WELDING MILD STEEL TO ALUMINIUM
AND ITS ALLOYS.

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SYNOPSIS.

There is an increasing need - in various industries - for a reliable joint between aluminium and steel. Part I of this report is concerned with the development of a welding technique to accomplish this. The effects of varying the practical conditions of welding are discussed. The first part of the investigation resulted in the conclusion that a tin, zinc or aluminium coating on the steel provided suitable conditions for a satisfactory joint to be made by means of an inert-gas welding technique. In Part II, a study of the metallurgical considerations related to the use of these metals as buffer coatings, is reviewed. In addition, a section of the work has been directed towards establishing the relationship between bead geometry and weld strength.

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1. INTRODUCTION.

There are increasing demands from all branches of the engineering industry for reliable techniques which can be applied to the joining of dissimilar metals and alloys. Applications are arising in the nuclear field, refrigeration industry, rail transport, ship building, the motor industry, and the electrical engineering industry. For example, in the electrical field, aluminium bus bars are used extensively and are connected to copper by carefully designed bolted joints. However, where elevated temperatures are encountered, a welded joint is needed to provide good service. Bolted joints experiencing high temperatures or thermal cycling are often found to be unsatisfactory because of the gradual deformation of the aluminium under compression, coupled with oxidation of the contact surfaces. Copper and aluminium can be joined satisfactorily by soldering, brazing, electric arc or pressure welding. Considerable care must be exercised in the design of the joint. Copper is also joined to aluminium, in the shape of rod and tube, by flash welding techniques and industry now makes full use of this process. As a result of this welding operation, only the ejected flash material contains the brittle constituents of low melting point, while the joints are ductile. Similar success has not been obtained in joining aluminium to steel in this way for the brittle iron-aluminium constituents have high melting points and tend to be retained at the joint interface rather than be ejected into the flash during the pressure cycle.

As an example of the joining of steel to aluminium on a commercial scale, evaporators for gas refrigerators are constructed from coils of seamless mild steel tubes and joined to thick aluminium plates by brazing. A suitable flux is of vital importance and a satisfactory furnace atmosphere necessary. Aluminium has been successfully brazed to stainless steel to make cylinders from material of 0.030 in. thickness in each case, when the two halves are joined together by a lap type of brazed joint. Rapid heating and cooling is required to obtain a sound joint and there is danger of collapse of components at the joint if cooling is not sufficiently fast.

Pressure welding requires the application of deforming pressure at any temperature below the melting point of the components and solid phase methods for bonding aluminium to steel have been investigated.

Resin bonding may be employed as a process of making metal-to-metal or non-metal joints by means of organic or resinous cements, generally with the application of heat and pressure. A large number of adhesives, both cold and hot-setting, are commercially available in this country. The strength developed depends markedly upon the adhesive but also on the joint design. Aluminium has been joined to brass, stainless steel, and to other metals and alloys in this way, but it is recommended that thorough testing should be carried out, particularly if service at elevated temperatures is contemplated. Aluminium has also been joined to non-metallic materials such as rubber, plastics, plywood and glass by the use of adhesives.

A dissimilar metal joint can be regarded as one in which the chemical composition of one parent material is quite different from the other. For the purpose of this report the joining of aluminium to copper is regarded as an example of dissimilar metal joining, but not the joining of aluminium to Duralumin (Al-4% Cu alloy). The necessity to use a dissimilar metal joint can arise from economic or technical considerations, or a combination of both.

The purpose of this investigation is to determine the practical conditions necessary for the production of a satisfactory weld between mild steel and aluminium or aluminium alloy, and then to carry out further work of a more fundamental nature on the microstructure and geometry of the weld. The second part of the work should enable a relationship to be established between the mechanical properties of the weld, metallurgical structure, and weld bead geometry. Part I of this report is, therefore, concerned with the development of a welding technique to achieve a reliable joint between mild steel and aluminium, and deals mainly with practical aspects and test results. The more fundamental work undertaken is described in Part II. There are two separate literature surveys, the first dealing with published and private information concerned directly with welding technique, and that in Part II with information relative to the physical metallurgy of the welds.

PART I.

2. LITERATURE SURVEY.

In the field of dissimilar metal joining, only a very limited amount of work has been reported. The reason for this is thought to be due to the difficulty of successfully joining dissimilar material, particularly aluminium to steel, and that, up to the present time, there have been few opportunities for industrial application.

The most interesting paper studied, concerned the joining of one inch thick steel and aluminium plate.[1] Gas and argon arc welding equipment was used, and the mild steel was tinned with a 91% tin-9% zinc coating. The majority of tests were made using the argon arc process and it was found that during the welding operation, the tinned steel surface required shielding from the arc by manipulation of the filler rod. If this was not done, the tin coating was burnt and the molten filler metal was therefore unable to wet the surface.

Filler materials, Alcan 56* (aluminium-5% magnesium) and Alcan 2S (pure aluminium) were found to be unsatisfactory. Alcan 35S (aluminium-10% silicon) and Alcan 33S (aluminium-5% silicon) were compared. Although joint quality was equally good in both cases, the aluminium-10% silicon material required a skill in excess of that obtainable from welders under industrial conditions. The experiments showed that preheat temperatures and welding current were critical.

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*Trade name - Aluminium Company of Canada.

The following table indicates the procedure for a lap joint between one inch thick tinned steel and one inch thick commercially pure aluminium.

Table I.

Current	Electrode dia.	Filler rod and dia.	Argon flow.	Preheat Temperature	
				Al.	Steel
360-370 amps.	$\frac{1}{4}$ in.	Alcan 33S $\frac{1}{4}$ in.	20 ft^3/h	216°C	310°C

The use of electroplated tin coated steel was found to give satisfactory joints with a similar technique. However, it was necessary to increase the preheat temperature for the steel by 50°C to facilitate wetting of the surface by the aluminium filler material.

Stainless steel was also coated with the tin-zinc alloy and welded to an aluminium alloy. No difficulty in making such joints is reported.

Metallographic examination of an oxy-acetylene joint between mild steel and aluminium, using the aluminium-5% silicon rod, revealed a layer of brittle aluminium-iron compounds, the thickness varying between 0.00025 in. and 0.00065 in. Cracks in this layer were well defined but there was no evidence of a tin rich zone. With an argon tungsten arc weld, using the same filler material, a thin, even layer of brittle compound was observed but, unlike that of the gas weld, this was smooth and free from defects, having an average thickness of 0.00015 in.

Again, no positive evidence of a tin rich zone was detected. An electroplated tin coated mild steel-aluminium bond, produced by argon arc welding, also possessed a thin intermetallic layer.

Although some useful information has resulted from the above work, no detailed investigation of any of the various aspects of steel-aluminium joining, is apparent. For example, a number of other metals, in addition to the tin alloy or tin, could have been used to coat the steel. The metallographic work might have been extended to investigate more fully the intermetallic compounds produced, so that their effects on weld structure and strength could have been determined. Again, the type of crack observed in the joint produced by oxy-acetylene welding is not mentioned. The author will demonstrate elsewhere (Section 4.2.2 Table V) that severe cracking occurred in welds when the 10% silicon rod was used in the present investigation.

In a review of the methods available for joining aluminium to other metals, Miller[2] concludes that an aluminium coating on the steel is the best surface preparation prior to actual joining of the dissimilar materials. Fusion and non-fusion methods, including resin bonding are briefly discussed. Hard soldering with zinc or zinc-base alloys is particularly mentioned as showing considerable promise for joining ferrous and copper alloys to aluminium. Flash welding aluminium to ferrous alloys is not recommended. Only very general comments have been made in this paper and there is little discussion of the many factors important in dissimilar metal joining, such as joint strength, ductility or corrosion resistance.

In patent specifications, Grenell[3] describes the coating of steel tubes with aluminium, followed by use of the inert-gas process for welding them to aluminium. Unfortunately, the available technical details do not allow a full assessment of the work to be made. Another patent description[4] is concerned with connections between aluminium and copper or steel, where electrical conductivity and strength are important factors. This would be the case for aluminium bus bar connections with copper flex or steel connector bars on electric smelting furnaces, for the reduction of aluminium. The technique described employs a buffer metal layer on the copper or steel member and the tungsten arc inert-gas welding process. Various silver alloys of the high temperature brazing type were found to provide satisfactory results. Compositions of these alloys are shown below.

Table II.

Composition (per cent.)

Ag	Zn	Cu	Cd	Ni	Mn
45	16	15	24	-	-
50	15.5	15.5	16	3	-
75	25	-	-	-	-
85	-	-	-	-	15

It is indicated that it is extremely difficult to produce a satisfactory bond between the aluminium and silver layer at a welding temperature satisfactory for the aluminium unless the copper or steel component is preheated (400-500°F). The filler material for both the aluminium-steel and aluminium-copper joints was aluminium.

In the resistance joining field, Hess and Nippes[5] experimented with sheet aluminium joined to S.A.E.4140 (an aircraft type steel - approx. 0.4%C, 1%Cr and 0.3%Mo). The investigation showed that it was possible to secure a satisfactory bond between the two materials, by resistance welding, if the steel was first coated with silver by an electroplating process. Actual tensile testing of the welds was found to be the only practical way of evaluating the brittleness of the iron-aluminium compounds at the interface.

In both the above cases, silver or a silver rich alloy, was used as a buffer layer on the steel. Although in this investigation the author has demonstrated that aluminium-steel joints can be made if the steel is coated with silver, the mechanical properties cannot be regarded as satisfactory (Table V). Silver plating is also expensive in comparison with, for example, aluminising and, in this respect, it seems likely that the joining of aluminium to silver coated steel would be regarded industrially as an uneconomic technique. This point has not been argued by these workers. It would have been helpful if there had been a detailed discussion on the strength of the welds produced by the tungsten-arc inert-gas process and resistance welding procedures.

Miller and Mason[6] have investigated tensile, shear, bursting and fatigue strengths of argon shielded tungsten-arc welded joints between aluminium and aluminium coated stainless steel tubes. They found that an aluminium coating was the most satisfactory surface preparation for steel prior to brazing or welding it to aluminium. Joint preparation and design, post heating, cyclic thermal shock and corrosion resistance, are discussed. Aluminium-steel joints of lap weld design were made and tested; the average tensile strength compared favourably with the typical tensile strength of the aluminium or aluminium alloy. Similarly, the average bursting strength of tube joints approximated the bursting strengths of the parent aluminium tube. The present author will show in Section 4.4.1 that butt welded tube joints are capable of much greater strengths than lap welds. This is not apparent from study of the paper by Miller and Mason and it is felt that the work could have been usefully extended to cover other joint designs.

These investigators had no data available, at the time of writing, on the effect of post heating the arc-welded aluminium-steel joints. Data were available, however, in published literature on pressure welded and cast-bonded joints. They have assembled some of this information into new relationships that correlate the effect of postheating on all types of aluminium-steel joints. This information indicates that the shear strength of arc-welded material is unlikely to be impaired by lengthy exposure to temperatures below approximately 500°F.

Other workers[7,8] have examined the effect of subsequent heat treatment upon bond strength during an investigation of the solid phase bonding of aluminium alloys to steel. They point out that post heating of welds between aluminium and steel would, under proper conditions, increase the tensile strength of such joints. Too high a temperature or too long a time at elevated temperature, however, would result in a decrease in joint strength.

Tylecote[8] found that heat treatment for thirty minutes at 400°C has some beneficial effect on the strength of aluminium-steel pressure welds made with low deformation. However, for a heat treatment period of thirty minutes, embrittlement leading to loss of shear strength appears at 500°C.

Very little seems to be known about the mechanism of this phenomenon but it is thought that the decrease in shear strength is probably due to diffusion, resulting in an increase in the thickness of the brittle aluminium-iron compound.

Solid phase methods for joining or bonding aluminium to steel are not so well known as methods involving a liquid phase in the aluminium. Cooke and Levy[7] have investigated three procedures for joining, using twisting, hot press and shear techniques. High mutual solubility between two metals in the solid state is commonly desirable in solid-phase bonding, for the formation of a satisfactory joint.

In the twisting procedure, annealed specimens, 1 inch in diameter and 6 inches in length, were placed in a press, end to end. Pressure was maintained until the desired bonding temperature was attained. The steel bar was then twisted through an arc of about 180° and some spiral grain flow was formed in the light alloy. With the hot press procedure, specimens, 1 inch diameter by 1 inch long, were assembled in sleeve dies and heated, while pressures of 2,000-3,000 p.s.i. were maintained and then increased to actual bonding pressures. In the case of the shear technique, bars were machined with tapers varying from $2^{o}-10^{o}$, and the specimens inserted in sleeve dies after heating and pressed until bonded.

Although a number of variables were investigated, the only one relevant to the present investigation was the effect of heat treatment and no fundamental theory was produced to explain the observations.

The metal arc process has been used to join aluminium to steel. A problem arises here from the fact that the fluxes which must be used for aluminium welding are not good fluxes for steel. It is suggested by van Someren[9] that this difficulty can be overcome by aluminium spraying the steel and then welding the dissimilar metals by means of aluminium-silicon electrodes. He carried out a number of tests and found that adequate joint strength could be obtained. The present author, during this investigation, has not found that a coating of aluminium applied by metal spraying produces a satisfactory buffer film. Satisfactory wetting and spreading of molten filler metal did not occur with metal sprayed finishes although several different aluminium alloy coatings were tried. It seems doubtful whether metal arc welding could produce comparable results with argon arc welding, particularly for material of $\frac{1}{8}$in. thickness, or less.

In a purely descriptive article, Chase[10] describes how evaporators for gas refrigerators, incorporating one or two serpentine coils of seamless steel tubing, are brazed to aluminium plates. It was found that the steel coils could be brazed to the light alloy sheets and also clad with aluminium alloy during the process. To do this, the coils are annealed and subsequently flattened to ensure that the flattened surface, with the exception of the tube ends, will lie close to the plate. Other literature describes cold pressure welding, brazing and soldering techniques[11,12], or the use of resinous cements and pressure.[13] Casting-on techniques have also been investigated and one description[14] describes how a steel bolt was dipped into an alloy of 74.5% tin, 25% zinc, and 0.5% of a rare earth metal mixture containing cerium, at 700°C. After three hours, the steel part was removed, cooled, and aluminium cast around it.

A general survey of the whole field of dissimilar metal joining is given in one paper[15], where the importance of equilibrium diagram study is emphasised in order to predict the formation of intermetallic compounds, the formation of eutectics, the likelihood of alloying, and the freezing range of weld metal. From both theoretical and practical points of view, little information is contributed to the problem of joining aluminium to steel.

2.1 Conclusions from literature survey.

Although a certain amount of work has been published, there is very little information available of real use to the investigator confronted with the problem of joining aluminium to steel by fusion welding. Few workers have produced any fundamental theories to explain their observations on this topic. Much of the information gives the impression that the experimental work was designed to obtain a quick answer to a particular problem, rather than a serious attempt to formulate general rules for the fusion welding of aluminium to steel. There is certainly a lack of appreciation of the many factors involved, such as steel coating thickness and complications arising from interdiffusion and alloying.

As it is not possible to obtain from the literature any general guide as to the conditions under which satisfactory welds can be made between aluminium and steel by gas or electric arc processes, it is evident that a detailed investigation, such as that which the present author has carried out, is required.

3. SCOPE OF THE INVESTIGATION.

The main difficulty in welding aluminium to steel is due to the distinctly different metallurgical characteristics of the two materials, such as their melting points, and thermal conductivities. To explore how this difficulty could be overcome, some preliminary work was undertaken. This involved butt-welding tests on sheet materials, and various dissimilar metal combinations of mild steel and aluminium or aluminium alloy were joined, using several types of filler rod. Both the gas and argon arc welding processes were employed. The shielded metal arc process was not used because it was considered that the lack of separate control over the filler rod would make it difficult to bring about even flow of the molten filler metal over the steel surface.

The argon arc process was selected for the main investigation because the metal area affected by heat is much less than with gas welding and, therefore, less opportunity exists for diffusion and brittle phase formation. In addition, fluxes are required with gas welding to disperse the oxide film and the presence of flux residues in the weld might cause severe corrosion.

It was apparent from this preliminary work that little success could be expected unless an intermediate layer was provided between the steel and aluminium. Tin, zinc or aluminium appeared to be the most satisfactory coating metals for the steel. Other coatings such as nickel, copper and cadmium did not provide suitable welding conditions and the joints were extremely weak.

In the argon arc welding process (or tungsten inert-gas process) an alternating current electric arc, with a superimposed high frequency current, is struck between a non-consumable tungsten electrode and the material to be welded. The filler wire is added separately. The electrode is supported by the main part of the torch and is surrounded by a ceramic, plastic or water-cooled cup through which the protective argon flows, preventing both oxidation of the electrode and the weld pool. Welds possess a better appearance than those produced by gas welding.

Although the manual argon arc process described above was generally employed in this investigation, some work was done with consumable electrode equipment, automatic argon arc non-consumable equipment, and a friction welding machine. The consumable electrode process (or metal inert-gas process) is a development of the tungsten inert gas equipment. It employs an arc struck between the material to be joined and a wire which acts as both filler and electrode. This wire is fed continuously at a predetermined rate through the torch nozzle while protected by an argon gas shroud. Direct current is used with reverse polarity (electrode positive) and a practically constant arc length is maintained since the arc is self-adjusting. Extremely high heat penetration is obtained so that high quality welds can be made at speeds much greater than are possible with the tungsten inert-gas process. The automatic equipment was basically an argon arc torch with filler wire feed device.

Friction welding, on the other hand, is a method of joining bar to bar by the friction created between the two component surfaces when one is rotated against the other.

As the joints obtained in this investigation by use of the inert gas non-consumable and consumable electrode processes are very unusual, it is desirable at this stage to illustrate a typical butt weld. Figure 1 shows mild steel joined to aluminium by use of the manual argon arc process. It will be seen that the aluminium alloy filler metal fused normally with the parent aluminium material, while at the same time flowing around the steel surfaces and fusing with the steel coating. Other arrangements, such as tube to sheet fillet welds, show a similar structure.

These unusual types of joints are difficult to describe within the standard definitions for 'welding', 'brazing' or 'braze-welding'.

When two pieces of metal are joined together so that the original interfacial division between them is no longer visible, they are considered to be welded together. The essence of the process of brazing on the other hand, is that the joint is produced by introducing a film of molten metal between the parent materials at a temperature at which they are both solid. There is a distinction between the brazing of aluminium and other metals in that, for aluminium, the brazing material is an aluminium alloy possessing a melting point below that of the parent material. With most other metals, for example mild steel, the brazing material is usually entirely different in composition. Copper is widely used for 'flux-free' brazing of mild steel in a suitable atmosphere. Bronze welding or braze welding is usually defined as a process in which the filler metal is

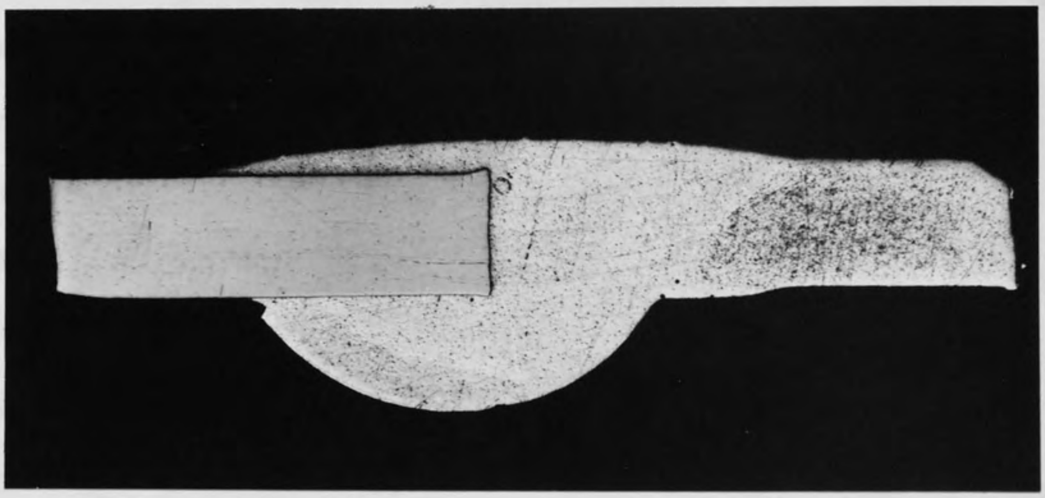


Figure 1

Aluminised mild steel - aluminium weld

Etch 0.5%HF x 5

basically a copper-zinc alloy. The filler material is applied in such a way that, although some penetration between the parts may be obtained, the main objective is to acquire the maximum joint strength by building up a fillet of the deposited metal.

