14  FACE= 2  AREA=  16.73         TAVE.TBULK =    64.    30.    HEAT FLOW=  .1132E-01
   ELEMENT    23  NODES=    14    21  FACE= 2  AREA=  16.73         TAVE.TBULK =    66.    30.    HEAT FLOW=  .1517E-01

    STEADY CONVERGENCE VALUE =  0.0     TRANSIENT OPTIMIZATION VALUE =   11.3107  STEP =    1  ITER =    5
```

Appendix No. 5

```
***** TEMPERATURE  SOLUTION *****     TIME =     1980.0      LOAD STEP=   1  ITERATION=  6  CUM..ITER.=   6

     NODE     TEMP            NODE     TEMP            NODE     TEMP            NODE     TEMP            NODE     TEMP

       1    53.644              2    53.638              3    53.910              4    53.863              5    53.852
       6    52.597              7    51.037              8    53.644              9    53.637             10    53.838
      11    53.796             12    53.775             13    52.897             14    51.414             15    53.647
      16    53.633             17    53.616             18    53.593             19    53.562             20    53.533
      21    53.523             22    53.608             23    53.594             24    53.577             25    53.[illegible]
      26    53.529             27    53.513             28    53.507             29    53.519             30    53.507
      31    53.503             32    53.486             33    .0                 34    .0                 35    .0
      36    53.436             37    53.403             38    .0                 39    .0                 40    .0
      41    .0                 42    .0                 43    53.398             44    53.395

STEADY CONVERGENCE VALUE =  0.0      TRANSIENT OPTIMIZATION VALUE =     8.1125  STEP =    1  ITER =    6

STEADY CONVERGENCE VALUE =  0.0      TRANSIENT OPTIMIZATION VALUE =     5.4412  STEP =    1  ITER =    7




                                    HOUSTON, PENNSYLVANIA  15342     PHONE (412) 746-3304
DUNLOP PED HEAT TRANSFERIN NEW TEST-PIECE (RUN TWO)                              4:36:23    8/ 1/79
                                                                           ELAPSED TIME =  12.584 SEC.

***** TEMPERATURE  SOLUTION *****     TIME =     3060.0      LOAD STEP=   1  ITERATION=  8  CUM. ITER.=   8

     NODE     TEMP            NODE     TEMP            NODE     TEMP            NODE     TEMP            NODE     TEMP

       1    38.842              2    38.840              3    38.942              4    38.924              5    38.920
       6    38.451              7    37.867              8    38.842              9    38.830             10    38.914
      11    38.899             12    38.891             13    38.563             14    38.008             15    38.843
      16    38.838             17    38.832             18    38.823             19    38.812             20    38.901
      21    38.797             22    38.829             23    38.823             24    38.817             25    38.[illegible]
      26    38.799             27    38.793             28    38.791             29    38.795             30    38.791
      31    38.790             32    38.783             33    .0                 34    .0                 35    .0
      36    38.764             37    38.752             38    .0                 39    .0                 40    .0
      41    .0                 42    .0                 43    38.751             44    38.749

STEADY CONVERGENCE VALUE =  0.0      TRANSIENT OPTIMIZATION VALUE =     3.5109  STEP =    1  ITER =    8

STEADY CONVERGENCE VALUE =  0.0      TRANSIENT OPTIMIZATION VALUE =     2.2121  STEP =    1  ITER =    9
```

Appendix No. 6

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THE THEORETICAL PREDICTION OF BOND FAILURE IN BUSHES
=====================================================


Based on calculated shrinkage stresses & experimentally determined