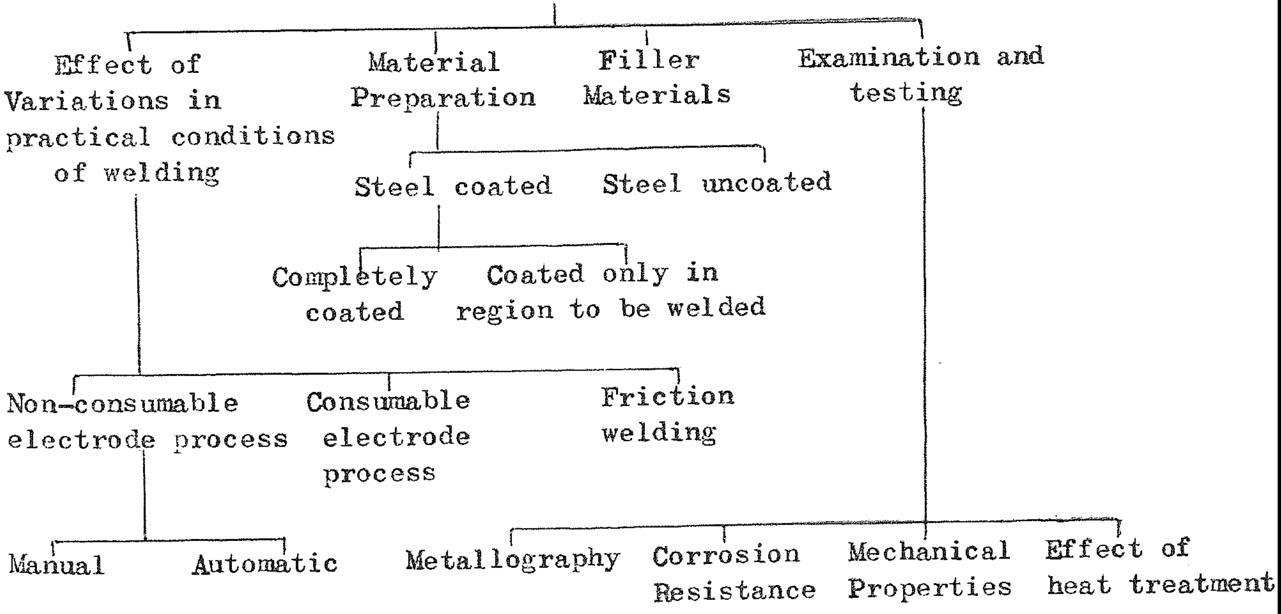
In the case of the technique developed during this investigation for joining aluminium to steel, fusion welding has taken place on the aluminium parent metal side with what may best be described as a brazed joint on the steel side. Under these circumstances, it seems advisable to describe the process simply as that of 'welding'.

Different operators were employed from time to time and the degree of skill required was found to be well within the capabilities of an experienced welder.

The scope of the programme is shown in Table III.

Table III.

Scope of Investigation.



The investigation to determine the practical conditions of welding includes butt, lap and fillet welds in sheet and tube materials using mainly aluminium-5% silicon and aluminium-5% magnesium filler metals. The specifications and thickness of the aluminium materials were selected on the basis of their relative importance to industry and the future applications of aluminium-steel joints on a commercial scale. Due to the lack of success with uncoated steel and even with certain types of metal coating during the early part of the investigation, the steel components were usually prepared by electroplating or hot-dipping with tin or zinc or aluminium.

Extensive examination and testing of the welds was necessary and the tensile test for the sheet butt and fillet welds was found to be an important guide to joint quality. Examination of the resulting fractures also provided a good deal of useful information. For the tube to tube butt, and lap joints, pressure testing was employed.

As shown in Table III, corrosion resistance was determined. This was necessary because with dissimilar metal joints there is always the possibility of severe corrosion of the less noble metal in certain environments. Heat treatment experiments were necessary to study the effect of elevated temperatures on the welded structures, particularly with regard to growth of the brittle intermetallic compound layers.

The more fundamental approach to the problem of joining aluminium to steel is made in Part II where the use of tin, zinc and aluminium coatings on the steel and the metallurgical considerations involved are studied. In addition, a study of weld bead geometry in relation to strength, has been made.

4. EXPERIMENTAL WORK.

It is intended, in this part of the thesis, to describe the development of a welding technique capable of producing a reliable joint between mild steel and aluminium. Mainly the practical aspects of sheet and tube, butt, fillet, and lap welding, will be considered.

The work will be divided into sections dealing with:-

a) Coating of the steel and the alloy layer.

b) Determination of the conditions needed to produce satisfactory sheet butt and fillet welds, sheet to tube fillet welds and tube butt and lap welds.

c) Investigation of the use of semi-automatic, automatic, and friction welding equipment for dissimilar metal joining.

d) Post heat treatment, fatigue strength and corrosion resistance of the welds.

As already mentioned in Section 3, preliminary investigation indicated that the argon arc welding process was most likely to lead to satisfactory results.

Apart from the use of a small number of 16 gauge steel sheet specimens, the material for sheet butt and fillet welds was of 10 gauge thickness. Standard test pieces, six inches square, were prepared, the welding edges being machined square. The one, and three inch diameter tube material, was of 16 gauge thickness; again, square edge preparation was used. Particular attention was paid to cleaning the surfaces prior to welding and degreasing was followed by careful wirebrushing. In practically all cases, the steel was coated with another metal by hot-dipping, electroplating or spraying. Metal coating considerations are surveyed in the next section (4.1).

The thermal conductivity of an aluminium alloy is about three to five times that of steel, hence it might be considered that preheating is required with a steel to aluminium joint. However, with argon-arc welding, preheating is seldom necessary except perhaps with thick plate and it was apparent in this investigation that it was neither required, because of the thickness of the sheet, nor indeed advisable, because of possible damage to the steel coating.

Usually a commercial aluminium-5% silicon or aluminium-5% magnesium filler rod was used, for joining the steel to the aluminium or aluminium alloy. However, as various workers have shown that copper reduces the intermetallic layer thickness of a hot-dipped aluminised coating on steel (Section 4.1), some work was done with an aluminium-silicon-copper rod. This material was prepared in the laboratory.

According to binary alloy cracking diagrams[16], an aluminium-silicon alloy shows the greatest tendency to crack under restraint below 1% silicon. With the aluminium-magnesium alloys for ring castings, the cracking tendency is greatest below 2% magnesium but with restrained welds the maximum is reached at about 4% magnesium.

Loss of alloying elements from the filler rod - especially loss of magnesium - may be very small in the case of argon-arc welding. It is generally recommended that when welding aluminium-magnesium alloys a filler rod should be selected with magnesium content slightly higher than that of the parent metal. This rule has been followed with the work on the aluminium-magnesium alloy (NS.5) but tests were also made using an aluminium-5% silicon filler metal in order to observe the effect on mechanical strength.

As experience was acquired, it was found that very high rates of argon gas flow were unnecessary and some reduction was possible without affecting welding conditions and joint quality (Tables V and VI).

As an alternative to a continuous underflow of inert-gas, purging immediately before starting the weld run was considered. This technique was employed in several instances but as a general practice it is not to be recommended, as it was apparent that good underbead formation could not be guaranteed.

The metallographic preparation of aluminium-steel interfaces is difficult for a great difference in hardness exists between the aluminium, steel, and intermetallic compounds. Different levels may therefore exist due to the polishing removing metal at a greater rate from the softer material. Etching is also difficult and, in many cases, a double etch had to be employed to reveal the structure in the parent and filler metals, and the compounds.

4.1 Coating of the Steel and the Alloy Layer.

The ferrous components used in the early work were prepared by coating with 90/10 or 50/50 tin-zinc alloys, pure tin, spraying with commercially pure aluminium or an aluminium alloy, silver plating and the application of aluminium or aluminium-silicon, using a gas welding torch.

For various reasons, these techniques were not satisfactory, for example, under laboratory conditions it was found difficult to produce an even tin-zinc coating. Most of the steel components, therefore, were sent to specialist firms for coating with tin, zinc and aluminium. In the case of tin and zinc, both electroplated and hot-dipped finishes were used.

A 0.001 in. thickness of electroplated tin was just sufficient to provide the right conditions for welding to take place. The hot-dipped tin coatings were approximately 0.002 in. thick and no difficulty in maintaining the arc was experienced. A 0.001 - 0.002 in. thick electroplate of zinc resulted in unsatisfactory joints and frequently no adhesion of the filler metal occurred; 0.0025 in. thickness must be regarded as the minimum acceptable. The galvanised material was of 0.003 - 0.004 in. coating thickness and proved satisfactory. The hot-dipped aluminium coatings averaged about 0.003 in. and were also satisfactory.

A small quantity of aluminised steel was available from the U.S.A. Only a few tests could be made but it was considered that the use of such material provided all the necessary conditions for producing a sound joint.

Test plates were also prepared by electroplating the steel with nickel, but the molten filler metal was unable to wet the steel coating and the dissimilar materials could not be welded together.

Nearly all the steel coating techniques employed, resulted in complete coverage of sheet and tube. It would be advantageous to be able to use a technique for local coating of the steel as there might be considerable difficulty in hot-dipping or electroplating large components. With this point in mind, an ultrasonic process was considered, for ultrasonic techniques can be used for the coating of mild steel by tin, zinc, and some other metals. The action of the ultrasonic energy is to break down the surface films of the molten globule, allowing it to spread over the surface. Unfortunately, however, in many instances there is no true bond between the metal coating and the base metal. As weld strength is very dependent on the metal coating-steel bond properties (Section 4.2.2) the use of an ultrasonic coating process is not advisable. Ultrasonic processes would also be very much more expensive and probably slower than conventional techniques, such as hot-dipping.

Study of metal coating is very important in the field of aluminium to steel joints, as the welding operation and weld strength is greatly dependent on the kind of metal coating used and its quality. Sometimes difficulties were encountered at the start of the welding operation because the mild steel coating was of insufficient thickness, at that point, to permit easy striking of the arc between the electrode and material, although the general thickness was sufficient for welding to take place once the argon-arc torch commenced movement. In the few instances where this difficulty occurred, it was found that a hot-dip coating was involved and some variation in coating thickness was apparent across the steel surface. However, usually the operator was able to deal with the situation by skilful manipulation of the welding torch, and filler rod.

For the production of satisfactory welds between aluminium and steel, under industrial conditions, uneven coating thickness could not be tolerated for it would demand a skill in excess of that which could reasonably be expected. Some measure of quality control would therefore be required.

Hot-dip aluminising is very similar in many respects to hot-dip galvanising. Careful pretreatment of the ferrous material is essential and it is necessary to protect the steel surface immediately prior to immersion in the aluminium-silicon bath. The reason for the addition of silicon to an aluminium bath for the hot-dipping of steel is explained in the papers of Gittings, Rowland and Mack[17], Stroup and Purdy[18] and many other workers.

The microstructure of a hot-dip coating reveals the presence of an interfacial layer of iron-aluminium compound and this layer often appears as a series of laps. Such laps indicate that there has been preferential diffusion at certain points along the steel surface. This alloy layer occurs between the relatively pure aluminium on the surface and the base metal.

Work has shown[17,18] the effect that alloying elements have on this compound layer thickness and the three most effective additions are beryllium, copper and silicon. Beryllium produces the greatest decrease and 0.5% reduces the layer approximately 75%, further additions up to some 2% result in only a further slight decrease; copper additions have to be greater than this to show a similar reduction. Approximately 2% of silicon produces a 60% reduction and this element appears to be the most convenient choice for adding to the aluminium bath, as beryllium raises difficulties from health considerations and copper has been found to affect coating adherence, apart from the objection which might be raised to the large addition required. Also, in the case of beryllium and silicon, the alloy layer hardness is reduced, but with copper it is increased unless silicon is also present.

Apart from bath composition, compound layer thickness is dependent on temperature and immersion time. The thickness is very important for in many instances, a coating must be able to withstand considerable deformation and like many interfacial compounds, this layer is very brittle. In the preparation of mild steel for joining to aluminium, therefore, it is necessary to ensure that the intermetallic compound layer is as thin as possible.

Chemical analysis of a bath used for preparing one batch of aluminised test plates for this programme was as follows:-

Copper	0.04 per cent
Nickel	Trace
Magnesium	0.01 " "
Silicon	6.1 " "
Tin	0.02 " "
Titanium	0.06 " "
Iron	2.1 " "
Lead	Trace
Manganese	Trace
Zinc	Trace
Aluminium	Remainder

Microexamination revealed that the average thickness of the intermetallic compound layer was 0.00025 in.

The hardness of the alloy layer in silicon-free aluminised steel coatings was given as 900 Knoop hardness number (obtained with a 25 gm load) by Gittings and his colleagues, and at 3.75% silicon it was found to be 339 and at 6.0% silicon, 340. Hughes and Moses[19] reported that hardness increased with distance from the steel/alloy layer interface (the reverse is true of galvanised coatings). At 6.0% silicon they found a slightly softer alloy than Gittings.

A microhardness survey of the alloy layer resulting from welding with an aluminium-5% silicon rod, produced an average value of 345 V.P.N. This figure is in good agreement, therefore, with those quoted in published work on aluminising. A similar hardness survey of the alloy layer produced when the 94.5/5.0/0.5 aluminium-silicon-copper rod was used, showed that it was softer with an average value of 200 V.P.N.

This reduction in hardness should have a beneficial effect if it is necessary to perform, for example, a sheet bending operation after welding.

In the case of hot-dipped tin coatings, it is generally accepted that the phase $FeSn_2$ is hard and brittle but there is far lessof it present and, therefore, of less concern than the compounds formed during galvanising and aluminising of steel. The thickness of the iron-tin compound is a matter of a few micro inches compared with 0.0003 inch or more of iron-zinc or iron-aluminium. This would tend to suggest that greater ductility of a tinned steel/aluminium joint could be expected, compared with zinc or aluminium coatings on the steel. However, the absence of a pronounced compound layer and the low melting point of tin may result in a very fluid coating during welding, and this may cause difficulties.

4.2 Sheet Butt Welds.

This work is concerned with the joining and testing of welds between aluminium or an aluminium alloy and mild steel sheet.

The nominal analyses of the sheet materials are given in Table IV.

Table IV.

	Composition (per cent.) (Single values are maxima unless otherwise stated)							
	Al	Cu	Mg	Si	Fe	Mn	Zn	Others
S1C	99 (min.)	0.1	-	0.5	0.7	0.1	0.1	
NS3	rem.	0.15	-	0.6	0.7	1.0-1.5	0.1	Ti 0.20
HS30	rem.	0.1	0.4-1.5	0.6-1.3	0.6	0.4-1.0	0.1	Cr 0.50 Ti 0.20
NS5	rem.	0.1	3.0-4.0	0.6	0.7	1.0	0.1	Cr 0.5 Ti 0.20
Mild Steel - C.R.C.A. - 0.08%C								

NS3 - ½ hard

S1C - ½ hard

HS30-WP (Solution treated and precipitation treatment)

NS5-O (Annealed condition)

Standard argon arc manual welding equipment was employed. The early work was carried out using a grooved backing bar of mild steel, cut to fit an existing jig. The groove was necessary to control weld bead penetration. This jig was replaced in later tests by that shown in Figure 2 (indicated by * in Table V). The 1/16 inch diameter holes permitted an underflow of inert-gas. This additional supply of shielding gas prevented oxidation of the steel coating on the underside.

4.2.1 Material Testing.

Using six inch square test plates of both aluminium and steel, it was possible to obtain three tensile specimens and one bend test

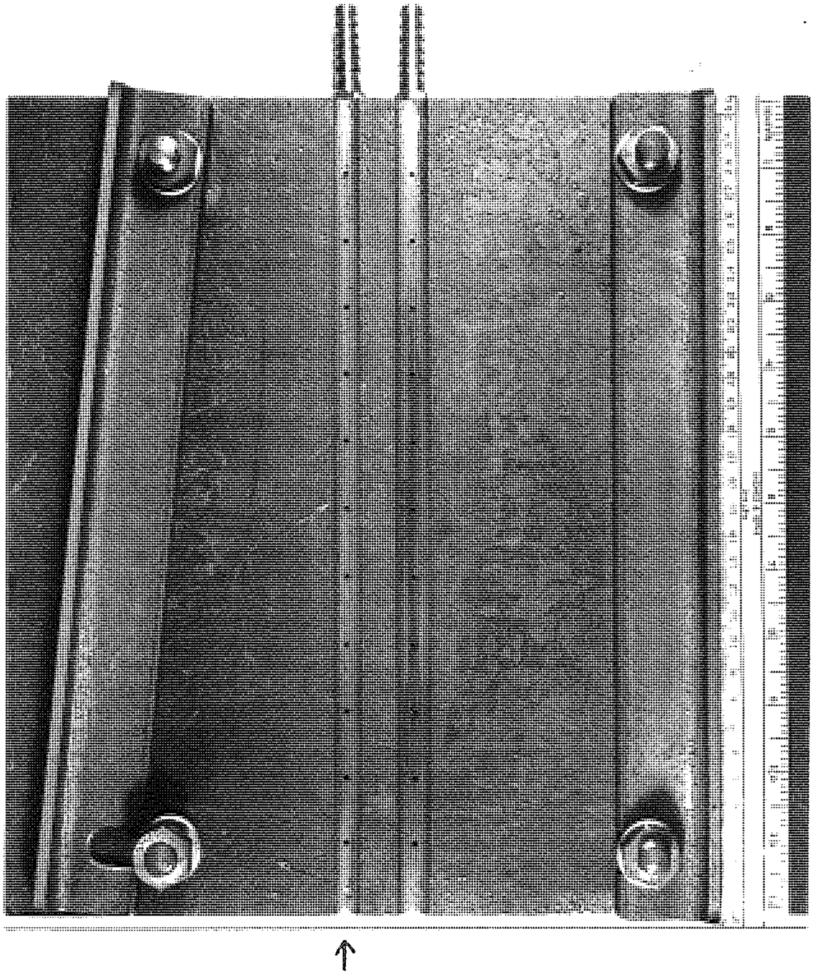


Figure 2

Butt welding jig for sheet material.

The groove indicated by the arrow was used in this investigation. It was $\frac{1}{8}$" deep, $\frac{1}{4}$" radius with 1/16" diameter holes for argon gas supply.

specimen from each welded panel. If a gauge difference existed, as in the early tests, tensile strength was calculated on the cross-sectional area of the thickest material. For mechanical testing it was general practice to leave the weld bead in the undressed condition.

Bending properties were difficult to determine because of the unusual nature of the joint. With unsatisfactory welds fracture took place along the boundary between the steel and intermetallic compound or through the centre of the compound. With satisfactory joints the steel or aluminium parent metal bent just outside the welded area. If the latter occurred under service conditions, adequate ductility could be claimed for most purposes.

Inspection of the welds was carried out immediately at the conclusion of the joining operation, and after machining of the mechanical test specimens. A low power binocular microscope was used to supplement the normal visual examination. In this way it was possible to check on such features as bead geometry, the presence of major cracks in weld and/or parent material, and the effect of welding heat on the metal coating. Examination of the specimens after testing also revealed a great deal of information, and many welds were subjected to metallographic examination. Although radiography is a useful method of detecting weld defects, tests indicated that, with these particular weld structures, X-ray examination did not satisfactorily reveal lack of adhesion or penetration.

4.2.2 Summary of Results.

Test results for sheet butt welds are tabulated in Tables V and VI; these results are separated into two main groups because certain differences in welding conditions existed. For example, all the steel test plates in Table V, except the silver plated and aluminised specimens were coated under laboratory conditions, whereas in Table VI the steel was coated by various specialist firms. The experimental work shown in Table V indicated that an improvement in coating quality was necessary and that an underflow of shielding argon gas was essential.

The aluminium-manganese alloy (NS3) joined to aluminised steel and electroplated zinc on mild steel resulted in satisfactory tensile strength and good bending properties, failure occurring in the parent metal. With a hot-dipped zinc coating, however, the tensile and bending properties were sometimes abnormally low with failures occurring in both parent metal and joint. The reason for this lower strength is discussed in Part II of this report (Section 9.2).

Hot-dipped tin, zinc or electroplated tin on mild steel welded to the aluminium-magnesium alloy (NS5) with the aluminium-5% silicon filler metal resulted in low tensile strength and with NS5 joined to aluminised mild steel the weld was found to be extremely brittle on bending. No necking of the aluminium occurred on tensile testing, failure always taking place at the centre of the weld. Microexamination revealed a structure of aluminium solid solution with fine eutectic but, in addition, considerable quantities of Mg_2Si were present, thus accounting for the pronounced brittleness and very low tensile strength. With the aluminium-magnesium alloy and the aluminium-5% magnesium filler rod, satisfactory results were obtained with aluminised, galvanised and electroplated tin coated steel, but in the case of hot-dipped tin coatings, the welds were severely cracked. Electroplated zinc coated specimens were not tested due to difficulty in material supply at that time. The cause of cracking of these hot-tinned steel welds is discussed in Part II (Section 8.2).

From examination of tensile and bend test specimens after fracture it appeared that in many cases it was the steel coating which caused failure. For example, in the case of the aluminised steel the adhesion or alloying of the filler metal to the aluminium coating was stronger than the bond between steel and coating.

The effect of a poor quality aluminium coating on the steel was demonstrated in test 274, where a greater range of tensile strength was obtained with a lower minimum value.

With electroplated nickel on steel it was immediately apparent that no success could be expected from such a coating technique and further tests were not made.

In order to demonstrate the importance of having the edge of the steel coated with a buffer layer, a number of test panels were prepared with the edge coating (hot-dipped tin) removed but left intact on top and bottom surfaces. During welding uneven flow of the molten filler metal was observed, the operator having great difficulty in controlling the weld pool and the underbead did not form correctly. Very low mechanical strength would be obtained from such a weld.

Figures 3, 4 and 5 illustrate failure of the weld by stripping of the bead (often due to a weak bond between the coating and steel), typical tensile fractures, and a bend test specimen.

Table V.

Sheet butt welds - manual argon arc welding process.

Summary of Tests Nos. 1-83.

Electrode diameter	$\frac{1}{8}$ in.
Welding current range	145-165 Amps.
Filler rod diameter	$\frac{1}{8}$ in. except for laboratory rods 3/16 in.
Argon flow	24 ft^3/h
*Underflow	4 ft^3/h
Material combination	
+ (a)	16 gauge M/S 10 " Al-1$\frac{1}{4}$% Mn (NS.3)
(b)	10 " M/S 10 " Al-1$\frac{1}{4}$% Mn (NS.3)

Edge preparation - machined square (except where stated otherwise)

Joint spacing - close contact.

+ Strength calculated on the cross-sectional area of thickest material.

Table V.

Material Combination	Coating	Filler Rod	U.T.S. ton/in^2	Bending Properties	Remarks
(a)	Steel uncoated	Comm. pure aluminium		-	No joint obtainable
"	" "	Al - 5% Si		-	" " "
"	" "	Al - 10% Si		-	" " "
"	Al" sprayed	Al - 5% Si		-	" " "
"	" "	Al - 5% Mg		-	" " "
"	Tinning compound	Al - $1\frac{3}{4}$% Mn		-	" " "
"	Tin-zinc 90/10	"	3.9 4.1 4.2	poor	Tendency to cracking
"	" "	Al - 5% Mg	2.9 3.0 3.8	"	Cracks observed
"	" "	Al - 1% Zn	-	-	No joint obtainable
"	" "	Al - 5% Si	2.6 3.5 4.3	poor	-
"	" "	Al - 10% Si	-	-	Severe cracking occurred
"	" "	Al - 5%Si - $\frac{1}{2}$% Cu	2.5 3.9 6.3	fair to good	-
"	" "	Al - 5%Si - 1% Cu	2.5 4.3 6.3	poor	-
"	Tin-zinc 5 0/50	Al - 5%Si - $\frac{1}{2}$% Cu	5.3 5.7 6.2	good	-
"	" "	Al - 5%Si - 1% Cu	1.9 3.0 4.2	poor	-
"	" "	Al - 5%Si	2.3 2.5 3.1	"	-
"	" "	Al - 10%Si	1.2 1.7 2.5	"	Considerable cracking in weld bead.
"	Comm. pure tin	Al - 5% Si	3.1 3.5 3.9	"	-
"	" " "	Al - 5%Si - $\frac{1}{2}$% Cu	2.6 4.1 6.4	good	-
"	Tin-zinc 90/10 (45° preparation)	Al - 5% Si	2.6 3.1 3.7	"	-
"	Tin-zinc 90/10 (45° preparation)	Al - 5% Si - $\frac{1}{2}$% Cu	2.1 3.5 4.7	"	-
"	Silver plated	Al - 5% Si	-	-	No joint obtainable.
"	* " "	" "	1.4 2.1 3.2	poor	Coating stripped on bending.
"	*Hot-dip aluminised	" "	5.6 5.9 6.3	good	Fractures in parent metal.
(b)	*Tin-zinc 90/10	" "	1.3 3.5 6.3	"	Fractures in parent metal and weld.

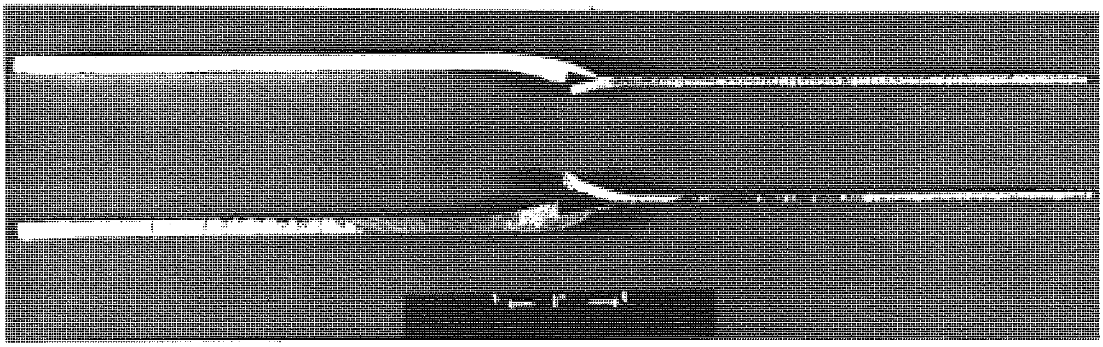


Figure 3

Failure of joint by stripping of bead

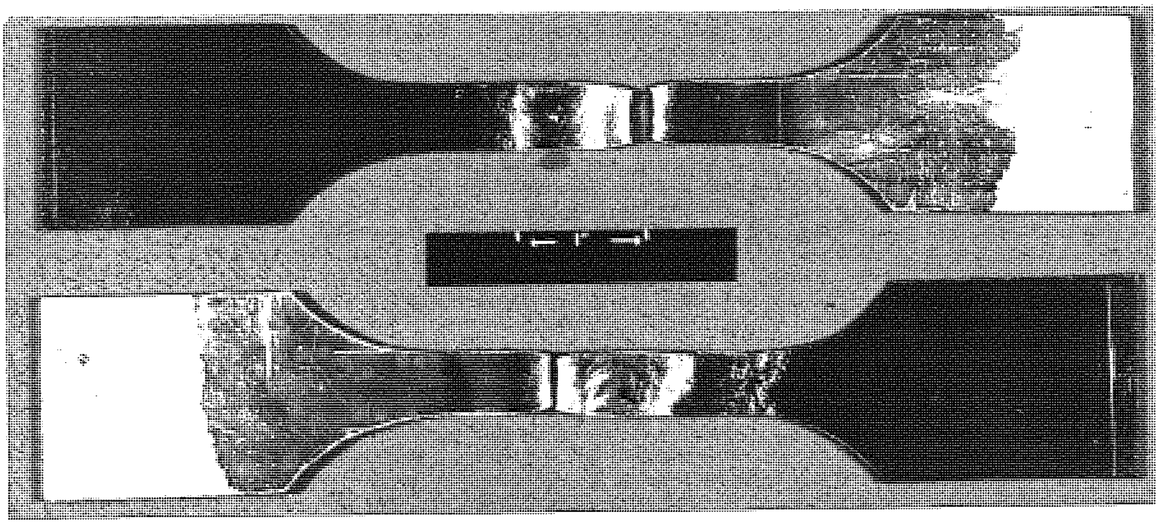


Figure 4

Typical fractures in parent material.

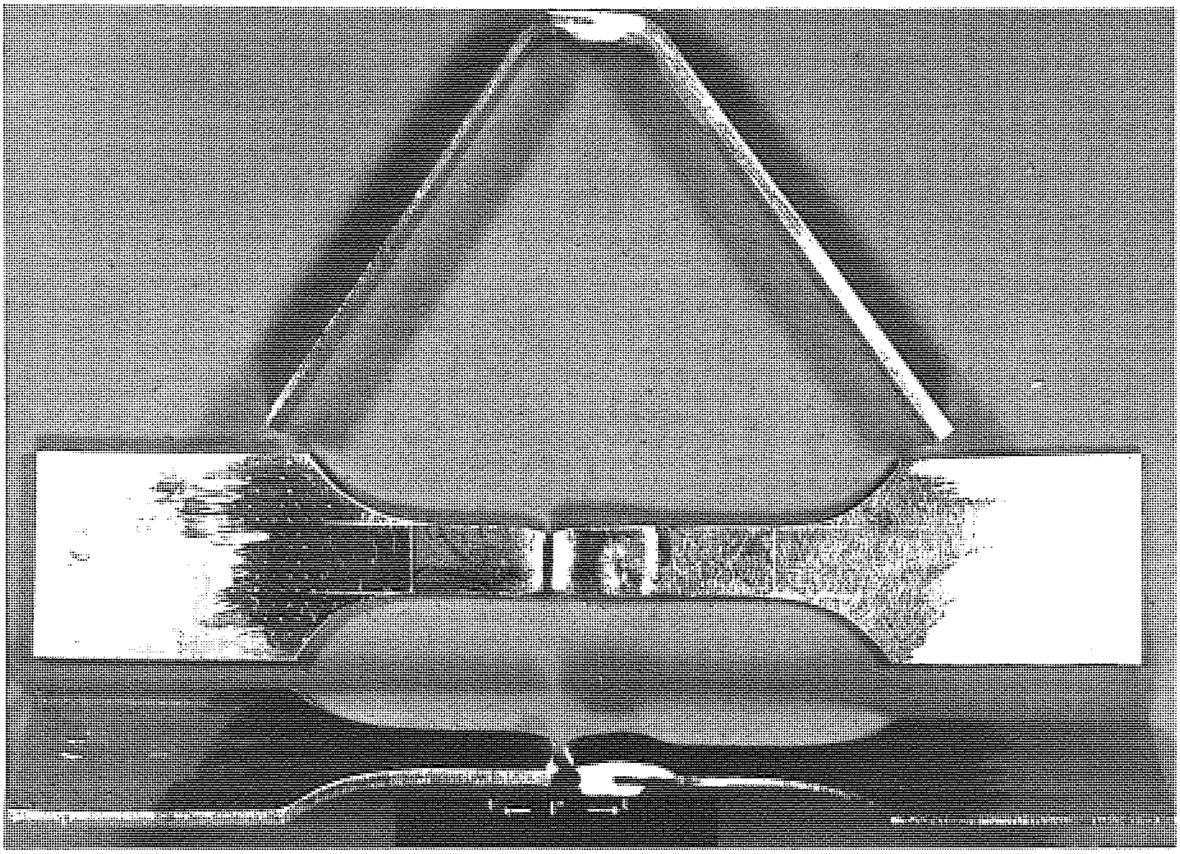


Figure 5

Typical tensile and bend specimens.

Fracture has occurred on the aluminium side of the weld.

Table VI.

Sheet butt welds - manual argon arc welding process.

Filler rod diameter - $\frac{1}{8}$ in.

Tensile strength calculated on cross-sectional area of 10 gauge material ($\frac{1}{8}$ in.)

Notes.

H/D - Hot dipped coating.

E/P - Electroplated.

S - Sprayed.

VG, G, F or P - Bending properties very good, good, fair or poor.

FP - Failure in parent aluminium or transition zone.

FJ - Failure in weld.

R - Retained for other tests.

Table VI.

Test No.	Al	Steel Coating	Filler	Elec Dia.	Argon Torch. ft^3/h	Argon Backing bar	Current Amps	U.T.S. ton/in^2	Bending Properties	Remarks
84	NS3	H/D Al	5% Si	$\frac{1}{8}$ in	18	2	154	6.2 6.3 6.4	V.G.	F.P.
85/90	S1C	"	"	"	"	"	"	4.0 4.4 4.6 4.7 4.9	"	F.P. and F.J.
92	NS3	S Al	5% Si $\frac{1}{2}$% Cu	"	"	"	"	-	-	No joint possible
93	"	S Al/ $\frac{3}{4}$%Cd	"	"	"	"	"	-	-	" " "
104/105	"	H/D Al	5% Si	"	"	"		5.9 6.0 6.1	G	F.P.
102	"	E/P Zn	"	"	"	"	"	6.3 6.3 6.5	V.G.	"
103	"	H/D Zn	"	"	"	"	"	4.0 5.0 6.3	P.	F.P. and F.J.
122/123	S1C	H/D Al	"	"	"	"	145	-	-	R. Excellent
124	"	E/P Sn	"	"	"	"	"	4.8 4.8 4.9	G.	-
125	"	H/D Sn	"	"	"	"	"	4.8 4.9 5.0	"	-
165/166	"	H/D Al	"	"	"	"	"	-	-	R.
167	"	H/D Sn	"	"	"	"	"	-	-	R.
168	HS30	E/P Sn	"	"	"	"	"	-	-	R.
180	NS5	H/D Sn	"	"	"	"	"	0.8 0.9 1.2	F.	Bend failure commenced by top bead stripping.
181	"	H/D Zn	"	"	"	"	"	0.9 0.9 0.9	P.	
182	"	E/P Sn	"	"	"	"	"	0.7 0.7 0.7	P.	
184	S1C	H/D Al	"	"	14	"	139	-	-	R.
185	NS5	E/P Sn	"	"	"	"	"	-	-	R.
186		H/D Sn	"	"	"	"	"	-	-	R.
187	S1C	H/D Zn	"	"	18	"	"	-	-	R.
188	NS5	"	"	"	"	"	"	-	-	R.

Continued ....

Table V I (cont'd)

Test No.	Al	Steel Coating	Filler	Elec Dia.	Argon Torch. ft³/h	Argon Backing bar	Current Amps	U.T.S. ton/in²	Bending Properties	Remarks
196		H/D Al	5% Si	⅛ in	14	2	139	0.8 0.9 1.2	P	-
220	S1C	S Al/Si	"	"	18	"	134	-	-	No joint possible.
221/222	HS10	Armco	"	"	14		62	-	-	-
270/272	NS5	H/D Sn	5% Mg	"	16	"	126	-	-	Severe cracking in all welds.
273	"	H/D Al	"	3/32"	14	"	"	11.2 11.8 12.2	V.G.	F.J.
274	"	"	"	"	"	"	"	5.0 6.3 10.4	G.	F.J. Uneven thickness of steel coating.
275	"	"	"	"	"	"	"	-	-	R.
276	"	E/P Sn	"	"	"	"	"	8.6 9.8 12.0	G.	-
277	"	H/D Zn	"		"	"	"	6.8 8.1 8.4	F.	-
278	"	E/P Ni	5% Si	"	"	"	"	-	-	Considerable difficulty in wetting Ni.
281	HS30	H/D Sn	"	"	"	"	"	7.0 7.5 9.7	F.	-
282	"	"	5% Mg	"	"	"	"	7.6 8.1 10.3	"	-
283	"	E/P Sn	"	"	"	"	"	-	-	R.
284	NS5	H/D Al	"	"	"	"	"	-	-	R.
285	"	H/D Sn	"	"	"	"	"	-	-	Severe cracking.

4.2.3. Discussion.

It is evident that the manual argon arc welding process enables satisfactory welds to be made between aluminium or aluminium alloy and mild steel sheet materials. The work has shown that the coating on the steel has an important influence on weld strength. A sufficient thickness is required to ensure ease of welding (Section 4.1.), edge coverage is necessary, and the coating must be smooth, even, and free from non-metallic inclusions.

The failure of metal sprayed coatings to form a suitable buffer layer is mainly attributable to the high oxide content. This is unfortunate since local coating problems could be overcome in many instances if the use of metal spraying was feasible. It is known that rapid oxidation of a sprayed coating takes place within say twenty-four hours and this oxide in addition to that already present, prevents wetting of the surface.

For aluminium (S1.C), aluminium-manganese alloy (NS.3) and the aluminium-magnesium-silicon-manganese alloy (HS.30), an aluminium-5% silicon filler metal can be recommended with electroplated or hot-dipped tin, zinc or aluminium coated mild steel. For the aluminium-magnesium alloy (NS.5), the aluminium-5% magnesium filler material can be used in conjunction with all the steel treatments except that of the hot-tinned coating.

The Al-5%Si-$\frac{1}{2}$%Cu filler rod results in a softer compound layer compared with the commercial filler examined (Section 4.1), while the mechanical properties of the Al-5%Si-1% Cu are inferior to the Al-5%Si-$\frac{1}{2}$%Cu

(Table V). It might, therefore, be worthwhile in future work to investigate more fully the use of the low copper material, such study to include corrosion resistance tests to determine the effect of the copper addition.

The tinned steel/aluminium-magnesium weld problem, and the lower weld strength with hot-dipped zinc as the steel coating compared with aluminised steel, for example, is discussed in Part II.

4.3. Fillet Welds.

Experimental work was carried out on 10 gauge sheet to sheet, and 16 gauge three inch diameter aluminium tube to 10 gauge mild steel sheet.

Sl.C, NS.3 and HS.30 aluminium and aluminium alloy sheet material was used (for composition see Table IV) in conjunction with the coated steel. The aluminium alloy tube was of HT.10-WP specification.

Table VII.

	Al	Cu	Mg	Si	Mn	Others
HT10	rem.	0.1 max.	0.4-1.5	0.6-1.3	0.6 max.	Fe 0.6 Cr 0.5 Ti 0.2 max.

For joining the aluminium tube to the steel plate a turntable jig was designed and manufactured. This was of simple construction, being rotated by belt drive with manual operation. The tube was held in place while tack welds were made, the plate then being clipped to the turntable for making the complete joint.

The mild steel was coated with aluminium, tin, zinc or tin/zinc alloy as discussed in Section 4.1. As in the case of material preparation for sheet butt welding, degreasing was followed by wire brushing, particular attention being paid to the edge of the coated steel. Special care was taken to make close contact between the components when setting up and tackling the joint.

Four tensile test specimens were prepared from the welded components selected for mechanical testing; each specimen being one inch wide.

4.3.1. Welding Procedure.

Single fillet joints were made in the first instance followed by the construction of test pieces in a cruciform design. In the case of the latter, two sheets of light alloy were joined to a panel of coated steel. Both aluminium-silicon and aluminium-silicon-copper filler metals were used and the welding sequence was varied for the four weld beads.

Following this group of tests, further specimens were manufactured with the number of fillet welds reduced to two, forming a tee joint. This enabled the steel to be cut back to almost the weld bead for tensile testing so that the steel was gripped horizontally in one set of jaws while the aluminium was held normally.

For the tube to sheet joints, the alloy tube being thinner (16 gauge) than the steel (10 gauge), a lower amperage was used than that necessary for sheet to sheet fillet welds. In the majority of cases, welding over the tack welds did not cause any difficulty.

To increase the area of filler metal contact with the coated steel, a modification of the welding technique was now developed and this involved the laying down of two or three weld beads, slightly overlapping, on the coated steel, followed by the welding of the aluminium to these beads on the steel to form the tee joint.