bond strengths






Description of Output

     FAIL = (Stress greater than bond strength)

     PROB FAIL = (Stress greater than 75% of bond strength)

     POSS FAIL = (Stress greater than 50% of bond strength)

         -     = (Stress less than 50% of bond srength)


25/6/80
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App No. 6

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM 205/220	205/220/1559	205/252
13/0648/00	-	-	-
13/0648/01	-	-	-
13/0648/02	-	-	-
13/0648/03	-	-	-
13/0648/05	-	-	-
13/0657/00	-	-	-
13/0657/01	-	-	-
13/0660/00	POSS FAIL	-	-
13/0660/01	POSS FAIL	-	-
13/0660/02	POSS FAIL	-	-
13/0660/03	POSS FAIL	-	-
13/0660/04	PROB FAIL	POSS FAIL	-
13/0663/00	-	-	-
13/0663/01	-	-	-
13/0663/02	-	-	-
13/0663/03	-	-	-
13/0663/04	-	-	-
13/0665/00	-	-	-
13/0665/01	-	-	-
13/0665/02	-	-	-
13/0665/03	-	-	-
13/0669/00	POSS FAIL	-	-
13/0669/01	POSS FAIL	-	-
13/0687/00	FAIL	PROB FAIL	-
13/0697/00	-	-	-
13/0697/02	-	-	-
13/0714/00	-	-	-
13/0714/01	-	-	-
13/0714/02	-	-	-
13/0714/03	-	-	-
13/0714/04	-	-	-
13/0718/00	-	-	-
13/0718/01	-	-	-
13/0718/02	-	-	-
13/0718/03	-	-	-
13/0718/05	-	-	-
13/0718/06	-	-	-
13/0728/01	-	-	-
13/0728/02	-	-	-
13/0728/03	-	-	-
13/0728/04	-	-	-
13/0731/00	-	-	-
13/0736/00	-	-	-
13/0742/01	-	-	-
13/0742/03	-	-	-
13/0742/07	-	-	-
13/0742/08	-	-	-
13/0754/00	-	-	-
13/0754/01	-	-	-
13/0754/02	-		

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM		
	205/220	205/220/1559	205/252
13/0754/03	-	-	-
13/0754/04	-	-	-
13/0754/06	-	-	-
13/0754/07	-	-	-
13/0754/08	-	-	-
13/0754/10	-	-	-
13/0754/11	-	-	-
13/0756/00	-	-	-
13/0756/01	-	-	-
13/0756/02	-	-	-
13/0767/00	POSS FAIL	-	-
13/0767/01	POSS FAIL	-	-
13/0767/02	POSS FAIL	-	-
13/0767/03	PROB FAIL	-	-
13/0767/04	FAIL	PROB FAIL	POSS FAIL
13/0767/05	POSS FAIL	-	-
13/0767/06	POSS FAIL	-	-
13/0771/00	-	-	-
13/0771/01	-	-	-
13/0779/00	-	-	-
13/0780/00	-	-	-
13/0785/00	-	-	-
13/0785/01	-	-	-
13/0785/02	-	-	-
13/0790/00	-	-	-
13/0790/01	-	-	-
13/0791/00	-	-	-
13/0791/01	-	-	-
13/0791/02	-	-	-
13/0791/03	-	-	-
13/0791/04	-	-	-
13/0791/05	-	-	-
13/0797/00	POSS FAIL	-	-
13/0797/01	PROB FAIL	POSS FAIL	-
13/0797/02	PROB FAIL	POSS FAIL	-
13/0797/03	PROB FAIL	POSS FAIL	-
13/0797/04	-	-	-
13/0797/05	-	-	-
13/0801/00	-	-	-
13/0801/01	-	-	-
13/0801/02	-	-	-
13/0801/03	-	-	-
13/0801/04	-	-	-
13/0801/05	-	-	-
13/0802/00	-	-	-
13/0803/00	-	-	-
13/0803/01	-	-	-
13/0812/00	-	-	-
13/0812/01	-	-	-
13/0815/01	-	-	-

App No. 6

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM 205/220	205/220/1559	205/252
13/0830/00	-	-	-
13/0830/01	-	-	-
13/0830/02	-	-	-
13/0832/00	-	-	-
13/0832/01	-	-	-
13/0832/02	-	-	-
13/0838/00	-	-	-
13/0865/00	-	-	-
13/0865/01	-	-	-
13/0865/02	-	-	-
13/0865/04	-	-	-
13/0872/00	-	-	-
13/0872/01	-	-	-
13/0872/02	-	-	-
13/0872/03	-	-	-
13/0872/04	-	-	-
13/0877/00	-	-	-
13/0878/00	-	-	-
13/0878/01	-	-	-
13/0878/02	-	-	-
13/0886/00	POSS FAIL	-	-
13/0888/00	-	-	-
13/0888/01	-	-	-
13/0890/00	-	-	-
13/0890/01	-	-	-
13/0890/02	-	-	-
13/0890/03	-	-	-
13/0890/04	-	-	-
13/0890/05	-	-	-
13/0897/00	-	-	-
13/0897/01	-	-	-
13/0897/02	-	-	-
13/0897/03	-	-	-
13/0898/00	POSS FAIL	-	-
13/0898/01	PROB FAIL	-	-
13/0901/00	-	-	-
13/0901/01	-	-	-
13/0902/00	-	-	-
13/0902/01	-	-	-
13/0902/02	-	-	-
13/0902/03	-	-	-
13/0902/04	-	-	-
13/0902/06	-	-	-
13/0902/07	-	-	-
13/0902/08	-	-	-
13/0902/10	-	-	-
13/0912/00	-	-	-
13/0912/01	-	-	-
13/0917/00	-	-	-
13/0917/01	-	-	-

Appendix No. 6

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM 205/220	 205/220/1559	 205/252
13/0917/02	-	-	-
13/0917/03	-	-	-
13/0922/00	-	-	-
13/0922/01	-	-	-
13/0922/02	-	-	-
13/0923/03	FAIL	FAIL	PROB FAIL
13/0927/00	-	-	-
13/0927/01	-	-	-
13/0937/00	POSS FAIL	POSS FAIL	-
13/0937/01	POSS FAIL	-	-
13/0937/02	FAIL	POSS FAIL	-
13/0937/03	POSS FAIL	-	-
13/0941/00	-	-	-
13/0941/01	-	-	-
13/0941/02	-	-	-
13/0941/03	-	-	-