For this experimental work, aluminised steel was used, as previous investigation had shown that this material resulted in lower strength fillet welds compared with tin and zinc coated steel. The non-ferrous material selected was commercial purity aluminium.

For the first group of tests, $\frac{1}{8}$ inch diameter filler wire of commercial aluminium was used. Two or three weld beads were laid on the aluminised steel, side by side with slight overlapping, the total width being some $\frac{3}{4}$ inch at maximum. For this surfacing a current of 129 amperes was satisfactory. The aluminium sheet was then joined to these beads on the steel using a current of 139 amperes.

In the second group of tests a similar procedure was followed except that the aluminium-5% silicon filler rod was used. An argon flow of 18 ft^3/h was maintained in all cases.

4.3.2. Summary of Results.

The single fillet joints (test nos. 94-96, Table VIII) were subjected to microexamination only. This indicated that satisfactory welds had been produced with sufficient penetration of the aluminium. The cruciform specimens (Table VIII) were prepared in order to provide means of tensile testing, but the tests were not successful. Incomplete fusion between the aluminium filler metal and the steel coating, oxide inclusions in the weld metal, and the insufficient penetration of the aluminium all contributed to the poor results. The main difficulty, however, was the heat effect of more than two runs, as four welds in the restricted area provided by a cruciform design and ten gauge material imposed too severe conditions on the coated steel. For this reason, testing was continued on single or double fillet joints. Figure 6 illustrates the typical macrostructure of a double fillet weld.

With galvanised steel (group tests 111 and 112) an average strength of over two tons per square inch was obtained. Only a little volatilisation of the zinc occurred but it was noticed that the second weld in each case was less clean.

Panels of aluminised steel and commercially pure aluminium joined by aluminium-5% silicon, aluminium-5% silicon-0.5% copper, and commercial aluminium filler metals were disappointing (tests 117-120). From examination of the microstructure it was apparent that the fractures mainly occurred at the mild steel-intermetallic compound interface, rather than between weld metal and compound or through the centre of the compound. By subjecting a specimen to some three-quarters of the known load required to produce failure and then examining the microstructure further evidence of this type of failure was obtained (figure 7).

It is known that aluminised steel does not behave as well as galvanised steel when shear stresses are involved. This has been demonstrated by deep drawing, for a comparison of deep-drawn cups in these two materials showed this difference very clearly[20]. Similarly, the wire drawing of hot-dipped aluminised steel is more difficult than with hot-dipped galvanised materials.

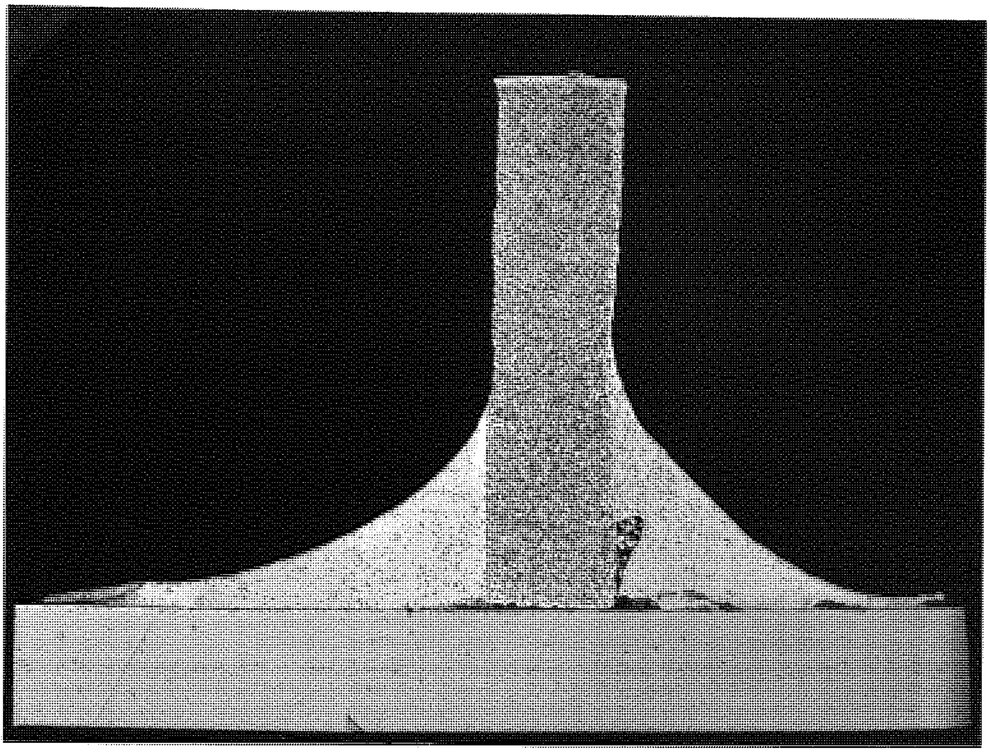


Figure 6

Galvanised mild steel - aluminium weld.

Etch 0.5% HF x 5

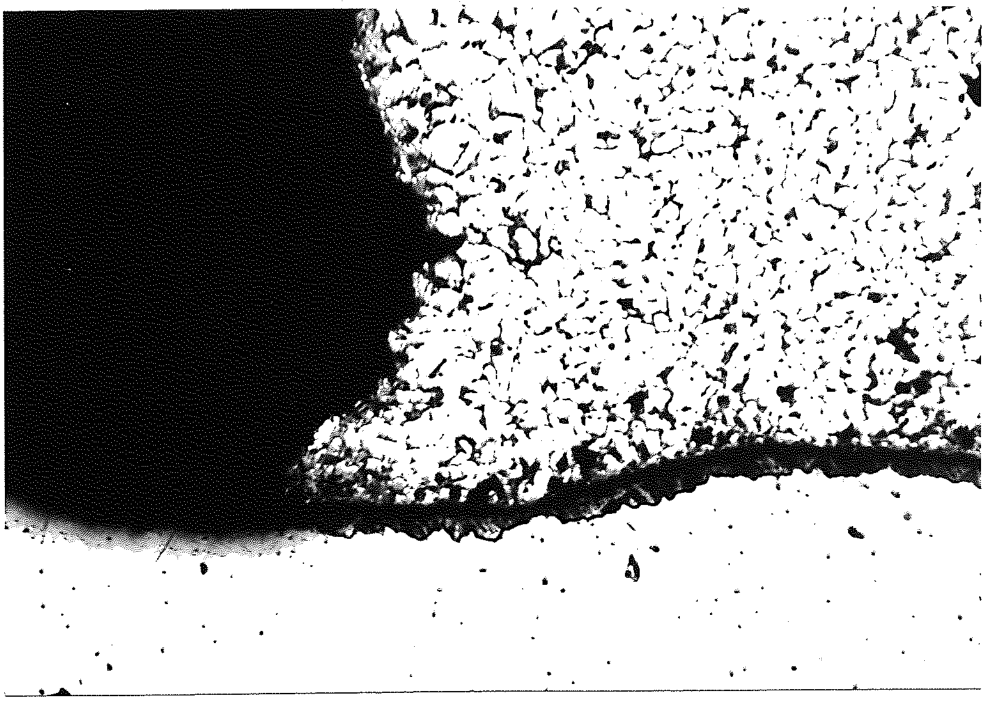


Figure 7

Aluminised mild steel - aluminium weld.

Failure has occurred at the steel-compound interface.

tch 0.5% HF x250

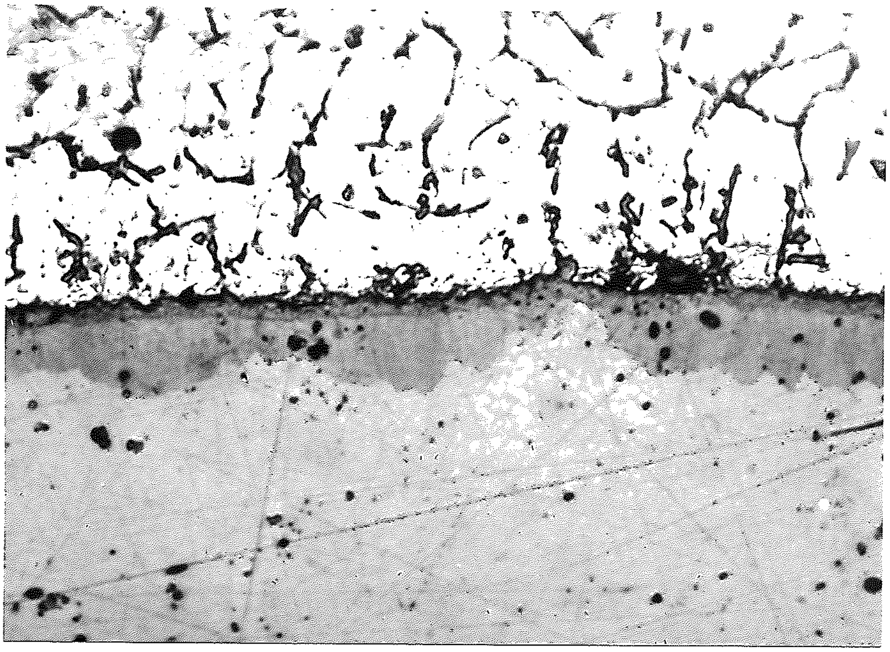


Figure 8

Aluminised mild steel - aluminium weld.

Note varying thickness of intermetallic compound.

Etch. 0.5% HF x 750

With tube to sheet joints (test nos. 142 and 144, Table IX) using aluminised steel there was very little discolouration of the coating on the underside. This indicated that heat input was not excessive and that under service conditions the protective value of the aluminium coating would not be reduced. However, with the tin coated steel specimens (e.g. test no. 135, Table IX), there was considerable discolouration of the surface, particularly on the underside of the component. The protective layer was now slightly porous due to a moderate amount of tin flow having occurred during the welding process.

Microexamination showed that there was only a thin line of demarcation between the steel and weld metal in the case of hot-dipped tin coatings (Figues 9 and 10). There was far less of the compound $FeSn_2$ present, compared with intermetallic compounds formed when hot-dipped zinc and aluminium coatings protected the steel.

(Summary continued on page 46)

Table VIII.

Fillet welds in sheet materials - manual argon arc welding process. Tensile strength calculated on cross-sectional area of 10 gauge material ($\frac{1}{8}$ in.). The actual load was divided by the number of welds involved.

Electrode diameter	$\frac{1}{8}$ in.
Argon flow	torch 18 ft.^{3}/h *underflow 2 ft.^{3}/h
Filler rod diameter	$\frac{1}{8}$ in.

Abbreviations as for Table VI.

*Tests 94 - 118, no underflow used.

Table VIII

Test No.	Type of Joint	Al	Steel Coating	Filler	Current Amps	U.T.S. ton/in^2	Remarks
94	Single Fillet	S1C	H/D Al	5% Si	154	-	Microexamination and simple fracture tests only.
95-96	"	"	"	5%Si $\frac{1}{2}$%Cu	"	-	
97-98	Four Fillet welds	NS3	"	"	126-154	0.74 0.76 0.83 0.80	-
99-100	"	S1C	"	5%Si and 5%Si $\frac{1}{2}$%Cu	"	0.26 0.26 0.27 0.28	-
101	"	"	Sn/Zn alloy	5% $\frac{1}{2}$%Cu	"	-	No joint possible
106	"	"	H/D Al	5% Si	110	0.75 0.82 0.9 0.95	-
107	"	"	H/D Sn	"	"	-	Extensive cracking
109	"	HS30	H/D Al	"	"	-	Specimens broke without giving any measurable strength
110 & 113/114	Double Fillet	S1C	E/P Zn	"	"	-	No adhesion due to inadequate thickness of plate (0.001")
111/112	"	"	H/D Zn	"	"	1.99 2.1 2.3 2.56	F.J.
115	"	"	H/D Al	5%Si $\frac{1}{2}$%Cu	110	1.2 1.3 1.35 1.44	F.J.

Table VIII (cont'd)

Test No.	Type of Joint	Al	Steel Coating	Filler	Current Amps	U.T.S. ton/in^2	Remarks
116	Double Fillet	S1C	H/D Al	5% Si	110	-	No measurable strength - coating quality poor
117	"	"	"	Pure Al	"	-	Choice of filler material prevented joints of measurable strength being made.
118	"	"	"	5% Si		1.0 1.5 1.6 2.0	F.J.
119	"	"	"	"	"	2.0 2.0 2.0 2.2	F.J.
120	"	"	"	5%Si ½%Cu	"	2.0 2.0 2.1 2.1	F.J.
126	"	"	E/P Sn	5% Si	"	4.0 4.35 4.5 5.1	F.J.
127	"	"	"	"	"	-	Electroplate of inadequate thickness - impossible to weld
128	"	"	H/D Sn	"	"	3.9 3.9 4.0 4.79	F.J.
129/131	"	"	H/D Zn	"	"	4.65 4.7 5.0 5.9	F.J.
132	"	"	E/P Sn	"	"	4.1 4.2 4.28 4.63	F.J.
133	"	"	H/D Al	"	"	2.0 2.5 3.6 4.1	F.J.

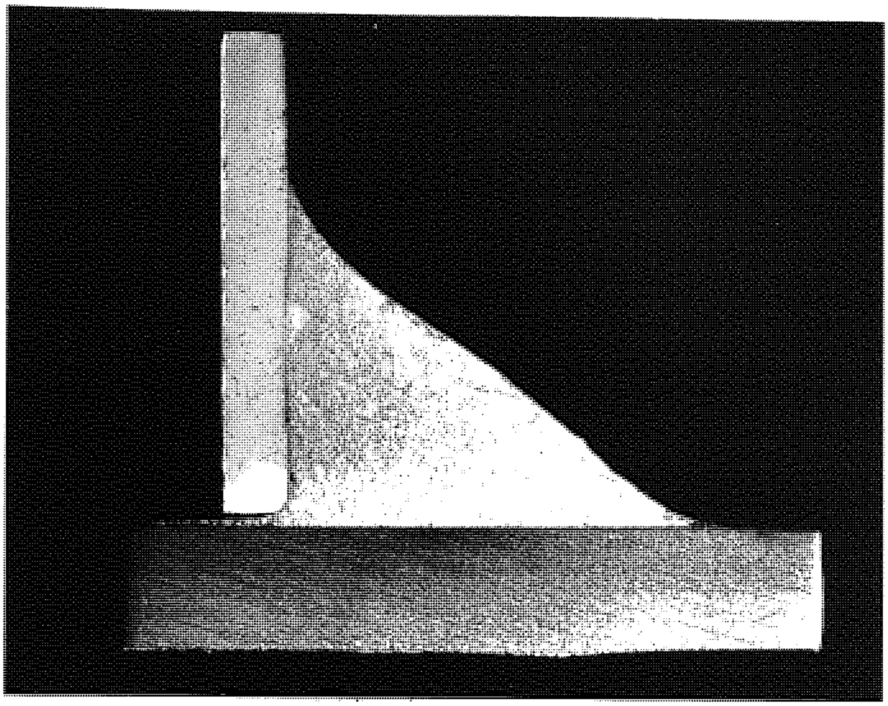


Figure 9

Tinned mild steel - aluminium alloy tube.
Typical fillet weld obtained without preliminary surfacing.

Etch. 1% Nital x 5

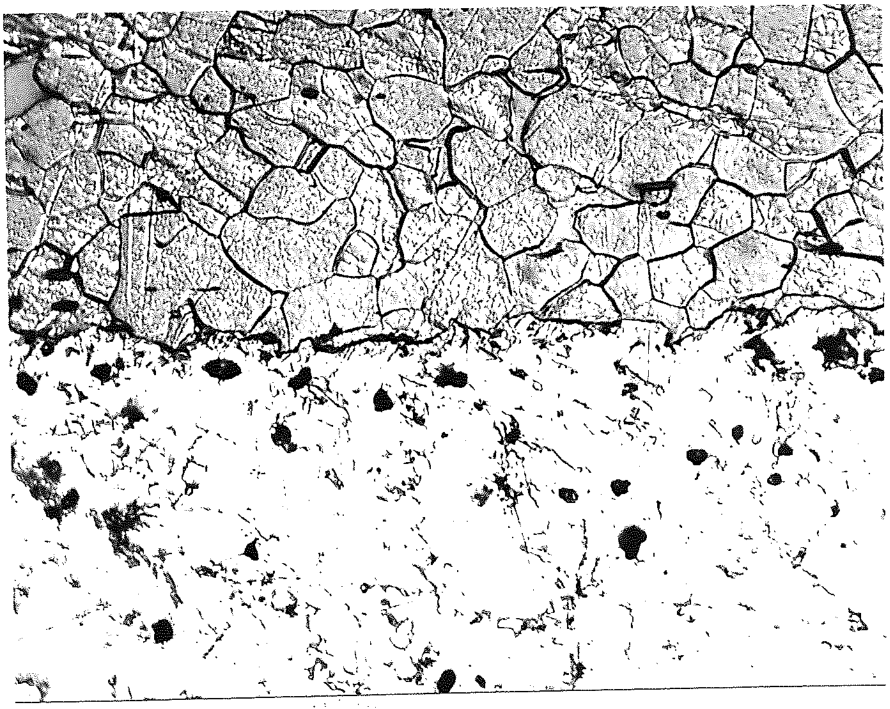


Figure 10

Interface region of above specimen. Observe absence of pronounced intermetallic layer.

Etch. 1% Nital x 500

Table IX.

Tube to sheet fillet welds - manual argon arc welding process.

Aluminium tube (HT.10) ....Mild steel
16 G 10 G

Electrode diameter ....$\frac{1}{8}$ in.

Argon flow ....torch 18 ft.^{3}/h.
(no secondary supply used)

Filler rod diameter and specification ....3/16 in. aluminium-5% silicon

Abbreviations as given in Table VI.

Test Number.	Steel Coating.	Amps.	Remarks.
134	H/D Al	80	Weld quality poor-current too low.
135	E/P Sn	103	Discolouration of tin surface, particularly on underside.
136	H/D Sn		Weld satisfactory (Figures 9 and 10)
137		62 103	For Al tube to Al tube. For Al tube to steel. (component design as shown in Figure 11)
139		103	Weld satisfactory.
140	E/P Sn	103	Poor weld shape.
141	E/P Zn		Welding over tack weld found more difficult than with other coatings.
142	H/D Al		Excellent appearance, very little discolouration of surfaces.
143	E/P Sn		Weld quality varied.
144	H/D Al		As 142.
145	H/D Sn		Satisfactory weld.
146		62 108	For Al tube to Al tube. For Al tube to steel. (component shown in Figure 11). Slightly higher current compared with 137 resulted in improved weld quality,

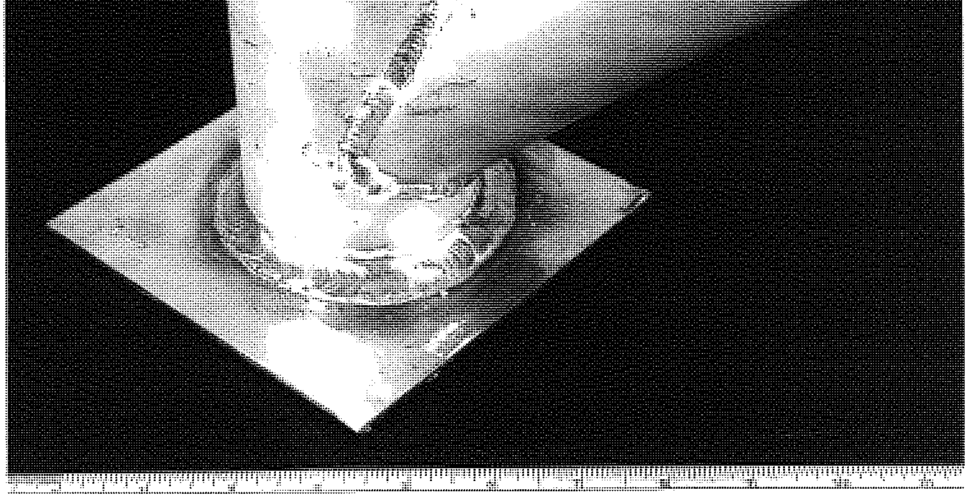


Figure 11

3 in. diameter aluminium alloy tube welded
to tinned mild steel

It was apparent, at this stage in the investigation, that the mechanical properties of the fillet welds were not as good as obtained for the butt welds (Section 4.2.2). Particularly with aluminised steel specimens, the joint ductility was disappointing. The welding technique was therefore modified to include the preliminary surfacing of the coated steel as described in Section 4.3.1.