13/0948/00	-	-	-
13/0948/01	-	-	-
13/0949/00	-	-	-
13/0949/01	-	-	-
13/0949/02	-	-	-
13/0949/03	-	-	-
13/0949/04	-	-	-
13/0949/05	-	-	-
13/0949/06	-	-	-
13/0950/00	FAIL	FAIL	-
13/0957/00	-	-	-
13/0957/01	-	-	-
13/0957/02	-	-	-
13/0957/03	-	-	-
13/0960/00	-	-	-
13/0960/01	-	-	-
13/0968/00	-	-	-
13/0970/00	-	-	-
13/0971/00	-	-	-
13/0971/01	-	-	-
13/0975/00	-	-	-
13/0975/01	-	-	-
13/0975/03	POSS FAIL	POSS FAIL	-
13/0975/05	-	-	-
13/0985/00	-	-	-
13/0985/01	-	-	-
13/0985/02	-	-	-
13/0989/00	-	-	-
13/0989/01	POSS FAIL	-	-
13/0994/00	-	-	-
13/0994/01	-	-	-
13/0994/02	-	-	-
13/0994/04	-	-	-
13/0995/00	-	-	-

App No. 6

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM		
	205/220	205/220/1559	205/252
13/0995/01	-	-	-
13/0995/02	-	-	-
13/0995/03	-	-	-
13/0995/04	-	-	-
13/0998/00	-	-	-
13/0998/01	-	-	-
13/1004/00	-	-	-
13/1004/01	-	-	-
13/1004/02	-	-	-
13/1004/03	-	-	-
13/1004/04	-	-	-
13/1004/06	-	-	-
13/1009/00	POSS FAIL	-	-
13/1012/00	POSS FAIL	-	-
13/1012/01	POSS FAIL	-	-
13/1013/00	-	-	-
13/1013/01	-	-	-
13/1014/00	-	-	-
13/1016/00	-	-	-
13/1025/00	-	-	-
13/1025/01	-	-	-
13/1027/00	-	-	-
13/1027/01	-	-	-
13/1027/02	-	-	-
13/1027/03	-	-	-
13/1032/00	-	-	-
13/1036/00	-	-	-
13/1038/00	-	-	-
13/1038/01	-	-	-
13/1039/00	-	-	-
13/1039/01	-	-	-
13/1039/02	-	-	-
13/1039/03	-	-	-
13/1040/00	-	-	-
13/1040/01	-	-	-
13/1055/00	-	-	-
13/1055/01	-	-	-
13/1055/02	-	-	-
13/1062/00	-	-	-
13/1076/00	-	-	-
13/1076/01	-	-	-
13/1079/00	-	-	-
13/1079/01	-	-	-
13/1079/02	-	-	-
13/1080/01DUAL	-	-	-
13/1080/01DUAL	-	-	-
13/1080/03DUAL	-	-	-
13/1080/03DUAL	-	-	-
13/1090/00	-	-	-
13/1090/01	-	-	-

App No. 6

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM		
	205/220	205/220/1559	205/252
13/1110/00	-	-	-
13/1110/01	POSS FAIL	-	-
13/1132/00	-	-	-
13/1132/01	-	-	-
13/1136/00	-	-	-
13/1136/01	-	-	-
13/1136/02	-	-	-
13/1136/03	-	-	-
13/1141/00	-	-	-
13/1155/00	-	-	-
13/1162/00	-	-	-
13/1162/01	-	-	-
13/1162/02	-	-	-
13/1164/00	-	-	-
13/1177/00	-	-	-
13/1177/01	-	-	-
13/1184/00	-	-	-
13/1184/01	-	-	-
13/1189/00	-	-	-
13/1205/01	-	-	-
13/1230/00	-	-	-
13/1230/01	-	-	-
13/1231/00	POSS FAIL	-	-
13/1232/00	-	-	-
13/1232/01	-	-	-
13/1258/01	PROB FAIL	-	-
13/1258/02	PROB FAIL	-	-
13/1263/00	-	-	-
13/1265/00	-	-	-
13/1265/01	-	-	-
13/1266/00	-	-	-
13/1266/01	-	-	-
13/1266/02	-	-	-
13/1267/00	-	-	-
13/1267/01	-	-	-
13/1267/02	-	-	-
13/1273/00	-	-	-
13/1273/01	-	-	-
13/1273/02	-	-	-
13/1273/03	-	-	-
13/1273/04	-	-	-
13/1274/00	-	-	-
13/1274/01	-	-	-
13/1274/02	-	-	-
13/1280/00	-	-	-
13/1284/03	-	-	-
13/1284/04	-	-	-
13/1287/02	-	-	-
13/1287/03	-	-	-
13/1288/00	POSS FAIL	-	-

App No 6

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM		
	205/220	205/220/1559	205/252
13/1288/01	PROB FAIL	-	-
13/1288/02	FAIL	POSS FAIL	-
13/1296/00	-	-	-
13/1296/01	-	-	-
13/1296/02	-	-	-
13/1302/00	-	-	-
13/1302/01	-	-	-
13/1302/03	-	-	-
13/1305/00	-	-	-
13/1308/00	-	-	-
13/1317/02	-	-	-
13/1317/03	-	-	-
13/1317/04	-	-	-
13/1322/00	POSS FAIL	-	-
13/1324/00	-	-	-
13/1326/00	-	-	-
13/1326/01	-	-	-
13/1326/02	-	-	-
13/1345/00	-	-	-
13/1349/00	-	-	-
13/1349/01	POSS FAIL	-	-
13/1362/00	-	-	-
13/1363/01DUAL	-	-	-
13/1363/01DUAL	-	-	-
13/1363/02DUAL	-	-	-
13/1363/02DUAL	-	-	-
13/1386/00	POSS FAIL	-	-
13/1389/00	-	-	-
13/1411/00	POSS FAIL	-	-
13/1414/01	-	-	-
13/1415/00	POSS FAIL	-	-
13/1415/02	POSS FAIL	-	-
13/1416/00	-	-	-
13/1416/01	-	-	-
13/1423/00	-	-	-
13/1433/00	-	-	-
13/1433/01	-	-	-
13/1433/02	-	-	-
13/1433/04	-	-	-
13/1442/00	-	-	-
13/1459/00	-	-	-
13/1459/01	-	-	-
13/1459/02	-	-	-
13/1459/03	-	-	-
13/1459/05	-	-	-
13/1459/06	-	-	-
13/1460/00	-	-	-
13/1460/01	-	-	-
13/1460/02	-	-	-
13/1460/03	-		

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM		
	205/220	205/220/1559	205/252
13/1460/04	-	-	-
13/1469/00DUAL	-	-	-
13/1469/00DUAL	-	-	-
13/1469/01DUAL	-	-	-
13/1469/01DUAL	-	-	-
13/1469/04DUAL	-	-	-
13/1469/04DUAL	-	-	-