In the first group of tests using the aluminium filler wire, investigation revealed that the compound layer, resulting from the weld beads laid on the coated steel surface and the joining of the aluminium to these beads, varied in thickness between 0.0008 and 0.002 inch. No particular region showed prominence in width. The boundary between aluminium and intermetallic compound was fairly regular but very irregular between mild steel and compound with a clearly defined tongue-shaped configuration showing columnar growth. There was, therefore, considerable variation in the amount of diffusion of aluminium into the iron. Needles, and occasionally plates, of aluminium-iron compound existed in the aluminium weld metal adjacent to the usual intermetallic layer, the needles often approaching 0.005 inch in length. Sections cut from these test specimens and subjected to tensile and impact tests showed that the joints were stronger and more resistant to sudden shock than fillet welds laid directly on coated steel.

In the second group of tests, utilising the commercially available aluminium-5% silicon filler wire, it was now found that the intermetallic layer thickness range was 0.00025 - 0.001 inch (generally between

0.00025 and 0.0005 inch). The layer was even, with complete absence of an acicular constituent as noted in the first test group. Bend tests showed that specimens of the second group (aluminium-5% silicon wire) possessed greater ductility than the first group (commercial aluminium wire). They were undoubtedly stronger than fillet welds produced without preliminary surfacing of the coated steel. The tensile strength was now equal to that obtained for butt welded joints between aluminised steel and aluminium (e.g. tests 85 and 90 Table VI).

4.3.3. Discussion.

A number of important factors emerge from study of these test results. For example, work on the cruciform specimens has clearly demonstrated that joint design must be carefully studied, with the thickness of the material, number of welds, and metal coating considerations, all being taken into account. Where possible an underflow of argon should be used, for there was a considerable improvement in strength when a secondary inert gas supply was employed. This is shown by tests 126-133, Table VIII, although the aluminised steel coating produced variable results compared with tin or zinc. Again, it is evident that an indifferent quality coating, especially with regard to thickness, is likely to result in welds having little strength.

For fillet welds, preliminary surfacing, by laying down a number of weld beads on the coated steel, prior to joining the aluminium to the steel component, is to be strongly recommended. The use of this technique produces joints of maximum strength, especially where resistance to shock is required. This particularly applies to the use of a hot-dipped aluminium coating as without such preliminary treatment tin or zinc coated steel is preferable, at least as far as mechanical strength is concerned.

4.4. Tube Butt and Lap Welds.

This section is concerned with butt and lap welds between 16 gauge, one inch diameter aluminium or aluminium alloy, and mild steel tubing. TlC, HT9 and NT4 aluminium material was employed, while the ferrous tube was of the seamless type.

Table X.

	Composition (per cent) (Single values are maxima unless otherwise stated)						
	Al	Cu	Mg	Si	Mn	Fe	Others
TlC	99 (min)	0.1	-	0.5	0.1	0.7	Zn 0.1
HT9	rem.	0.1	0.4 -0.9	0.3 -0.7	0.5	0.6	Zn 0.1 Ti 0.2
NT4	rem.	0.1	1.8 -2.7	0.6	0.5	0.7	Zn 0.1 Cr 0.5 Ti 0.2

Steel	C - 0.15% approx.
TlC-O and NT4-O	Annealed condition
HT9-WP	Solution and precipitation treated.

The steel was coated with aluminium, zinc or tin by hot-dipping or electroplating techniques (Section 4.1) and the tubes degreased and wire brushed immediately prior to welding. The same welding jig was used for both butt and lap welds (Figure 12). The shaft of this jig was constructed

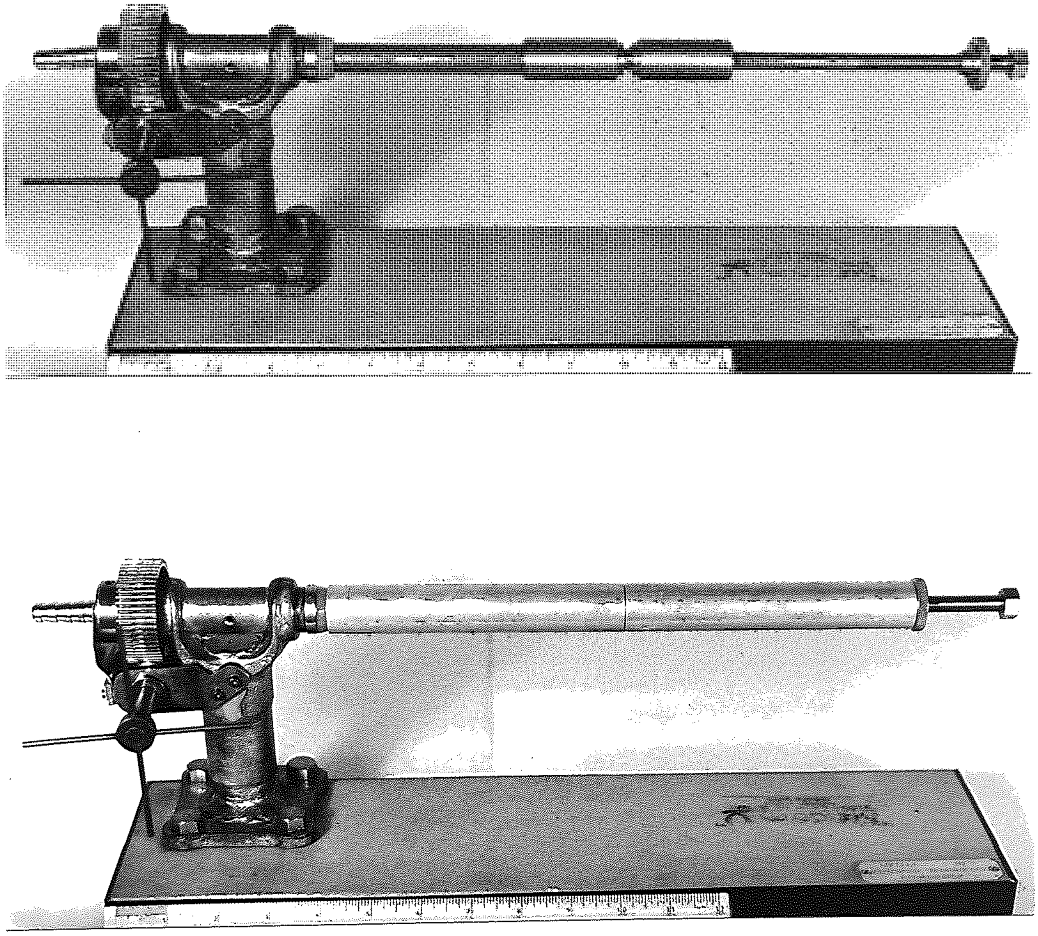


Figure 12

Welding Jig for 1 in. diameter tubes.

Groove measurements - $\frac{1}{8}$" radius and 3/32" deep with 1/16" diameter holes.

in two halves which could be separated after the weld was completed and it was machined so that during welding, argon gas could be supplied to the underside of the joint, through 1/16 in. diameter holes.

A Tangye pressure pump was adapted for testing of the welds. This was a two speed single-acting pump of simple rectangular form bolted to a large base plate. Several tube fixtures were tried before a satisfactory testing technique was obtained. This comprised a gland union fitted at each end of a 4½ in. length specimen. The gland nut on the pump end was attached by means of a ½ in. B.S.P. thread to the machine. The test tubes were inserted through a clearance hole in the outer nut, the tightening of which on the fixed gland nut, brought end pressure to bear on the taper polythene seal. The same principle was employed on the outer end except that the gland nut, outer nut and seal were entirely separate from the machine and could therefore be assembled on the welded tube prior to making the pump end connection. To prevent the end seals from parting under test pressure, three tie bars encompassing the total length of the assembly were incorporated but which, unless very high pressures were reached, did not create compressional stresses within the test piece.

4.4.1. Summary of Results.

It was general practice to section the welded tubes after pressure testing and examine the macrostructure. Low pressure test results were generally associated with incomplete penetration or the presence of an underbead defect. For example, specimens 172 and 174 were compared (Table XII). The underbead in specimen 172 had formed correctly and penetration was complete while that of specimen 174 was uneven with an underbead defect (Figure 13).

Defective underbeads are sometimes observed in argon arc welds of aluminium alloys. The defect is associated with a gap between the edges of the parent materials, insufficient cleaning of the surfaces to be joined, and inadequate protection by shielding gas of the undersurfaces during welding[21].

Thorough cleaning was always undertaken in this investigation and close contact maintained between the tubes. Where underbead defects occurred, they were due to experimental difficulties, such as slight interruption of the shielding gas supply. In other cases, test 195, for example, good underbead shape was achieved but porosity caused failure at a lower pressure than would otherwise have been obtained. In fact, welds between the coated mild steel and the aluminium-magnesium-silicon alloy (HT9) seemed more likely to contain pinholes than the aluminium (T1C) and aluminium-magnesium (NT4) materials. HT9 being a heat-treatable aluminium alloy, some loss of properties was to be expected as a result of the welding operation (compare pressure test figures in Tables XI and XIII).

For production of the lap welds, the aluminium tubes were expanded sufficiently to enable a length of approximately one inch of mild steel tube to be fitted inside of them. Pressure test results for this design of joint were much lower than recorded with tube butt welds (tests 177, 178 and 191-193, Table XII).

Average pressure test results for the aluminium tubes were as shown

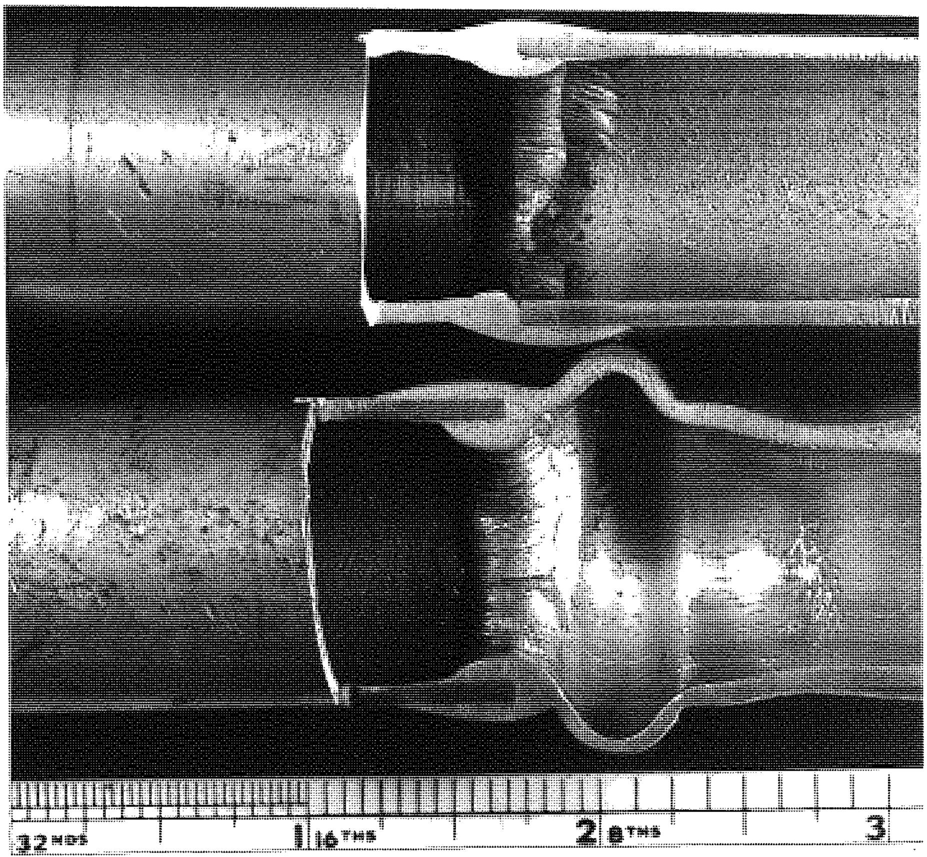


Figure 13

Sectioned tube joints after pressure test.

Top - test 174. Bottom-Test 172

in the following table.

Table XI.

Aluminium Tube	Manufacturers' Figure	Pressure Test Apparatus
T1C	2,000 lb/in^2	1,900 lb/in^2
HT9	4,900 lb/in^2	5,500 lb/in^2
NT4	3,750 lb/in^2	4,100 lb/in^2

Table XII.

Tube butt and lap welds - manual argon arc process.

Tests up to 195
(Electrode .... $\frac{1}{8}$ in. diameter
(Filler rod .... $\frac{1}{8}$ in. diameter
Al - 5% Si

Tests from 199
(Electrode .... 3/32 in. diameter
(Filler rod .... 3/32 in. diameter
Al - 5% Si

Notes.

H/D - hot-dipped coating.

E/P - electroplated.

F.P. - failure in parent material or transition zone.

F.J. - failure in weld.

F.A. - test stopped at recorded figure due to fault developing in test equipment.

R. - retained for various purposes.

Table XII

Test No.	Joint	Al	Steel Coating	Current amps	Argon Torch.	Argon Jig ft^3/h	Pressure Test lb/in^2	Remarks
147-152	Butt	T1C	H/D Al	66-105	18	2	-	Exploratory tests
153	"	"	E/P Sn	75	"	"	2,250	F.A.
154	"	"	"	"	"	"	2,100	F.P.
155	"	HT9	"	"	"	"	3,250	F.J.
156	"	"	"	"	"	"	4,000	F.P.
157	"	NT4	"	"	"	"	4,000	F.A.
158	"	"	" "	"	"	"	3,400	F.J. Pinholes in bead.
159	"	HT9	H/D Sn	"	"	"	-	R.
160	"	"	"	"	"	"	3,800	F.J.
161	"	NT4	"	"	"	"	4,250	F.J. Heavy penetration.
162	"	"	H/D Al	"	"	"	-	R.
163	"	HT9	"	"	"	"	-	R.
164	"	"	H/D Sn	"	"	"	4,100	F.P.
169	"	T1C	E/P Zn	"	"	"	2,100	F.P.
170	"	HT9	"	"	"	"	3,400	F.J. Pinholes in bead.
171	"	NT4	"	"	"	"	4,100	F.P.
172	"	T1C	H/D Zn	"	"	"	4,600	F.J.
173	"	HT9	"	"	"	"	4,000	F.J. Failure due to pinholes in bead
174	"	NT4	"	"	"	"	3,500	F.J.
175	"	"	H/D Al	"	"	"	3,800	F.J.

Continued ....

Table XII (cont'd)

Test No.	Joint	Al	Steel Coating	Current Amps	Argon Torch. ft^3/h	Argon Jig ft^3/h	Pressure Test lb/in^2	Remarks
176	Butt	HT9	H/D Sn	75	18	2	4,000	F.P.
179	"	NT4	"	"	"	"	-	R.
190	"	HT9	"	"	"	"	-	R.
194	"	"	E/P Zn	"	"	"	4,500	F.P.
195	"	"	H/D Al	"	"	"	3,200	F.J. Failure due to pinholes in bead.
199	"	NT4	E/P Zn	66	15	"	5,600	F.J.
200	"	HT9	"	"	"	"	4,800	F.J.
201	"	NT4	H/D Zn	"	"	"	5,000	F.J.
202	"	HT9	"	"	"	"	4,350	F.J.
203	"	NT4	H/D Sn	"	"	"	4,500	F.A.
204	"	T1C	H/D Sn	66	15	"	3,350	F.J.
206	"	T1C	"	62	"	"	2,300	F.J.
207	"	HT9	H/D Al	"	"	"	4,400	F.J.
208	"	NT4	H/D Zn	"	"	"	4,550	F.J.
209	"	T1C	H/D Al	"	"	"	2,400	F.J.
210	"	HT9	"	"	"	"	4,000	F.J.
211	"	"	"	"	"	"	-	R.
228	"	NT4	H/D Sn	64	18	"	4,200	F.A.

Continued ....

Table XII (cont'd)

Test No.	Joint	Al	Steel Coating	Current Amps	Argon Torch. ft^3/h	Argon Jig ft^3/h	Pressure Test lb/in^2	Remarks
229	Butt	NT4	H/D Al	64	18	2	3,850	F.J. Variable quality steel coating
230	"	HT9	"	67	"	"	3,500	F.J. Pinholes in bead.
231	"	"	E/P Sn	"	"	"	4,200	F.P.
177	Lap	NT4	H/D Al	75	"	"	2,300	F.J.
178	"	HT9	H/D Sn	"	"	"	2,000	F.J.
191	"	NT4	H/D Al	"	"	"	2,500	F.J.
192	"	HT9	E/P Sn	"	"	"	-	R.
193	"	T1C	H/D Zn	"	"	"	1,900	F.J.

Table XIII.

PRESSURE TEST ANALYSIS

lb/in^2

TUBE	ELECTRO-PLATED ZINC	HOT-DIPPED ZINC	ELECTRO-PLATED TIN	HOT-DIPPED TIN	HOT-DIPPED ALUMINIUM
T1C	2,100^{o}	4,600^{x} 1,900$^{\emptyset x}$ 2,300^{o} 2,500^{x}	2,250^{+} 2,100^{o}	3,350^{x} 2,700^{x} 2,300^{x}	2,200^{o} 2,400^{x}
HT9	3,400^{x} 4,500^{o} 4,800^{x}	4,000^{x} 4,350^{x}	3,250^{x} 4,000^{o} 4,200^{o}	3,800^{x} 4,100^{o} 4,000^{o} 2,000$^{\emptyset x}$	3,200^{x} 4,400^{x} 3,500^{x} 4,000^{x}
NT4	4,100^{o} 5,600^{x}	3,500^{x} 5,000^{x} 4,550^{x}	4,000^{+} 3,400^{x}	4,250^{x} 4,500^{+} 4,200^{+}	3,800^{x} 2,500$^{\emptyset x}$ 3,850^{x} 2,300$^{\emptyset x}$

NOTES.

+	Apparatus failure (e.g. seal) at this pressure
o	Parent metal failure
x	Weld metal failure
∅	Lap weld

4.4.2. Discussion.

Throughout the complete research programme welded test specimens were prepared in groups from time to time by different operators. It was not always possible, therefore, for each technician to become fully skilled and most weld defects could be traced to lack of experience. This was particularly evident with the joining of the one inch diameter tubes because the tube size made manipulation of torch and filler rod a more difficult process.

With approximately half of the welded components, the underbead penetration was not complete and, in fact, in some instances examination showed that only some 50% of the bead formed correctly. In such cases, higher test figures could have been obtained with 100% correct underbead formation, with the possibility of a greater proportion of failures taking place in the parent aluminium material. It is considered that a fault such as lack of penetration, or the presence of an underbead defect, would rarely occur with fully skilled operators working under production conditions.

The butt weld design is undoubtedly superior to a lap weld as there is insufficient area for adhesion in the latter case, and full mechanical properties cannot be achieved. It would appear from study of the pressure test analysis (Table XIII) that any one of the five steel coatings can be considered suitable as a buffer layer for joining these dissimilar metal tubes, but other factors must be taken into account, for example, corrosion resistance.

4.5. Other Techniques.

A wider range of welding processes is used for joining aluminium and its alloys than for almost any other commonly used material. In view of this fact it was decided that useful knowledge might be acquired by carrying out tests employing consumable electrode gas-shielded arc welding equipment. In addition, a number of tests were made using automatic non-consumable electrode equipment. Experimental work on friction welding has also been carried out to determine whether this technique could be employed to join aluminium to steel, and finally in this section are included some notes on bead-on-plate tests using aluminium clad steel and electrophoretically deposited aluminium on steel.

4.5.1. Lynx Welding Equipment.

This equipment is designed for consumable electrode gas shielded arc welding, the bare wire being fed into the pool at constant speed whilst a blanket of gas shields the weld zone from atmospheric contamination.

A current of 150 amperes was used in conjunction with a 3/64 inch diameter wire. This wire was the smallest in the range normally employed in industry.

A number of 10 gauge sheet butt, and three inch diameter tube to sheet fillet welds were attempted but the tests were unsuccessful. It was evident that a much lower current was required to avoid melting of the steel edge. When the current was reduced, the mode of metal transfer from the electrode abruptly changed from a rapid stream of small droplets, 'spray transfer', to a large intermittent globular transfer. Workers have shown that the critical current below which metal transfer is unsuitable for welding is proportional to wire diameter and not cross-sectional area.[22]

4.5.2. Sigmette Fine Wire Equipment.

A design of gun which will take a wire smaller than the 1/16 inch diameter, which is commonly used for self-adjusting arc welding of aluminium, extends the use of this process into a lower current range allowing the welding of thin gauge materials at increased speed.

Comparison with tungsten arc welding suggests the fine wire technique is more suitable for fillet welds and less difficult for positional work, but lacks the separate control over heat input and filler metal additions where parent metal thickness varies along the joint.

The electrode available was 0.030 inch diameter aluminium-5% silicon wire and tests were made using tin, zinc and aluminium coated steel in combination with several aluminium alloys. A current of approximately 90 amperes and an arc voltage of 16 was used with an argon flow of 18 $ft.^3/hr.$

Tests indicated that the square butt joint was not satisfactory even though the effect of variables in the technique were fully investigated[23]. This confirmed the opinion held by the equipment manufacturers who prefer the use of the torch on fillet and lap joints. A number of aluminium alloy plates were machined with approximately a 45^0 angle and no root face. However, the penetration was not improved with this joint preparation and sealing runs were necessary on the underside in each case.

The equipment was suitable for the production of fillet welds, and satisfactory joints were obtained. The intermetallic layer was quite thin but some porosity was evident. Hydration of the surface oxide film on the aluminium does not normally cause trouble with the non-consumable electrode process, but it can be a serious source of porosity in consumable welding processes. This is thought to be partly due to the very high freezing rate of such welds not giving the hydrogen time to diffuse out before the metal solidifies. Another reason is that it may well be necessary to clean the surfaces more adequately.

4.5.3. Automatic Welding.

Automatic welding with a non-consumable electrode is particularly suitable for straight butt and corner welds and has also been applied successfully to circumferential joints. Whether the torch or the material to be welded is moved, depends on several factors. In this investigation the torch was moved, with the material to be joined clamped in a jig, and these conditions allowed constant arc length to be maintained, thus encouraging uniformity in weld quality and profile. The automatic welding head comprised an argon-arc torch with filler wire feed device. The equipment was fitted with controls which made possible a great variation in experimental conditions such as carriage travel speed and filler wire feed. The jig used was that shown in Figure 2 and edge preparation was square. Correct alignment of abutting edges is important in welding especially with thin material and usually the electrode is set immediately above the edges, but in these tests such a setting produced an irregular weld bead. The electrode was therefore offset about $\frac{1}{8}$ inch on the aluminium alloy side and this produced a distinct improvement in weld quality. It is possible that overheating of the steel coating was avoided in this way. Experimental work involved the use of tin, zinc and aluminium coated steel in combination with aluminium or aluminium alloy.

Many difficulties were encountered such as undercutting of the aluminium, and wire speed increase alone did not overcome this; cracking was often associated with the undercutting. Tilting the material and backing plate very slightly in order to assist flow of molten metal did not improve weld quality. It is suggested that perhaps an oscillating head might possess advantages in laying down a bead, in order to obtain in automatic work, rather similar conditions to those prevailing in manual tungsten-arc welding where the operator encourages the filler metal to wet the steel evenly. Using such equipment, any local variation in coating thickness or oxide inclusions, might have little effect in preventing even wetting of the coated steel.

After investigating a wide range of welding conditions, it was found that the aluminised steel resulted in the most satisfactory joint. Details are given in Table XIV.

Table XIV.

Automatic Welding Technique.

Steel coating H/D Al -	HS30 (10 s.w.g.)
Electrode diameter	$\frac{1}{8}$ inch.
Filler wire (Al-5%Si)	3/32 inch diamater.
Argon flow	18 ft.^{3}/h - electrode 2 ft.^{3}/h - backing plate
Current	170 amperes
Wire speed	40 inches/minute
Carriage speed	4 inches/minute
Arc length	$\frac{1}{8}$ inch.

4.5.4. Friction Welding.

This section describes the practical approach made to joining aluminium and steel by a friction technique. The theoretical aspect with particular reference to interface structure is discussed in Part II.

Basically friction welding is a method of joining bar to bar or bar to flat parts in which the heat for welding is supplied by the friction created between the two surfaces when one is revolved against the other.

Experimental work was intended to explore whether aluminium could be joined to mild steel but the tests were also of value from the fundamental point of view in permitting examination of the joint interface without the introduction of another element like silicon, as occurs in the inert-gas process.

Welds were produced on a machine developed by the British Welding Research Association. Within certain limits it was possible to vary interface pressure, relative rotation speed and the rate at which the stock shortened during welding. Three quarter inch diameter bars were employed for both components of the weld and the combinations were either mild steel with commercially pure aluminium (ElC), or aluminium-magnesium alloy (NE5).

Welding Procedure.

(a) Mild steel to commercially pure aluminium.

Unsatisfactory joints were obtained when rough finished or machined surfaces of aluminium and steel were presented to each other at various machine settings. The aluminium deformed to form a flange around the steel but bonding was almost non-existent. Preheating the steel at temperatures up to approximately 800°C and / or the use of flux was also unsuccessful.

Various joint designs were considered, for example, the diameter of the mild steel bar might have been reduced compared with the aluminium or the joint area contained within a short length of loosely fitting tube to force the aluminium between the walls of the solid rod and tube. The most successful joint was obtained when a disc of $\frac{3}{4}$ inch diameter mild steel bar was in contact with the aluminium surface, the disc being joined to the main mass of steel by a spigot of approximately 5/16 inch diameter and about 3/32 inch width.

Microexamination showed that the original fine grain size of the steel was retained. The spigot was forced into the metal disc and at the corners was separated from this disc by an oxide film. This might lead to early failure in a weld should it otherwise have been satisfactorily made. Thickness of the intermetallic layer averaged 0.0001 inch without any great variation, but a few short lengths seemed almost free of this constituent. From such evidence it is reasonable to assume that bonding did not exist at these areas.

(b) Mild steel to aluminium-magnesium alloy.

With the spigot design described above the spigot area rapidly reached about 800°C, which was considerably higher than the case with commercially pure aluminium. An attempt was made to join directly the $\frac{3}{4}$ inch diameter bar without machining the spigot. Successful joints were obtained as shown by free bend tests, the plastic deformation being confined to zones on either side of the dissimilar metal joint which did not fracture.

The most satisfactory joint was obtained using approximately a half ton friction load and two ton forging pressure, a relative rotation speed of 1400 r.p.m. and 0.25 inch of bar stock was burnt away.

Metallographic investigation showed that in one or two cases there was evidence of cold working effects in the steel at the interface and of projections on the ferrous material being folded back to give a structure rather similar in appearance to a "roke".

Discussion.

It is apparent that joint design and material composition play an important part in determining the type of bond obtained. The difference in thermal conductivity between commercial aluminium (0.54 C.G.S. units) and the aluminium-magnesium alloy (0.32-0.34 C.G.S. units) probably explains why the alloy was welded to the steel without machining the spigot while the aluminium could only be welded with the spigot.

If the thermal diffusivity is determined, using the formula:

$$\text{Thermal diffusivity} = \frac{\text{thermal conductivity}}{\text{sp. ht. x density}}$$

the figures for aluminium and the alloy are 0.8 and 0.54 respectively. With a material of high thermal diffusivity there will be rapid heat dissipation away from the metal surface to be welded, making it very difficult to attain the required temperature for welding the steel to the aluminium. The effect of the rapid heat transfer was overcome in this work by presenting a disc of steel to the aluminium, thus reducing the mass of metal to be heated. With the lower thermal diffusivity of the alloy, heat was not transferred from the end of the bar to the main mass of metal so readily, and therefore the required surface temperature was reached without the necessity of machining a spigot behind a thin disc.

Oxide film composition should also be considered, as according to Brouckère[24], alloys containing up to 8 per cent. magnesium, heated to temperatures between 120° and 350°C are covered with crystalline $\gamma - Al_2O_3$. On heating above this temperature the surface of the film consists of MgO. Progressive heating up to 400°C can cause a duplex film of magnesia superimposed on alumina. It is unlikely that a difference in oxide structure between the aluminium and aluminium-magnesium alloy affects weldability because it is considered that the oxide film will be shattered during plastic deformation. The film will therefore be dispersed, metallic contact will take place and welding will occur at a suitable temperature and pressure. The oxide film is assumed to be "balled-up" by a mechanical process.

The cold worked areas in the steel at the interface indicate that the temperature of the steel bar did not rise to any great extent, as even incipient recrystallisation was not apparent. Therefore, a joint between steel and aluminium produced by the friction welding technique described might be regarded as a variant of cold pressure welding.

4.5.5. Bead-on-Plate Tests.

(a) Aluminium Clad Steel.

Welding tests were made to determine whether aluminium clad steel could be employed as a suitable material for joining to aluminium. Unfortunately, the material available at the time of the investigation was much thinner (0.028 inch) than that used in the main programme (0.125 inch) and the coating thickness was not sufficient to give the technique a fair trial. The intermetallic layer thickness of the clad material was much less than that of aluminised steel.

For welding, an air-cooled torch was used at a current of 30 amperes with argon flow of 14 ft^3/hr and 1/16 inch diameter aluminium-5% silicon wire.

Microexamination indicated that the compound layer was thicker in the region of the welding bead but at no point was it more than 0.0001 inch. The steel grain size was small and unaffected by heat from the electric arc, while at the bead edge the cladding was almost undisturbed. On the underside, immediately opposite the bead, considerable growth had occurred of the intermetallic compound, its thickness approaching 0.0003 inch and it was cracked in several regions.

It is suggested that the joining of clad steel to aluminium or its alloys is possible but a heavier gauge material would be advisable and this should minimize growth of the underside intermetallic layer. Chemical analysis showed that only a small percentage of silicon existed in the cladding so that the beneficial effects of that element were not available.

(b) Aluminium Deposited Electrophoretically.

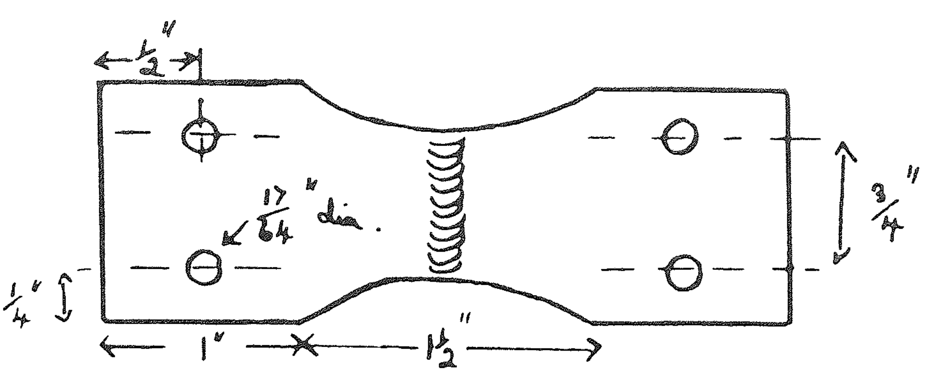
The steel was coated with aluminium by electrophoretic deposition of aluminium powder followed by rolling and heat treatment.

Tests proved unsatisfactory in every instance. The heat from the electric arc destroyed the continuity of the aluminium coating and small nodules of the metal formed around the edge of the bead. Invariably, slight bending of the plate resulted in the bead being stripped from the parent metal and it was evident that there was no adhesion of filler metal to the coated steel.

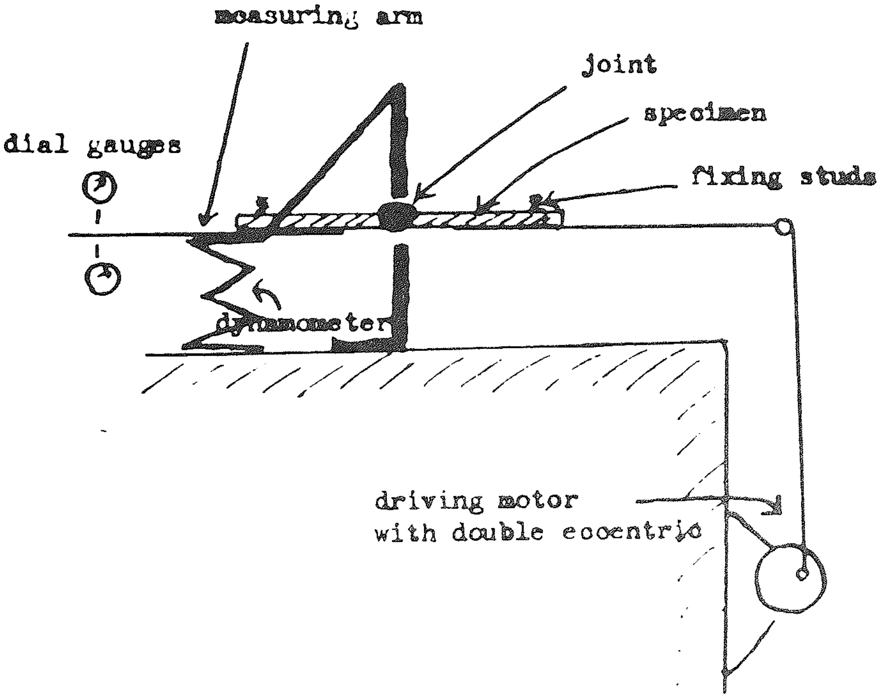
4.6. Fatigue Strength.

A dynamic fatigue testing machine was used to apply reversed bending stresses without any initial static load. Dimensions of the welded specimens used and an operating diagram are given in Figure 14.

A fatigue programme should normally involve the testing of a large number of specimens in order to obtain conclusive results. It was not possible to do this during the investigation but it was hoped that some indication might be given of where failure could be expected.



Dimensions of Specimen for Fatigue Test.



Operating diagram.

Figure 14

4.6.1. Results.

Group 184.

Aluminium joined to aluminised mild steel using the aluminium-5% silicon filler rod.

Specimen A. ± 3 tons 38,600 cycles.

Fracture occurred in the transition zone of the aluminium and there was no sign of failure at the steel/aluminium junction. Porosity in the underbead had no effect on the test result.

Specimen B. ± 3 tons 36,500 cycles.

Specimen C. ± 5 tons 26,700 cycles.

In both cases failure occurred in the transition zone on the aluminium side, with the dissimilar metal junction remaining intact.

Group 186.

Aluminium-magnesium alloy joined to hot-dipped tin coated steel with the aluminium-5% silicon filler rod.

Specimen A. ± 5 tons 669,000 cycles.

Specimen B. ± 5 tons 1,534,500 cycles.

Specimen C. ± 5 tons 574,900 cycles.

Specimen D. ± 5 tons 663,100 cycles.

Failure took place in each case on the alloy side of the joint, the dissimilar metal junction remaining intact.

Group 188.

Aluminium-magnesium alloy joined to galvanised mild steel by means of the aluminium-5% silicon rod.

This test panel was selected because the top bead was very flat and although the penetration was adequate, in other respects the weld quality appeared to be poor.

<u>Specimen A</u> ± 5 tons 102,100 cycles.

<u>Specimen B</u> ± 5 tons 174,400 cycles.

<u>Specimen C</u> ± 5 tons 124,400 cycles.

<u>Specimen D</u> ± 5 tons 150,300 cycles.

Failures occurred at the interface with fracture starting at the top surface where reinforcement was lacking and the bead surface was very irregular.

There appeared to be a relationship between the number of cycles to failure and the condition of the top bead.

4.6.2. Discussion.

Although investigation has been somewhat limited, there is sufficient evidence to show that these dissimilar metal welds are capable of fatigue strengths at least equal to the parent aluminium material. As complete removal of the bead reinforcement is not possible (Section 11), the weld bead, and the junction of the bead and the surface of the parent metal, should be smooth in order to improve fatigue performance. If the welding operation does not achieve this smoothness, and argon-arc welding does tend to produce a steep sided bead, then it might be advisable to polish the weld bead surface.

4.7. Effect of Heat Treatment.

Little is known of the effect of post-heating, thermal cycling or of thermal shock on aluminium-steel joints, although steel backed aluminium bearings and aluminium finned cylinders for aero-engines have operated successfully for years.

Miller[2], and Cooke and Levy[7], have pointed out that post-heating of pressure welds between aluminium and steel would, under proper conditions, increase the tensile strength of such joints. Too high a temperature or too long a time at elevated temperatures, however, decreases joint strength. Most workers consider that the reduction in strength is due to diffusion resulting in an increase in the thickness of the iron-aluminium compound layer at elevated temperatures.

A common problem to many of the aluminium coating processes is control of the compound layer both during application of the coating and during subsequent thermal treatments. Therefore, some preliminary investigation of the effect of heat-treatment on the welded joints seemed vital, particularly as parts in service might be subjected to prolonged heating at temperatures up to 400°C or so.

Investigation comprised (1) fairly long periods of exposure at temperatures ranging from 350°C - 560°C, followed by micro-examination of the interfacial layer, (2) similar periods at temperatures of 350°C, 400°C and 450°C followed by tensile testing and (3) thermal cycling between 0 - 300°C every two hours, for a prolonged period followed by a streching test.

4.7.1. Testing Procedure and Results.

1. A test panel of aluminised steel joined to commercially pure aluminium

was selected. The welded panel was cut to dimensions 5" long by $1\frac{1}{2}$" wide so that adequate metal was retained on either side of the joint. A small laboratory type resistance wound tube furnace was employed for the heating.

The procedure adopted was to subject the specimen to increasing temperature over a fairly long period of time, cutting off sections at the end of each step in the investigation.

For the purpose of comparison, a number of similar welds which had not been heat-treated were examined and compound thickness measured. This varied between a minimum of 0.0002" and a maximum of 0.0004".

Specimen 165 (a)

Treatment consisted of two weeks' exposure at 350 - 400°C. The average thickness of the alloy layer after this heat-treatment was 0.0008 inch.

Specimen 165 (b)

This specimen was subjected to the same treatment as 165 (a) with, in addition, two weeks' at 425 - 450°C.

The average thickness of the alloy layer was now 0.0009 inch. The microstructure is shown in Figure 15.

Specimen 165 (c)

In addition to that of (a) and (b) this specimen received two weeks' heat-treatment at 500°C.