13/1472/07	-	-	-
13/1472/08	-	-	-
13/1472/09	-	-	-
13/1472/10	-	-	-
13/1472/11	-	-	-
13/1480/00	POSS FAIL	-	-
13/1493/00	-	-	-
13/1498/00	-	-	-
13/1511/00	-	-	-
13/1519/03	-	-	-
13/1519/05	-	-	-
13/1531/00	-	-	-
13/1536/00	-	-	-
13/1547/00	-	-	-
13/1548/00	-	-	-
13/1548/01	-	-	-
13/1548/02	-	-	-
13/1548/03	-	-	-
13/1548/04	-	-	-
13/1567/00	-	-	-
13/1570/00	-	-	-
13/1585/00	-	-	-
13/1594/00	-	-	-
13/1594/01	-	-	-
13/1606/00	PROB FAIL	-	-
13/1609/00	-	-	-
13/1612/00	POSS FAIL	-	-
13/1612/01	POSS FAIL	-	-
13/1612/02	FAIL	POSS FAIL	-
13/1613/03	-	-	-
13/1620/00	-	-	-
13/1620/01	-	-	-
13/1620/02	-	-	-
13/1620/03	-	-	-
13/1620/04	-	-	-
13/1623/00	-	-	-
13/1624/00	-	-	-
13/1624/01	-	-	-
13/1630/00	-	-	-
13/1633/00	-	-	-
13/1644/00	-	-	-
13/1644/01	-	-	-
13/1657/00	-	-	-

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM 205/220	205/220/1559	205/252
13/1657/01	-	-	-
13/1657/02	-	-	-
13/1667/00	-	-	-
13/1667/01	-	-	-
13/1667/02	-	-	-
13/1667/03	-	-	-
13/1667/04	-	-	-
13/1667/05	-	-	-
13/1667/06	-	-	-
13/1667/07	-	-	-
13/1684/00	-	-	-
13/1698/03	-	-	-
13/1698/04	-	-	-
13/1708/00	POSS FAIL	-	-
13/1709/00	-	-	-
13/1718/00	-	-	-
13/1718/01	-	-	-
13/1729/00	-	-	-
13/1730/00	-	-	-
13/1733/00	-	-	-
13/1736/00	-	-	-
13/1740/00	-	-	-
13/1740/01	-	-	-
13/1740/02	-	-	-
13/1740/04	-	-	-
13/1740/05	-	-	-
13/1740/06	-	-	-
13/1741/00	-	-	-
13/1741/01	-	-	-
13/1761/00	-	-	-
13/1762/00	-	-	-
13/1763/00	-	-	-
13/1782/00	-	-	-
13/1782/01	-	-	-
13/1782/02	-	-	-
13/1782/03	-	-	-
13/1782/04	-	-	-
13/1782/05	-	-	-
13/1783/00	-	-	-
13/1783/01	-	-	-
13/1786/00	-	-	-
13/1786/01	-	-	-
13/1811/00	-	-	-
13/1812/00	-	-	-
13/1817/00	-	-	-
13/1817/02	-	-	-
13/1817/03	-	-	-
13/1817/04	-	-	-
13/1817/05	-	-	-
13/1817/06	-		

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM		
	205/220	205/220/1559	205/252
13/1817/07	-	-	-
13/1817/08	-	-	-
13/1817/10	-	-	-
13/1817/11	-	-	-
13/1817/14	-	-	-
13/1817/15	-	-	-
13/1817/16	-	-	-
13/1817/17	-	-	-
13/1823/00	-	-	-
13/1827/00DUAL	PROB FAIL	POSS FAIL	-
13/1827/00DUAL	-	-	-
13/1828/00DUAL	-	-	-
13/1828/00DUAL	-	-	-
13/1829/00	-	-	-
13/1839/00	-	-	-
13/1840/00DUAL	-	-	-
13/1840/00DUAL	-	-	-
13/1849/00	PROB FAIL	-	-
13/1849/01	PROB FAIL	-	-
13/1864/00	-	-	-
13/1872/00	-	-	-
13/1874/00	-	-	-
13/1880/01	-	-	-
13/1880/02	-	-	-
13/1891/00	-	-	-
13/1895/00	-	-	-
13/1897/01	-	-	-
13/1897/02	-	-	-
13/1905/00	-	-	-
13/1908/00	-	-	-
13/1910/00	-	-	-
13/1912/00	-	-	-
13/1912/01	-	-	-
13/1914/00	FAIL	PROB FAIL	POSS FAIL
13/1914/01	FAIL	PROB FAIL	POSS FAIL
13/1916/00DUAL	FAIL	POSS FAIL	-
13/1916/00DUAL	-	-	-
13/1920/02	POSS FAIL	-	-
13/1923/01	-	-	-
13/1928/00	FAIL	FAIL	-
13/1935/00	-	-	-
13/1940/00	FAIL	POSS FAIL	-
13/1944/00	POSS FAIL	-	-
13/1949/00	-	-	-
13/1956/00	-	-	-
13/1957/00	POSS FAIL	-	-
13/1958/00	FAIL	POSS FAIL	-
13/1959/00	-	-	-
13/1961/00DUAL	POSS FAIL	-	-
13/1961/00DUAL	-	-	-

App No. 6

PROBABILITY OF BOND FAILURE IN CONCENTRIC BUSHES

(For Product Groups 1,2,3,4,5,6,17,19)

BUSH No.	BONDING AGENT SYSTEM		
	205/220	205/220/1559	205/252
13/1981/00	-	-	-
13/1983/00	-	-	-
13/1983/01	-	-	-
13/1994/00	-	-	-
13/2001/00	-	-	-
13/2003/00	-	-	-
13/2004/00DUAL	FAIL	FAIL	FAIL
13/2004/00DUAL	-	-	-
13/2005/00	-	-	-
13/2005/01	-	-	-
13/2011/00	-	-	-
13/2013/00	-	-	-
13/2020/01	-	-	-
13/2020/01	-	-	-
13/2027/00	-	-	-
13/2030/00DUAL	-	-	-
13/2030/00DUAL	-	-	-
13/2036/00	-	-	-
13/2044/00	-	-	-
13/2045/00	-	-	-
13/2048/00	-	-	-
13/2053/00	FAIL	POSS FAIL	-
13/2056/00	-	-	-
13/2056/01	-	-	-
13/2070/00	-	-	-

FAIL	15	4	1
PROB FAIL	13	4	1
POSS FAIL	39	14	3

Appendix No. 7

Bush Bond Failures :- Data File

A key to the column headings in the data file is given below:-

A	Bush Number
B	Rubber Hardness (IRHD)
C	Shrinkage Stress (PSI)
D	Inner Metal Thickness (mm)
E	Inner Metal Length (mm)
F	Number of Bond Failures (Inner Metal)
G	Number of Bond Failures (Outer Metal)
H	Total Number of Parts "Tested"
I	Adhesive Key (inner metal)
J	Adhesive Key (outer metal)
K	Percent Bond Failure Level
L	Mould Group (Area)
M	Cure Time
N	Number of Mould Cavities

App No. 7

BUSH BOND FAILURES :- DATA FILE

A	B	C	D	E	F	G	H	I	J	K	L	M	N
13/0660/01	45	758	2.64	80.1	1	0	1227	1	2	0	34	20	36
13/0663/02	60	420	2.64	49.8	45	0	209	1	2	22	1	15	1
13/0663/03	70	621	2.64	49.8	69	0	134	1	2	51	1	15	1
13/0665/02	70	684	2.03	74.6	55	0	1278	4	2	4	34	12	18
13/0687/00	60	2260	11.71	244.5	1	0	28	3	2	4	23	60	1
13/0697/00	60	301	2.03	42.5	0	11	1048	5	2	1	34	8	12
13/0728/02	70	746	4.06	131.2	14	0	120	1	2	12	24	30	4
13/0742/07	55	451	2.03	45.5	1	0	4661	5	2	0	34	8	36
13/0756/01	60	668	2.64	79.8	16	0	417	1	2	4	2	15	1
13/0767/00	45	730	3.25	89.9	21	0	24	1	2	88	24	30	1
13/0767/01	55	925	3.25	89.9	7	0	163	1	2	4	24	30	1
13/0790/00	60	486	3.25	63.5	14	0	107	1	2	13	2	15	1
13/0791/00	45	62	3.25	69.9	8	35	713	1	2	6	4	20	4
13/0791/02	60	103	3.25	69.9	0	27	103	1	2	26	4	20	4
13/0791/03	70	155	3.25	69.9	45	25	268	1	2	26	4	15	4
13/0791/05	50	65	3.25	69.9	7	12	268	1	2	7	4	15	4
13/0797/02	73	1544	2.03	67.8	134	0	2351	4	2	6	32	7	12
13/0803/00	60	163	3.25	114.3	66	19	183	1	8	46	24	30	1
13/0865/01	60	56	3.25	50.8	37	0	445	1	2	8	4	20	1
13/0877/00	60	115	2.64	38.1	4	0	134	6	2	3	1	15	1
13/0888/00	75	633	2.03	40.6	0	4	54	6	2	7	1	15	1
13/0897/02	60	211	2.64	82.8	37	30	7036	1	2	1	34	10	12
13/0898/01	70	1520	2.03	64.3	15	0	15	1	2	100	1	15	1
13/0901/00	60	230	4.06	68.3	11	0	153	1	2	7	1	15	1
13/0902/01	60	110	1.22	20.2	27	8	492	17	2	7	1	15	7
13/0902/10	60	110	1.22	20.2	11	0	329	17	2	3	1	15	7
13/0922/02	45	155	3.25	60.1	5	0	161	1	2	3	1	15	1
13/0937/01	60	1248	4.06	73.0	12	0	114	1	2	11	1	15	1
13/0960/01	60	184	2.64	38.1	36	0	2574	4	2	1	34	9	18
13/0971/00	60	262	1.63	21.9	12	0	44	6	2	27	99	15	1
13/0989/00	60	668	3.25	95.3	46	0	833	1	2	6	4	20	3
13/0994/01	55	79	1.63	34.7	35	0	585	6	2	6	34	10	3
13/0995/01	60	92	3.25	98.4	67	127	3828	1	2	5	24	30	4
13/0998/01	60	167	1.63	36.8	15	0	22772	6	2	0	34	6	42
13/1016/00	60	208	4.06	67.8	1	0	68	1	2	1	4	20	1
13/1025/00	50	230	3.25	68.3	31	57	429	1	2	21	4	20	1
13/1039/01	55	667	4.06	128.5	6	16	38	1	2	58	4	20	1
13/1039/02	60	789	4.06	128.5	53	1	196	1	2	28	4	20	1
13/1110/00	60	828	4.06	95.3	49	40	370	1	2	24	1	15	1
13/1162/00	45	25	2.64	62.0	32	0	445	3	2	7	24	45	1
13/1230/00	55	81	2.03	19.3	0	175	2982	1	2	6	34	6	18
13/1265/01	60	99	2.03	20.1	0	4	570	6	2	1	99	15	1
13/1273/01	60	459	2.03	36.6	39	0	142	1	2	27	34	10	6
13/1273/04	70	677	2.03	36.6	0	26	332	1	2	8	34	10	6
13/1288/00	55	1295	3.25	98.8	94	25	804	1	2	15	4	20	1
13/1296/00	55	56	3.25	48.4	52	249	2507	6	2	12	4	20	7
13/1302/00	60	567	4.92	92.1	6	6	17	6	2	71	4	20	1
13/1305/00	60	103	1.63	31.2	2	0	6154	4	2	0	34	8	36
13/1326/01	60	286	4.06	123.8	0	3	9	7	2	33	4	20	1
13/1349/00	50	690	4.06	66.0	10	0	54	6	2	19	4	20	4
13/1349/01	60	1007	4.06	66.0	7	0	80	6	2	9	4	20	4
13/1362/00	45	39	9.75	54.0	59	3	243	10	1	26	24	30	1
13/1411/00	60	1348	2.03	62.7	79	0	2766	4	2	3	34	9	36
13/1414/01	70	1027	10.68	208.3	3	0	119	11	2	3	23	90	1
13/1415/00	60	1317	4.06	127.6	15	0	78	1	2	19	4	20	1
13/1433/02	45	41	1.22	25.4	41	40	196	12	4	41	1	15	4
13/1459/06	60	137	1.63	33.3	45	23	5796	6	2	1	34	8	12
13/1460/02	70	256	1.63	28.6	115	31	3118	1	2	5	34	6	12
13/1469/01D	60	568	4.06	43.3	47	0	1479	1	2	3	1	15	1
13/1469/01D	60	258	1.22	41.2	47	0	1479	1	2	3	1	15	1
13/1469/01D	60	568	4.06	43.3	47	0	1479	3	2	3	1	15	1

BUSH BOND FAILURES :- DATA FILE

App No. 7

A	B	C	D	E	F	G	H	I	J	K	L	M	N
13/1469/01D	60	258	1.22	41.2	47	0	1479	3	2	3	1	15	1
13/1472/08	55	372	2.64	111.1	15	2	91	1	2	19	4	20	3
13/1472/10	60	443	2.64	111.1	120	20	698	1	2	20	4	20	3
13/1519/03	40	61	2.03	66.2	1069	227	12997	4	3	10	34	14	25
13/1536/00	55	79	2.03	60.4	29	0	2475	4	3	1	6	20	55
13/1548/04	60	588	4.06	88.9	1685	357	18961	1	2	11	34	16	25
13/1606/00	60	1622	2.64	45.9	12	2	202	3	2	7	1	15	1