As will be noted in Figure 16, in addition to the intermetallic layer there now occurred a further constituent, probably of similar

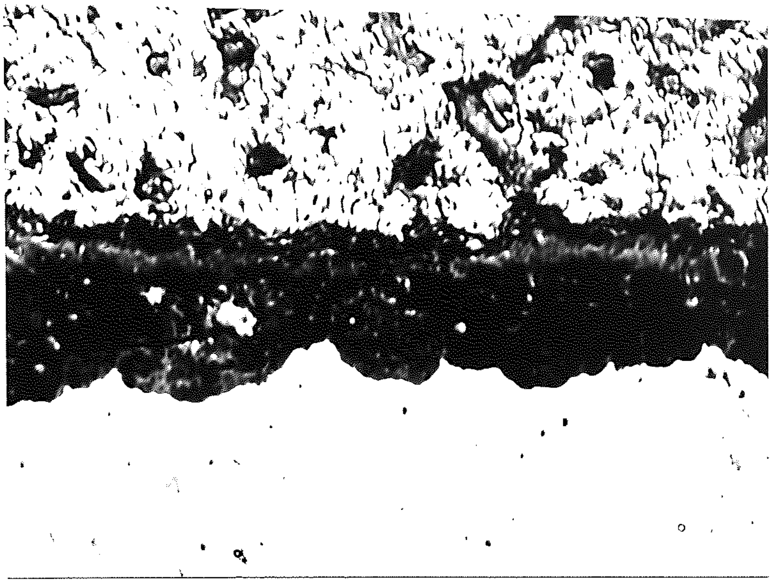


Figure 15

H/T specimen - test 165b

Etch 0.5% HF x 1000

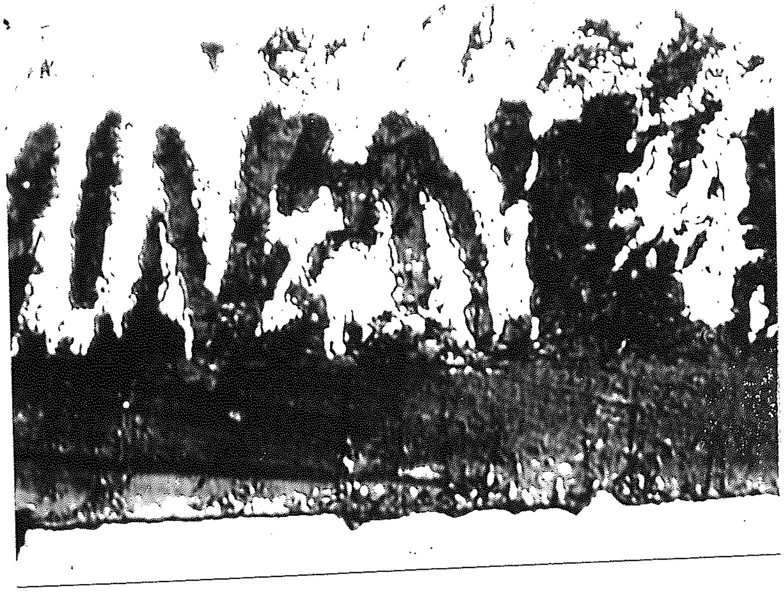


Figure 16

H/T specimen - test 165c

Etch 0.5% HF x 1000

chemical composition, which was acicular in nature. The average alloy layer thickness was 0.0009 inch, while the depth of penetration of the acicular constituent was 0.001", thus the total thickness of brittle compound approached 0.002".

Specimen 165 (d)

Treatment of 165 a, b and c with, in addition, two weeks at 540°C. The usual layer of intermetallic compound occurred and its thickness was similar to that of 165 (c), however, the acicular constituent extended approximately 0.002 inch, into the filler metal zone. It should be noted that although the length of the acicular compound had increased, the width remained similar to that of 165 (c).

Specimen 165 (e)

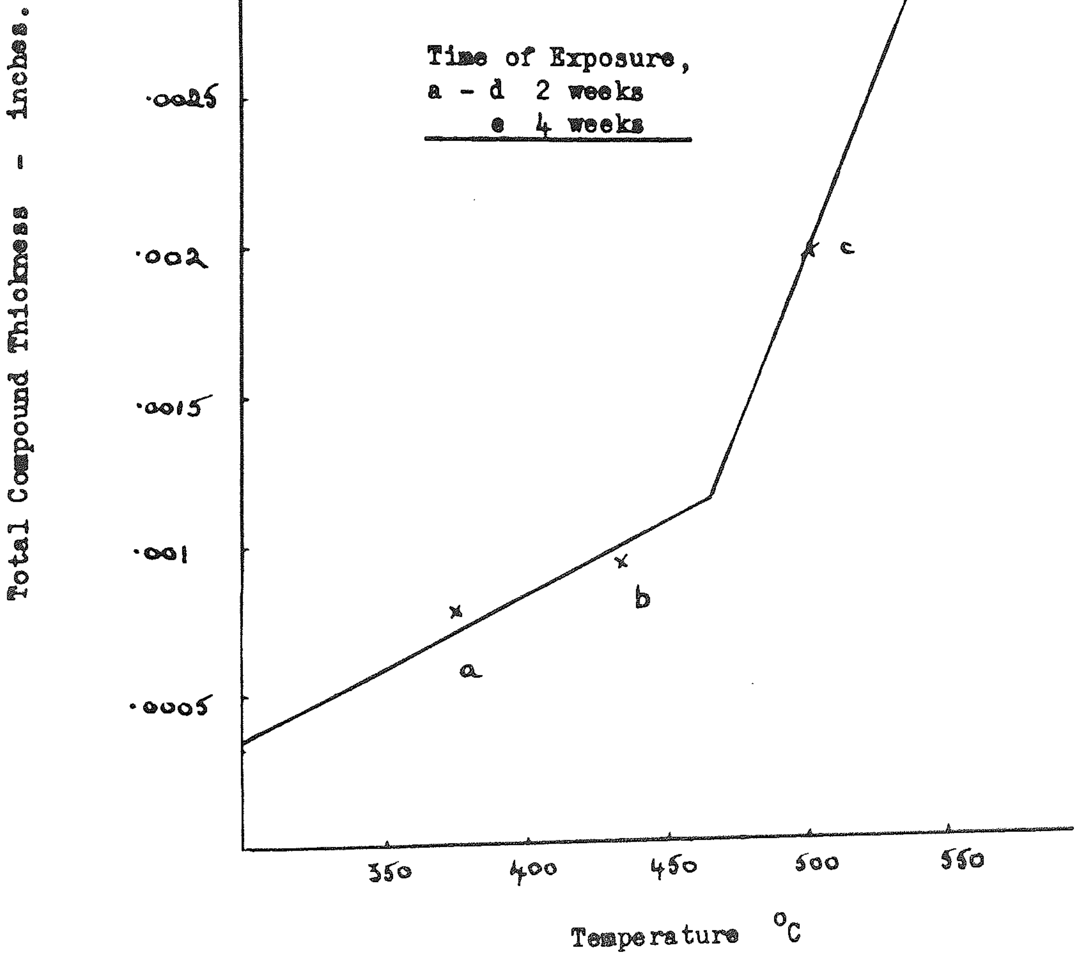
Treatment of 165 a, b, c and d with, in addition, four weeks at 560°C.

A very wide band of compound was now evident, showing distinct signs of disintegration. Figure 17 is a plot of total intermetallic compound thickness vs temperature, the total thickness comprising the width of the normal aluminium-iron layer and the extent of penetration of the acicular constituent into the filler metal. The constitution of these phases is discussed in Part II.

2. Specimen 167.

Aluminium joined to hot-dipped tin coated steel using the aluminium-5% silicon filler rod.

Three test pieces 167 a, b and c were heated for 15 days at



Effect of temperature and time on compound formation.

Figure 17

temperatures of 350°, 400° and 450°C respectively. The control specimen, number 125, which had not been heat-treated gave a tensile strength range of 4.8 - 5.0 ton/in^2 with failure in the parent metal.

<u>Tensile strength after heat-treatment.</u>

167a - 0.76 ton/in^2
167b - 0.76 ton/in^2
167c - 0.81 ton/in^2

The aluminium failed by necking in each case well away from the joint area; there was no indication of failure in the bond.

<u>Specimen 273.</u>

Aluminium-magnesium alloy joined to aluminised steel using the aluminium-5% magnesium filler rod.

The test pieces were heated at 350°C for a period of three weeks. The control specimens tested in the as-welded condition gave a range of 11.2 - 12.2 ton/in^2.

<u>Tensile strength after heat-treatment.</u>

273a - 10.4 ton/in^2
273b - 10.1 ton/in^2

Failure in this case took place at the interface.

3. The weld selected for this part of the investigation was between an aluminium-magnesium-silicon-manganese alloy (HS 30) and steel electroplated with tin. The panel was cut in such a manner that the whole length of the joint with approximately ½ inch of parent metal each side, could be placed in a small electrically heated tube furnace. The treatment consisted of a two-hourly 0 - 300°C cycle maintained for twenty weeks.

After heat-treatment, the weld was stretched using a load of approximately 30 ton/in^2.

4.7.2. Discussion.

The results of the diffusion experiment indicate that considerable growth of the alloy layer must be expected when welded components are subjected to elevated temperatures for prolonged periods. Perhaps the most important observation is that, between approximately 450 and 500°C, the diffusion mechanism changes so that this layer does not show a further increase in width but compound growth continues in the form of an acicular constituent which increases in length rather than width until a very high temperature is reached. The low ultimate tensile strengths of the specimens taken from panel 167 are accounted for by the effect of the heat treatment on the parent aluminium material rather than weakness in the intermetallic layer where fracture might reasonably have been expected to occur. The prolonged period of exposure to an elevated temperature resulted in a very large crystal size in the aluminium and, under tensile loading conditions, the material deformed plastically at a low stress.

As fracture at the interface had occurred in the control specimens for panel 273, it was to be expected that the heat treated components would fail in a similar manner. The reduction in strength was not as great as anticipated and the results can be considered satisfactory.

Testing a weld longtitudinally produced no sign of weakness in adhesion of the filler metal to the parent metals.

Figure 17 shows that exposure to any temperature above 450°C will lead to a rapid increase in the amount of brittle aluminium-iron compound present at the weld interface. Even below this temperature, the increase is marked and it is considered that 300°C is the maximum temperature of exposure that can be tolerated over a long period.

4.8. Corrosion Aspects.

Several specimens have been exposed to an industrial or marine atmosphere for approximately three years. Sheet butt, and tube to sheet fillet welds, were selected for testing, and those in the industrial atmosphere were examined fairly frequently, while those exposed to coastal conditions were inspected at about six monthly intervals.

In each case the aluminium parent metal and joint area is satisfactory, in fact in one or two cases, the joint condition can be described as perfect. Where the steel component is coated with tin, however, considerable attack has occurred, and with the marine atmosphere, rusting is evident over some 80% of the surface through pores and particularly at the heat-affected zone on the underside of the sheet. The galvanised steel, whether subjected to industrial or marine conditions, does not show the same general attack, but there is more corrosion on the underside heat-affected zone than is the case with tin, and rather more rusting on the cut edge. With aluminised steel, very slight rust spotting is apparent and on the cut edge rusting is similar to tin and zinc coatings. Signs of weathering are mainly confined to the more protected side of the panel.

5. CO-ORDINATING DISCUSSION.

The results of the various groups of tests have been reviewed separately but it is useful, at this stage, to examine the common facts which have emerged as a consequence of Part I of this investigation.

Before commencing this work, consideration was given to the possible use of oxy-acetylene welding equipment. It is now clearly evident that many reasons can be found for rejecting this process in favour of inert gas techniques. It would, for example, be extremely difficult to control intermetallic compound thickness using the gas welding process. A major difference between flame and electric arc welding is the shorter time at temperature for the latter process and this limits the amount of diffusion taking place and therefore minimizes brittle phase formation. Brittleness can be reduced by the operator keeping the flame of the gas welding torch well directed toward the aluminium, and by very careful manipulation of the filler rod to protect the steel coating from excessive heat. Even so, the amount of compound will be greater than with arc welding and cracking within the layer is a distinct possibility. Control of oxidation of the buffer coating on the steel will also be very difficult during gas welding and the presence of flux residues in the weld bead is likely to aggravate corrosion problems.

It is necessary to use a buffer coating on the steel since all attempts to join aluminium to steel without preliminary coating of the steel proved unsuccessful.

For aluminium to steel joints, utilising hot-dip coatings on the ferrous material, there are three ways in which compound layer thickness can be restricted. In the first place, additions can be made to the molten metal bath, such as silicon to aluminium or a small percentage addition of aluminium to zinc in the case of aluminizing and galvanizing respectively. The effect seems to be one of slowing down the reaction rate between the molten metal and the ferrous metal surface. Secondly, the welding process employed will have an important influence, and thirdly, many of the test panels were prepared with an aluminium-5% silicon filler material. This silicon content undoubtedly assists in minimizing the alloy layer thickness at the joint interface. With electrodeposited coatings, only the second and third considerations apply.

The weld strength depends a great deal on the mechanical properties of the intermetallic compound and thickness is a most important factor in controlling the strength of the layer. As growth rate determines its thickness, it is an advantage to be able to control reaction rate between the liquid metal and steel surface. A thick layer is weak and very brittle and unable to deform plastically as in the case of a thin layer. With sufficient strength in the intermetallic layer, fracture will occur in the parent aluminium material, or at the steel-steel coating interface. Therefore, the weld can be stronger than the aluminium or aluminium alloy or weaker if an interface of low strength exists in the joint area.

Most of the investigation has been carried out using either aluminium, tin or zinc as the coating metal on the ferrous material. It is not difficult to coat the steel with any of these metals; in fact, this was one of the basic reasons for their selection. However, the coating quality may vary considerably between one supplier and another, so that surface condition should be carefully studied, particularly as weld repair, whilst not impossible, is a difficult process and requires considerable skill on the part of the operator. The quality of the coating must be assessed by examination of the microstructure (particularly to determine the thickness of intermetallic compound in the case of hot-dipped coatings), coating thickness measurement and general visual examination. The work has shown the need for a smooth, even coating, free from both oxide and from pronounced metal build-up at the edges and corners of the steel. A simple adhesion test will often reveal any weakness in the bond between steel and metal coating. Generally, a thickness of 0.002" - 0.004" aluminium, tin or zinc metal coating on $\frac{1}{8}$" thick steel is adequate to provide suitable conditions for welding these dissimilar materials.

In addition to intermetallic layer strength and steel-steel coating bond, the properties of the weld will also depend on the adhesion or alloying of filler metal to the coating and on the area of filler metal contact with this coating. Increased contact area can be brought about by the preliminary surfacing technique described in Section 4.3.1. The use of this technique facilitates the welding of the aluminium component to the steel because the fillet weld is made between the aluminium component and a layer of aluminium filler metal rather than a relatively thin metal coating on the steel. A larger effective weld area will now exist and the stress on the weakest part of the welded assembly will be much less. Increased contact area should only be required with components where there is insufficient strength to meet design requirements. Such a situation might arise when a fillet weld is necessary between, for example, aluminised steel and a high strength aluminium alloy and it is desirable that the mechanical properties of the joint are at least equal to the parent aluminium material.

On very large steel components the difficulty of local coating of the area required for joining will have to be overcome, as neither electroplating nor hot-dipping techniques can be applied very easily. In addition, a difference in potential will exist between the locally coated or protected steel and the uncoated areas, so that corrosion may be severe on the steel surface under certain circumstances.

Pressure test results for the butt and lap joints in the small diameter tube investigation (Section 4.4.) indicate that the filler metal should be in contact with the top, bottom and edge surfaces of the steel. This is considered to result in maximum strength being obtained, but additional experimental work reported and discussed in Part II, Section 11, enables a clearer picture to be obtained of the effect of bead geometry on weld strength.

In each joint design, except perhaps that of the three inch diameter alloy tube to steel sheet fillet weld, a secondary supply of argon gas was found to be necessary. Oxidation of the steel coating on the underside of a butt weld, or on the other side of a fillet weld, proceeds rapidly during welding unless a protective atmosphere of argon is supplied.

Without such protection, intimate contact between molten metal and coating cannot result and the spreading power of the filler metal is very much reduced. It must be remembered that these metal coatings are relatively thin, and liable to heavy oxidation under these conditions of welding. Such oxidation might well result in little or no metallic coating being left on the steel. The molten filler metal will then flow unevenly and the arc may be interrupted, causing a defect in the joint. The operator will also have some difficulty in restriking the arc where the coating is thin and/or covered with an oxide film. Consumption of argon gas during welding was gradually reduced as experience was acquired, and later tests in the investigation were made with a flow through the torch of 14 $\text{ft.}^3/\text{h}$ and an underflow of 2 $\text{ft.}^3/\text{h}$. It is possible that the rate of primary flow could be reduced further under production conditions, and tests would very quickly establish a safe minimum.

No special difficulty was encountered with the 5% silicon filler rod until work on the aluminium-magnesium material commenced. It soon became apparent that this material caused embrittlement with the parent aluminium material so that joints failed directly across the line where the steel edge was in contact with the aluminium. On changing to the aluminium-5% magnesium filler, satisfactory results were obtained with aluminised and galvanised steel but the hot-dipped tin coatings resulted in severe cracking in the weld and this is the subject of further work in Part II.

In spite of the general practice of using an aluminium-silicon filler rod, because of its attractive welding properties, it should not be used when special corrosion resistance to some particular environment is required. For instance, heavy attack of aluminium-5% silicon welds on nitric acid storage vessels has been observed.

PART II.

6. LITERATURE SURVEY.

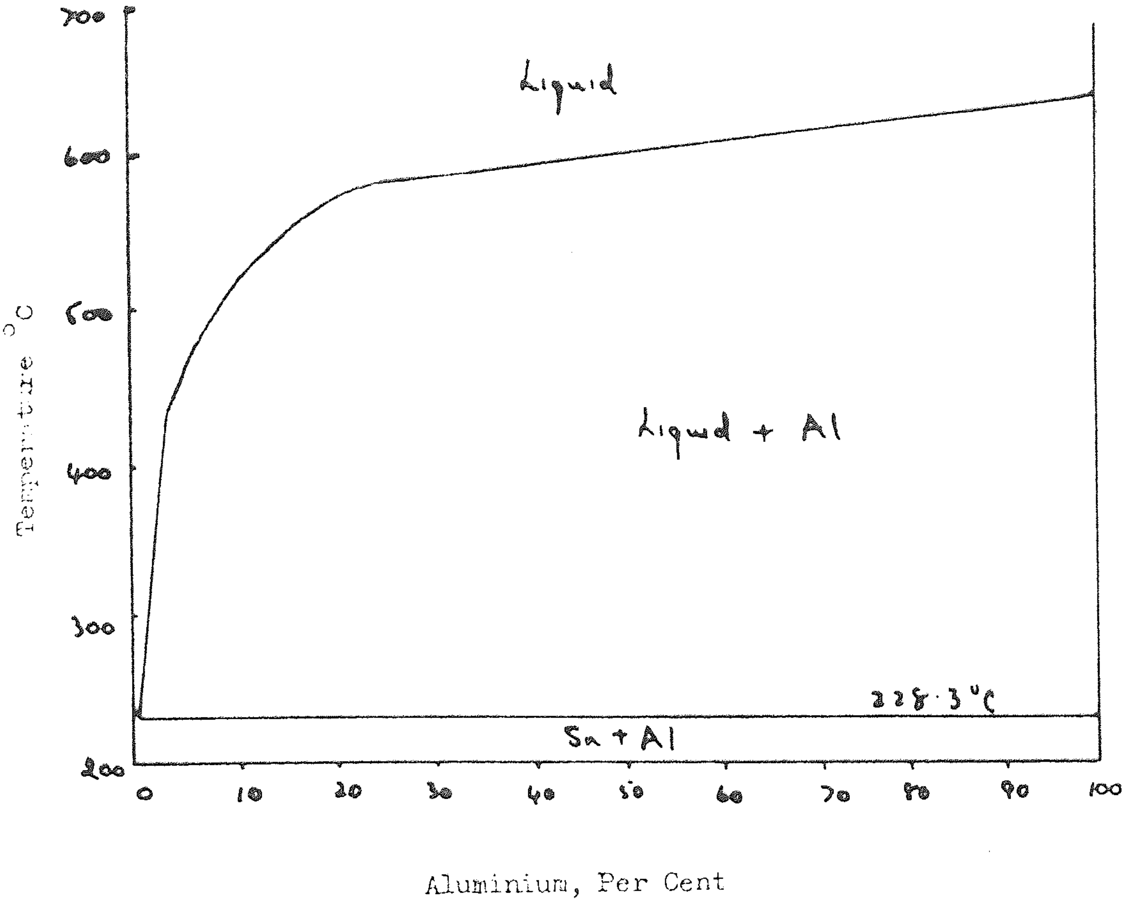
Consideration of the results obtained from the work described in Part I indicated that sound, reliable joints could be produced under suitably controlled conditions. It was evident, however, that a more fundamental approach was desirable from the point of view of the use of tin, zinc and aluminium coatings on the steel, the metallurgical considerations involved, and the effect of bead geometry on strength.

A number of problems needed investigation, for example, the reason for cracking occurring in welds produced under certain conditions when tin was the buffer coating. A study of solute element diffusion in the weld zone was also necessary, particularly in connection with zinc coated mild steel.

Before commencing this part of the research programme a survey of related literature was undertaken.

6.1. Tin Coatings.

The equilibrium diagram for the binary system, aluminium-tin, contains a simple eutectic at about 0.5% aluminium and 3.6°C below the melting point of tin (Figure 18). As might be expected, the eutectic material is much harder than pure tin. With chill cast alloys up to 99% tin, the microstructure consists of primary aluminium with inter-dentritic areas of tin-rich material. The examination of data and equilibrium diagrams shows that the solubility limit of tin in aluminium is considered to be as shown in Table XV.