13/1620/00	60	195	2.03	46.0	99	0	2556	6	2	4	34	10	11
13/1623/00	55	63	4.88	52.7	10	1	270	1	2	4	1	15	1
13/1644/00	60	55	2.03	38.1	42	0	1267	5	2	3	34	10	36
13/1667/06	55	302	1.63	34.9	1	0	80	6	2	1	1	15	1
13/1684/00	60	39	1.68	22.2	1608	256	14893	13	2	13	2	15	10
13/1708/00	60	943	4.83	82.5	29	7	78	6	2	46	4	20	3
13/1709/00	60	861	4.06	78.5	198	0	9302	1	3	2	34	12	28
13/1730/00	60	273	2.03	21.7	192	0	1328	6	2	14	34	15	3
13/1782/03	60	72	2.03	31.8	0	133	1140	6	2	12	34	8	42
13/1811/00	60	658	4.06	108.0	53	5	372	7	2	16	24	30	3
13/1812/00	50	53	1.63	64.7	470	524	30893	5	9	3	6	20	53
13/1827/00D	60	1712	2.03	55.3	80	292	5450	5	2	7	34	10	25
13/1827/00D	60	680	1.63	44.5	80	292	5450	5	2	7	34	10	25
13/1827/00D	60	1712	2.03	55.3	80	292	5450	3	5	7	34	10	25
13/1827/00D	60	680	1.63	44.5	80	292	5450	3	5	7	34	10	25
13/1828/00D	60	408	2.03	50.3	73	0	9656	1	2	1	34	10	12
13/1828/00D	60	196	1.63	41.2	73	0	9656	1	2	1	34	10	12
13/1828/00D	60	408	2.03	50.3	73	0	9656	3	2	1	34	10	12
13/1828/00D	60	196	1.63	41.2	73	0	9656	3	2	1	34	10	12
13/1849/00	60	1409	2.03	85.7	1	5	582	12	2	1	34	18	25
13/1864/00	50	620	2.64	85.7	350	84	10328	1	2	4	6	20	35
13/1895/00	50	21	1.63	9.8	4131	341	52796	1	2	8	2	15	14
13/1897/01	55	180	2.03	51.3	122	0	10772	5	2	1	11	15	56
13/1905/00	50	361	2.64	73.0	24	0	1898	1	2	1	4	20	3
13/1916/00D	45	1290	2.03	56.0	2876	257	19002	4	2	16	11	15	70
13/1916/00D	45	452	1.22	44.4	2876	257	19002	4	2	16	11	15	70
13/1916/00D	45	1290	2.03	56.0	2876	257	19002	3	3	16	11	15	70
13/1916/00D	45	452	1.22	44.4	2876	257	19002	3	3	16	11	15	70
13/1920/02	70	958	6.82	64.0	132	475	4320	1	2	14	34	20	25
13/1928/00	70	3220	6.00	108.0	72	1	4869	14	8	1	23	45	7
13/1935/00	60	591	7.62	115.0	109	57	2486	15	2	7	24	30	3
13/1949/00	60	806	1.63	56.5	930	42	17903	4	2	5	34	9	42
13/1961/00D	40	741	2.03	74.8	1466	73	19612	4	2	8	11	15	67
13/1961/00D	40	497	1.22	41.6	1466	73	19612	4	2	8	11	15	67
13/1961/00D	40	741	2.03	74.8	1466	73	19612	3	3	8	11	15	67
13/1961/00D	40	497	1.22	41.6	1466	73	19612	3	3	8	11	15	67
13/1983/00	50	86	2.50	74.0	551	534	36789	5	5	3	6	20	53
13/1983/01	80	252	2.50	74.0	124	96	2565	6	2	9	1	15	1
13/2001/00	50	36	2.64	44.5	20	3	283	10	6	8	4	20	1
13/2003/00	60	222	4.06	34.5	2402	154	16206	4	2	16	11	15	53
13/2004/00D	40	4229	2.03	74.8	963	137	27826	4	2	4	11	15	45
13/2004/00D	40	462	1.22	41.6	963	137	27826	4	2	4	11	15	45
13/2004/00D	40	4229	2.03	74.8	963	137	27826	3	2	4	11	15	45
13/2004/00D	40	462	1.22	41.6	963	137	27826	3	2	4	11	15	45
13/2005/00	55	36	3.25	48.4	1	3	693	6	2	1	4	20	3
13/2005/01	60	46	3.25	48.4	1	0	451	6	2	0	4	20	3
13/2013/00	60	437	1.63	37.8	22	0	2495	4	2	1	34	10	42
13/2030/00D	40	238	3.66	95.1	37	0	480	8	2	8	24	30	1
13/2030/00D	40	142	1.63	66.6	37	0	480	8	2	8	24	30	1
13/2030/00D	40	238	3.66	95.1	37	0	480	3	2	8	24	30	1
13/2030/00D	40	142	1.63	66.6	37	0	480	3	2	8	24	30	1
13/2036/00	60	468	3.66	76.3	385	232	2229	1	2	28	1	15	1
13/2048/00	60	980	3.66	133.4	243	32	3037	1	2	9	23	45	4
13/2053/00	60	1890	7.74	133.4	152	1	1137	1	2	13	4	20	1

Large Scale Trial — Results

Appendix No. 8.1

Week One				13 Week Control Data
Product Number	Batch Size	Number of Parts Scrapped Codes 20 & 49	% Bond Failure	% Bond Failure
13/1709	1385	38	2.74	2.38
1852	4453	69	1.55	1.15
1863	142	0	0	0
1916	5338	528*	9.89	3.32
1961	8209	0	0	5.40
1983	2220	115*	5.18	0.73
2028	1496	0	0	1.31
2051	1225	0	0	3.16
0900	22	4	18.18	3.65
2036	647	403*	62.29	8.95
1680	128	0	0	0.10
2076	1709	0	0	0.02
2003	3059	160	5.23	15.10
2004	8048	0	0	3.05
2013	1448	7	0.48	0.68
2028	1496	0	0	1.31
0960	356	0	0	0.05
1411	3314	24	0.72	0
1852	4453	69	1.55	1.15
1897	8680	72	0.83	-
1295	115	0	0	0
1180	43	0	0	0.51
2077	77	0	0	0
2037	85	5	5.88	29.43
1006	115	0	0	0.44
1285	121	5	4.13	1.01
1895	8660	245	2.83	9.78
1935	219	39*	17.81	56.00
1999	204	0	0	0.10
2005	435	0	0	0
1472	175	0	0	14.18
1548	1633	0	0	4.84

App. No. 8.1 (Contd)

Week One				13 Week Control Data
Product Number	Batch Size	Number of Parts Scrapped Codes 20 & 49	% Bond Failure	% Bond Failure
13/1549	6	0	0	0
1596	245	0	0	100
1620	1108	0	0	0
1684	603	75	12.44	0.32
1804	3747	0	0	0.01
1165	12	1	8.33	11.04
1284	356	16	4.49	84.01
1355	298	18	6.04	0.61
0791	880	74*	8.41	12.48
0897	4554	37	0.81	0
0917	612	0	0	0
TOTAL	82131	2004	2.440	3.395

App No. 8.1

Week Two				13 week Control Data
Product Number	Batch Size	Number of Parts Scrapped Codes 20 & 49	% Bond Failure	% Bond Failure
13/1709	2925	23	0.79	2.38
1812	3578	0	0	0
1838	1913	0	0	0
1852	2607	0	0	1.15
1863	1959	0	0	0
1916	1320	132*	10.00	3.32
1961	9439	236*	2.5	5.40
1983	10021	267*	2.66	0.73
2028	1183	0	0	1.31
2051	2305	0	0	3.16
0960	308	0	0	0.05
1155	1575	0	0	0
1305	1440	0	0	0
1829	3960	0	0	0.37
1960	330	79	23.94	8.77
2004	14188	520	3.67	3.05
2003	1667	0	0	15.10
2053	160	12	7.5	56.88
1296	350	0	0	10.69
2036	119	47	39.50	8.95
1680	94	0	0	0.10
2076	1641	13	0.79	0.02
0728	52	2	3.85	5.97
2001	77	4*	5.19	100.00
0801	1748	0	0	0
0812	180	0	0	0.55
0872	20	0	0	5.04
0995	1204	43	3.57	2.67
1165	51	3	5.88	11.04

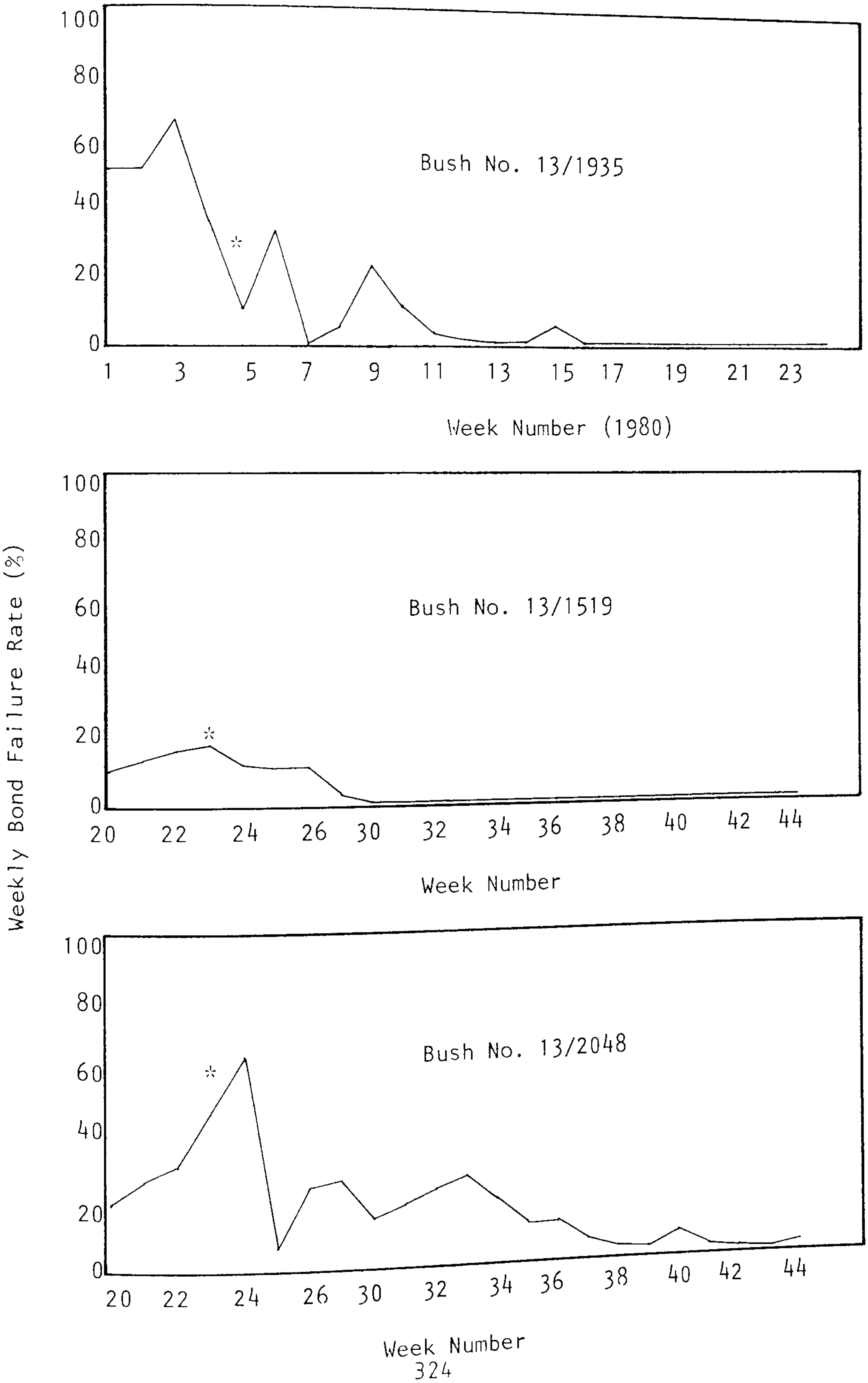
App No. 8.1 (Contd)

Week Two				13 week Control Data
Product Number	Batch Size	Number of Parts Scrapped Codes 20 & 49	% Bond Failure	% Bond Failure
1284	78	2	2.56	84.01
1295	20	0	0	0
1355	305	13	4.26	0.61
1459	432	0	0	0
1460	3112	0	0	0
1472	744	102	13.71	14.18
1548	2440	16	0.66	4.84
1596	1631	44	2.70	100.00
1684	1398	121	8.66	0.32
1804	1960	0	0	0.01
1864	1140	0	0	0
1895	10858	331	3.05	9.75
1935	510	7	1.37	56.00
2005	98	4*	4.08	0
1180	90	0	0	0.51
2037	152	1	0.66	29.43
2048	252	18	7.14	20.34
1006	299	0	0	0.44
1285	89	0	0	1.01
1515	120	0	0	-
Total	92148	2040	2.214	3.812

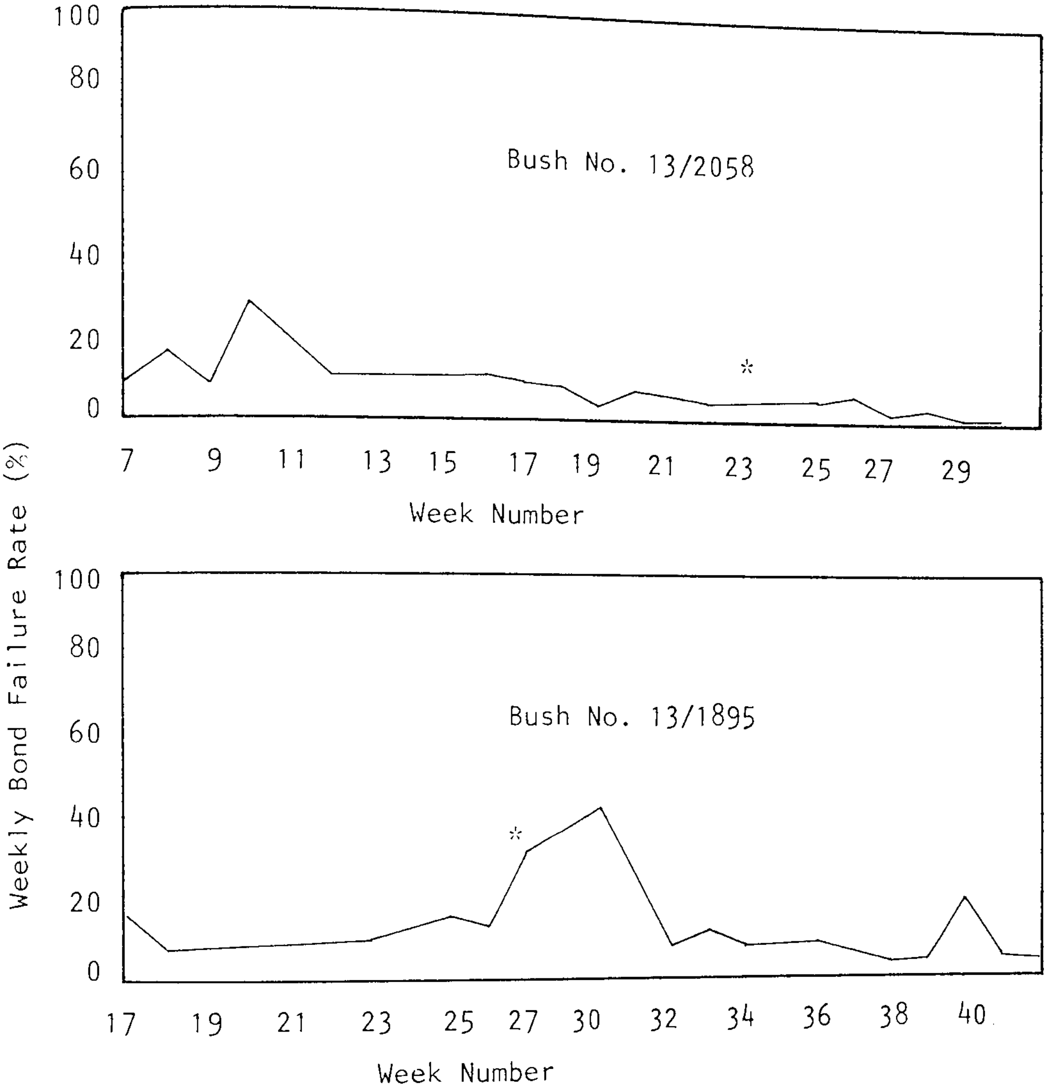
* Most failures on the outer metal; not prepared with Chemlok 252

Some Examples of the Reduction in Bond Failure Levels

Appendix No. 8.2



App. No. 8.2



* Chemlok 205/Chemlok 252 introduced on this product.

NB: 2-3 week delay between manufacture and testing

Appendix No. 8.3

Introduction of Chemlok 205/Chemlok 252:Financial Appraisal:Notes

1. Until the separation of most bushes into a completely self contained G.T.cell (expected by 1983), bushes pass through the general adhesive application areas. Therefore the adhesive change also applies to non-bushes and material, labour and overhead costs given in this appendix relate to the application of C205/C252 to the majority of Metalastik products except where stated.

2. The detailed appraisal applies only to the change from the main adhesive (Chemlok 205/Chemlok 220/Thixon AP1559) to C205/C252. However, this change accounts for over 85% of production in the main factory.

3. The replacement of small usage specialised adhesive systems is considered only in outline and no cost values are computed.

4. Prices and costs are based on the period 1.1.79 - 31.12.79 and predicted savings and costs do not reflect the subsequent industrial recession occurring after the introduction of Chemlok 252.

Material Costs

		C205/C220/AP1559			C205/C252		
		Price (£/litre)	Annual Usage (litre)	Annual Cost(£)	Price (£/litre)	Annual Usage (litre)	Annual Cost (£)
SPRAYING	1st Adhesive coat	1.92	5,280	10,137	1.920	5,280	10,137
	Methyl Ethyl Ketone	0.417	4390	1,880	0.417	4390	1,880
	2nd Adhesive coat	2.67	12,800	34,180	3.60	12,800	46,080
	Toluene	0.245	8,000	1,960	0.245	10,900	2,670
	Xylene	0.475	700	330	0.475	2,800	1,330
	3rd Adhesive Coat	2.50	8,200	20,500	-	-	-
	Petroleum Spirit	0.235	2,340	550	-	-	-
DIPPING	1st Adhesive coat	1.92	3,360	6,450	1.92	3,360	6,450
	Methyl Ethyl Ketone	0.417	20,500	8,540	0.417	20,500	8,540
	2nd Adhesive Coat	2.67	7,700	20,560	3.60	7,700	27,720
	Toluene	0.245	14,000	3,430	0.245	14,000	3,430
	3rd Adhesive Coat	1.59	5,500	8,750	-	-	-
	Petroleum Spirit	0.235	9,460	2,200	-	-	-
		Total Cost = £119,460 p.a.			Total Cost = £108,230 p.a.		

Labour Costs

Direct labour costs are only calculated for the spraying operation. For dipping, labour costs are included in the variable overhead cost apportioned to each part.

The following comparison of labour costs assumes that the unit labour cost will be reduced by one quarter when a 3 coat adhesive system is replaced by only 2 coats.(Based on the standard times for metal jigging, the actual spraying and the storage of metals in tote bins).

Spraying Area	Annual* Labour Cost (205/220/1559)	Annual* Labour Cost (205/252)	Approx Number Parts(p.a.)
Hand Spraying	6080	4560	1.8M
Automatic (TM 321)	990	740	1.0M
" (TM 401)	1040	780	0.5M
Total	£8110	£6080	

Total Savings = £2030

*Concentric Bushes only.

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Variable Overheads

Adhesive Spraying*

Overhead Allocation rate (Hand spraying) 1.5 p/sq in''/part
" " " (Automatic TM 321) 0.6 p/sqin''/part
" " " (Automatic TM 401) 0.35 p/sq in''/part

(Assume allocation rate reduced by third for 3 → 2 coats)

Spraying Area	Annual Overhead cost (205/220/1559)	Annual Overhead cost (205/252)	Annual Number Parts (p.a.)
Hand Spraying	27,000	18000	1.8 M
Automatic(TM 321)	6,000	4000	1.0 M
Automatic(TM 401)	1,750	1170	0.5 M
Total Cost	£34,750	£23,170	

Annual Saving = £11,580

Annual Saving*
(less material savings) = £4140

* Concentric bushes only

App. No. 8.3

Variable Overheads

Adhesive Dipping

The standard overhead allocation of 8.28 pence/square inch/part includes the adhesive material costs. For this study, material costs are treated separately and are deducted from the annual overhead cost given below:

Overhead allocation rate = 8.28 p/sq in''/part

Average surface area of bush outer metals = 30.45 sq in''

Approximate number of bush metals per annum = 3.0 M

(Assume allocation rate reduced by one third for 3 → 2 adhesive coats).

	3 coats (205/220/1559)	2 coats (205/252)
Annual Overheads*	75,640	75,640
Annual Overheads* (less material costs)	25,710	16,810

Annual Savings* = £8900

* Concentric bushes only

App. No. 8.3

Elimination of Specialized Adhesives

A number of specialized adhesives are purchased in relatively small quantities.

e.g. Chemlok 234 Annual Usage (1979) = 25 litres
Chemosil X2311 " " " = 430 "
(compared with Chemlok 220 " " ≏ 25,000 litres)

a) As small quantities are purchased, these adhesives carry a considerable price surcharge.

b) Small usage adhesives are normally brushed onto the metal surface, incurring heavy labour charges compared to spraying or dipping, e.g.

Brushing	3.0 - 4.0 pence/ part
Spraying	0.2 - 0.4 " "

c) Extra overhead charges result from the storing, handling and organisation of small quantities of adhesives.

Chemlok 252 is very versatile in respect of the range of rubber compounds (polar - non polar) to which it will bond and therefore could replace most of the small usuage adhesives.

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Savings Due to a Reduction in Bond Failure Scrap Levels

		£
Metalastik Annual Scrap Cost	≏	700,000
Annual Scrap(due solely to bond failure)	"	250,000
Annual Scrap(due solely to bond failure in concentric bushes)	"	125,000

Therefore a potential saving exists of £125,000* p.a. in respect of bush bond failure.

The large scale trial of C205/C252 indicated that bush bond failure levels would be reduced by approximately 38% following the introduction of the new material. This would produce an annual saving in scrap costs of about £47,500

Further measures taken as a result of the recommendations contained herein would produce extra savings in bond failure scrap costs although not as dramatic as shown above.

*Hidden costs due to the need for 100% testing, rescheduling and reloading, reclaimation of large metal components and the disposal of scrap parts are not included in this sum.

Appendix No. 8.4

Possible Reduction in Cure Times (Using Chemlok 252)

Hydramoulds

Bush Number	Rubber Compound	Cure Time/ Temperature (minutes/°C)	Bond Condition
13/1411	02x60	9 @ 165*	Good Bond
"	"	8 @ 165	Failure
"	"	7 @ 165	"
13/1548	02x60	18 @ 165*	Good Bond
"	"	13 @ 165	" "
"	"	10 @ 165	Failure
13/1709	02x60	12 @ 165*	Good Bond
"	"	10 @ 165	" "
"	"	8 @ 165	Failure
13/1864	01x50	14 @ 165*	Good Bond
"	"	12 @ 165	" "
"	"	10 @ 165	Failure
13/1920	01x70	20 @ 165*	Good Bond
"	"	15 @ 165	" "
"	"	10 @ 165	Failure
13/1949	16x60	9 @ 170*	Good Bond
"	"	8 @ 170	? Failure
"	"	7 @ 170	Failure

Conventional Transfer Moulds

Bush Number	Rubber Compound	Cure Time/Temperature (minutes/^{o}C)	Bond Conditions
13/791	16x50	20 @ 170*	Good Bond
"	"	15 @ 170	" "
"	"	10 @ 170	Failure
13/1039	01x60	20 @ 170*	Good Bond
"	"	15 @ 170	" "
"	"	10 @ 170	Failure
13/1288	01x55	18 @ 170*	Good Bond
"	"	15 @ 170	" "
"	"	10 @ 170	Failure
13/1684	01x60	15 @ 170*	Good Bond
"	"	13 @ 170	" "
"	"	11 @ 170	" "
"	"	9 @ 170	Failure
13/2004	16x40	15 @ 170*	Good Bond
"	"	13 @ 170	" "
"	"	10 @ 170	Failure
13/2036	16x60	15 @ 170*	Good Bond
"	"	13 @ 170	" "
"	"	11 @ 170	? Failure

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"Problem" Products

Bush Number	Rubber Compound	Cure Time/Temperature (minutes °C)	Bond Condition
13/687	01x60	60 @ 153*	Good Bond
"	"	40 @ 153	" "
13/1928	01x70	45 @ 170*	Good Bond
"	"	30 @ 170	" "
"	"	25 @ 170	" "
"	"	20 @ 170	Failure
13/1935	16x60	30 @ 170	Good Bond
"	"	30 @ 160*	" "
"	"	25 @ 170	" "
"	"	20 @ 170	" "
"	"	15 @ 170	" "
13/2045	16x60	45 @ 160	Good Bond
"	"	30 @ 160	" "
"	"	25 @ 160	" "
"	"	20 @ 160	Failure
13/2053	16x60	45 @ 170*	Good Bond
"	"	30 @ 170	" "
"	"	25 @ 170	Failure
"	"	20 @ 170	" "

* Present cure conditions

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