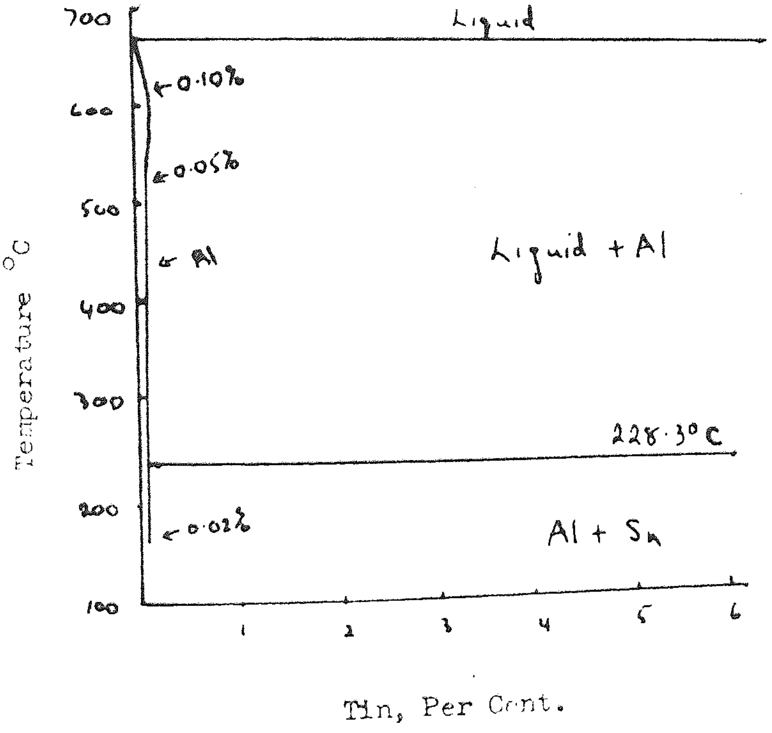


Figure 18

Aluminium - Tin

Equilibrium Diagram

Table XV.

Temperature	Weight % Sn
650°C	0.05
620°C	0.09
590°C	0.08!
560°C	0.06
530°C	0.04
160°C	extremely small

Sully, Hardy and Heal[25] observed a more or less continuous network of tin-rich eutectic in the cast condition which had little effect at room temperature, but exerted considerable influence on the properties at higher temperatures.

Additions of silicon, zinc, magnesium and manganese were found to have no substantial effect on dendrite size nor on the tin distribution in either sand or chill cast aluminium-10% tin alloys. Only nickel or perhaps nickel combined with copper tended to reduce the film forming tendency of the tin.

Of considerable interest to this dissimilar metals welding investigation are their findings that even below 100°C there is a pronounced drop in ductility in binary aluminium-tin alloys. Commercial aluminium-tin alloys and an aluminium alloy containing 5% tin with 2½% silicon retained their ductility to a greater extent at higher temperatures.

The room temperature strength of an aluminium-5% tin alloy has been reported as 4.2 tons/sq.in. and approximately one ton per sq. in. at 300°C. With a 5% tin - 2½% silicon material it was 7.5 and 2.25 tons/sq.in.

respectively. From these published figures for tensile strength and elongation it would appear that silicon has a beneficial effect. Therefore the use of an aluminium-5% silicon filler rod might be advantageous particularly at elevated temperatures.

At room temperature the aluminium-tin eutectic has a similar strength to the aluminium matrix. At higher temperatures, strength and ductility of the binary alloy is mainly determined by the rupture of the eutectic films and although these may have a high ductility, they are generally so thin that little deformation of the specimen occurs before actual fracture takes place.

6.2. Zinc Coatings.

It was considered that, because a weld between aluminium and coated steel is unusual, a study of solute element diffusion, for instance zinc through the weld metal, should be made.

From various investigators' results, at the approximate temperature of 500°C, the relative diffusion rates of solute atoms in aluminium in ascending order appear to be, manganese, copper, silver, silicon, magnesium and zinc.[26] Very little work has been published dealing with the influence of one solute element on the movement of another when aluminium is the solvent metal. However, it seems reasonably agreed that the diffusion of zinc in aluminium is relatively high compared with other metals.

This high diffusion rate must be considered when zinc coated steel is welded to aluminium-magnesium material (NS5) using the aluminium-5%

magnesium filler metal, as the age-hardening of aluminium-zinc-magnesium alloys can occur. Early investigations showed that these alloys possessed relatively high strength properties but unfortunately seemed very prone to stress-corrosion. It was found later that the addition of elements such as copper, manganese and chromium reduced the stress-corrosion tendency. Polmear[27] has shown that the most important effect of magnesium appears to be one of modifying the ageing process in the aluminium-zinc binary system. Other workers[28] have reported that high purity base alloys of aluminium-zinc-magnesium when quenched from 465°C and naturally aged, improved in certain mechanical properties but decreased in ductility as the alloying content and ageing time were increased. Artificial ageing also gave an increase in proof stress and tensile strength with increasing alloy addition, but it was found that above about 9% total zinc and magnesium, the material became very brittle. With an alloy of 12.5% zinc plus magnesium, a short period of natural ageing was sufficient to produce intercrystalline fracture.

The observations on the effect of air-cooling these ternary alloys are important in that proof and tensile figures were only slightly reduced. Ductility, as measured by elongation and izod values, was reduced especially in the more dilute alloys. Electron micrographs have shown the existence of denuded grain-boundary zones, even under normal ageing conditions, resulting in intercrystalline weakness.

Polmear and Scott-Young[29] have investigated the effects of small amounts of manganese, copper and chromium on the ageing characteristics of ternary aluminium-zinc-magnesium alloys. Polmear concluded that whilst manganese had little effect, chromium accelerated high temperature ageing but had the reverse effect at low temperatures.

Referring to practical welding considerations, it has recently been reported by Bel'chuk, Gluskin and Fedorov[30] that they obtained a lower weld strength with zinc as the steel coating compared with aluminium on the steel, but no explanation was suggested. This confirms results obtained by the present author (Section 4.2.2. and Table VI) where reduced strength was obtained when galvanised steel was welded to the aluminium-manganese alloy (NS3).

Reduced strength was not obtained for any of the galvanised steel-aluminium alloy specimens used in the bead geometry investigation (Section 11). This is because the strictest control was exercised over the galvanising operation so that the coating quality was superior to that obtained for test plates used in Part I of the investigation.

In further discussion, Bel'chuk[31] considers that in the case of galvanised steel, the melted aluminium drives back the zinc (which is burnt out) and enters into direct contact with the solid, warmed steel surface. This argument is pursued further in the discussion (Section 9.2.)

6.3. Aluminium Coatings.

The author has discussed elsewhere[32] the coating of steel by aluminium using spraying, calorizing, cladding, electroplating or hot-dipping methods. In addition, strip can be coated with the metal by electrophoretic deposition of aluminium powder followed by rolling and heat treatment[33], whereby the coating thickness can be controlled to fine limits and very little intermetallic forms.

Aluminium coated steel is firmly established in many fields where superior heat and corrosion resistance is demanded and the hot-dipped material is manufactured in two grades of coating analysis. One type has an aluminium-silicon coating and the other a commercially pure aluminium. Silicon alters the surface oxide characteristics of the bath and the viscosity of the aluminium.

In this welding investigation, a constant problem has been the control of compound layer thickness. This was worthy of attention because the mechanical properties, particularly ductility, elongation and Izod values, are very dependent on the interfacial zone condition. The question of intermediate layer composition as determined by the reaction between solid steel and molten aluminium (or alloy) during welding is similar to that when solid iron or steel is immersed in an aluminium melt, a process which has been the subject of numerous investigations. However, with the joining of steel to aluminium, apart from a small number of tests made with commercially pure aluminium or other filler metals, an aluminium-5% silicon filler material has been employed. Thus research results concerned with iron immersion in molten aluminium are not strictly comparable but nevertheless are of value. On the other hand, with friction weld specimens, no filler rod was necessary and hence a bond was made directly between the low carbon steel and commercially pure aluminium bar. In this case, published information is of direct interest.

Gebhardt and Obrowski[34] demonstrated that when iron is placed in molten aluminium, the eta phase - Fe_2Al_5 predominates in the intermediate layer. Theta has been widely accepted as the intermediate phase richest in aluminium. Bradley and Taylor[35] claimed that X-ray evidence strongly indicated that theta - $FeAl_3$ decomposed into a mixture of Fe_2Al_5 and Fe_2Al_7 below 600°C, Fe_2Al_7 being stable between approximately 77.5 and 78.6 at % aluminium. The diffraction pattern apparently only slightly differed from that of theta, the difference being defined as second-order effects. In more recent work, Black[36] reported that these results could not be reproduced and Raynor and co-workers[37] also reached the conclusion that $FeAl_3$ does not decompose.

In examination of both types of aluminium and aluminium silicon coatings on steel, it has been reported[38] that the intermediate layer for both coatings contained FeAl as one of the main constituents with Fe_3Al also present but in smaller quantity. Neither $FeAl_3$ nor Fe_2Al_7 were found with either of the coatings.

The diffusion of aluminium in iron is considered to be almost entirely determined by the Fe_2Al_5 phase[39]. The preferential formation of this phase, Fe_2Al_5, is brought about by a very high rate of diffusion, many times greater than that of other possible aluminium-iron phases.

In a study of the structural constitution of the Fe_2Al_5 phase, Schubert and fellow workers showed that it possessed an orthorhombic unit cell[40]. The dimensions are a = 7.66, b = 6.39 and c = 4.195 kX for an alloy containing 72 at % aluminium. Schubert also demonstrated that the lattice points of the c - axis are occupied only by aluminium atoms and that the vacant lattice sites are very numerous. It appears then, that the opportunity exists for preferential mobility of the aluminium atoms in the c - axis direction. These observations help to provide a sound reason for the directional dependence of the diffusion rate and the high velocity reaction rate in forming Fe_2Al_5. The growth rate of the phase is shown to be so great compared with other possible phases that no other intermetallic phases can, in this respect, really assume similar importance in the aluminium-iron system.

In the experiments of Heumann and Dittrich[39], test specimens which had been subjected to deformation were intended to achieve a more uniform boundary development for the intermetallic compound by assisting nucleus formation. It was found that a tongue-shaped structure indicating pronounced directionality still existed. They then devised test conditions employing smoothly ground, completely recrystallised iron specimens which were immersed in an aluminium bath with air excluded. The expected columnar structure was clearly revealed. The possibility exists of course, even with careful experimental work, that nucleation can arise at so many centres that the crystals growing from them would, at an early stage, begin to interfere with each other. The structure would therefore soon be modified and probably in the great majority of the welded specimens, this is, in fact, what occurred. They also found that when the Fe_2Al_5-phase is formed at temperatures above 1000°C, the compound no longer possesses a tongue-shaped structure.

Another important consideration relative to this welding investigation is the discussion in the same paper on aluminium clad iron or steel sheets. The recrystallising anneal of clad sheets which is generally undertaken after fabrication would be thought to cause disintegration within a short period, of the non-ferrous metal coating. In fact, in practice, annealing does not bring this about and the reaction phase only makes its appearance at annealing temperatures of about 500°C under exceptional circumstances such as the use of thin metal coatings. It is suggested that with an undeformed surface on the ferrous metal, nucleus formation is very restricted, so that the reaction can only be initiated at temperatures above approximately 600°C. If the metal has been severely deformed, the reaction takes place below this temperature but is gradually arrested as a result of increasingly poor contact between the aluminium and the Fe_2Al_5 boundary.

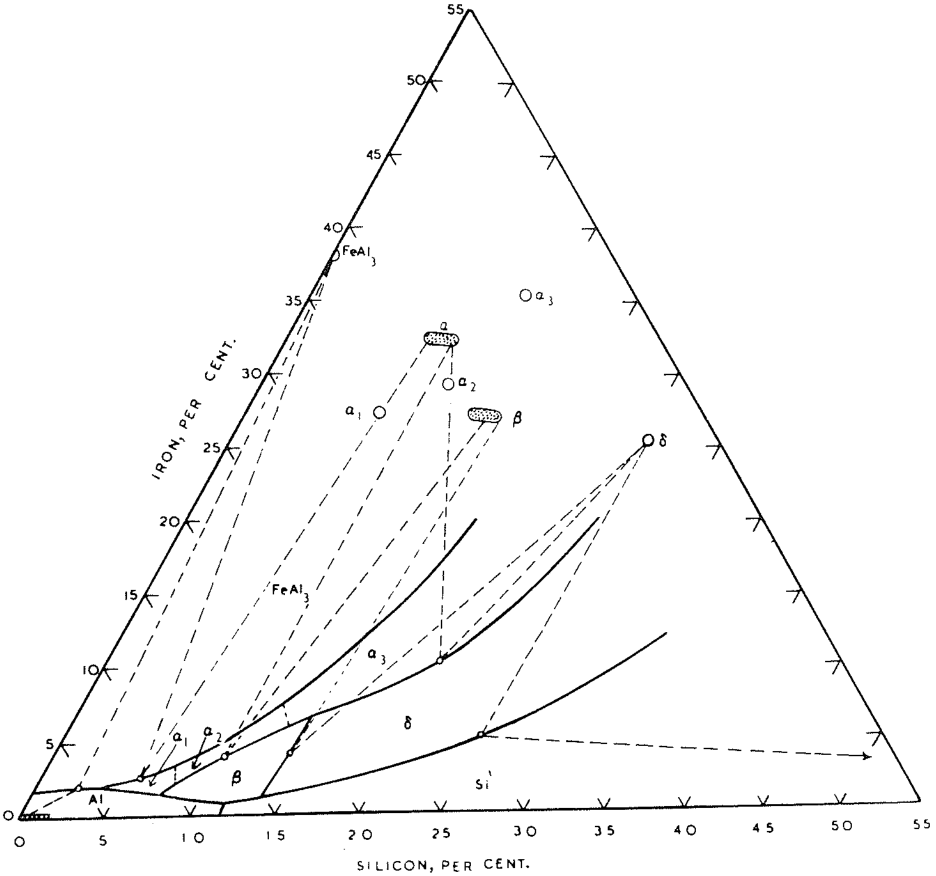
Referring now to the aluminium-iron-silicon system, which is of interest to this research programme, a considerable number of ternary phases, as listed in Table XVI, have been discussed in various papers.

Table XVI.

Phase.	Structure.	Composition.
α - Al - Fe - Si ($Al_{12}Fe_3Si$)	cubic unit cell isomorphous with α - Al - Mn - Si a = 12.523 kX	31.9% iron (41) 5.6% silicon
α - Al - Fe - Si ($Al_{12}Fe_3Si$)	cubic unit cell	27.3 wt % Fe (42) 7.0 wt % Si
α' - Al - Fe - Si	hexagonal structure	32.1 wt % Fe (43) 8.7 wt % Si
α_2-Al - Fe - Si	hexagonal structure	29.2% Fe (42) 11.3% Si
α_3-Al - Fe - Si	cubic	35.3% Fe (42) 12.8% Si
β - Al_9- Fe_2- Si_2	monoclinic unit cell	27.2 wt % Fe (41) 13.5 wt % Si
t - Al - Fe - Si	tetragonal unit cell	- (41)

Compositions of α_1, α_2 and α_3 are indicated by ringed points in Figure 19.

Solid aluminium is able to hold in solid solution fairly large amounts of manganese if melts are very rapidly quenched[44,45] and argon-arc welding might reasonably be thought to produce similar conditions with rapid cooling of the weld pool. Lattice parameter measurements indicated a high degree of supersaturation with as much as 9.2 wt (4.7 at) % of manganese in solid solution compared with the maximum equilibrium solubility of about 1.4 wt (0.7 at) % manganese. The aluminium-iron-manganese system has been investigated[46] but no ternary phases were found. The phase $MnAl_6$ is capable of dissolving iron to a considerable extent. Phragmen has also examined crystals in the quaternary system, aluminium-iron-manganese-silicon. He isolated and examined crystals of the phase which contained 15.7% Mn, 16.1% Fe and 6.8% Si.



Al-Fe-Si
System

H. W. Phillips - Inst. of Metals,
No. 25, Monograph and Report Series
Page 57.

Full line boundaries between the various primary fields are taken from an early paper by Gwyer and Phillips. The compositions of α_1, α_2, and α_3 are indicated by ringed points. The boundaries of the new fields are shown as dotted lines.

Figure 19

7. EXPERIMENTAL PROCEDURE (SECTIONS 8-10).

Using the dissimilar metal welds prepared during Part I of the research programme, metallographic examinations, hardness surveys and diffusion studies were undertaken. In addition to the optical microscope, the electron microscope was used to study weld interface structures. For the latter instrument specimens were etched by a 0.5% hydrofluoric acid solution followed by use of a 1% nital solution and carbon replicas were then prepared.

Diffusion studies involved the use of the electron probe microanalyser and chemical analysis. Specimens for the microanalyser were prepared from welded joints of hot-tinned steel and commercially pure aluminium (S1C), galvanised steel and aluminium-manganese alloy (NS3) and aluminised steel and aluminium (S1C). The filler metal in each case was the aluminium-5% silicon alloy.

Samples for chemical analysis were taken at approximate distances of 1/16, $\frac{1}{8}$ and $\frac{1}{4}$ inch from the interface of a welded panel of galvanised steel and aluminium-magnesium alloy (NS5), joined by means of the aluminium-5% magnesium filler rod.

8. TIN COATINGS.

8.1. Experimental Results.

Cracking was observed in welds between mild steel and aluminium-magnesium alloy (NS5), prepared by means of the aluminium-5% magnesium filler rod and hot-dipped tin as a buffer coating.

In most cases, the cracks appeared to originate from the mild steel-aluminium interface. Generally, the intermetallic compound thickness was approximately 0.0005 inch in the top bead and the edge of the steel compared with 0.0002 inch for the underbead.

At the edge of the steel and particularly in the underbead regions of various panels, an almost continuous film of tin-rich alloy existed and its general microstructure was that of primary aluminium with intergranular films or pools of tin-rich material (Figure 20). Using an etching technique of 0.5% hydrofluoric acid followed by 1% nital solution, the tin-rich zones were half-tone in colour with occasional dark regions indicating a certain amount of porosity. The porosity was evident in the unetched condition. The structure indicated that the molten filler metal had been in intimate contact with the steel for a very short time but sufficient for some diffusion to occur and compound to form. During this process some gravity separation of the tin-rich material was taking place. Interdendritic films and pools of tin-rich alloy were evident in other regions but mainly in the underbead zone. Cavities were observed in these pools in several instances. The hardness of these regions was approximately 40 V.P.N.

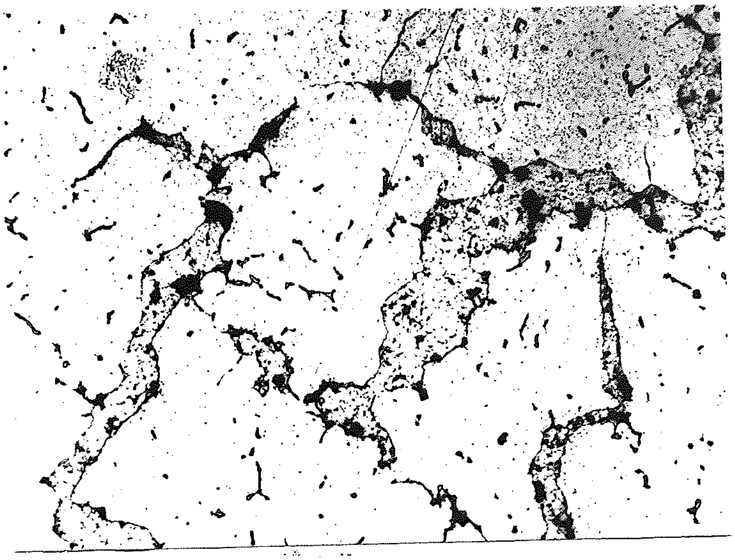


Figure 20

Tinned mild steel - aluminium magnesium alloy (Al-5% Mg filler). Solid solution with intergranular films and pools of tin rich material (half tone) and porosity (dark regions)

Etch 0.5% HF and 1% Nital x 500

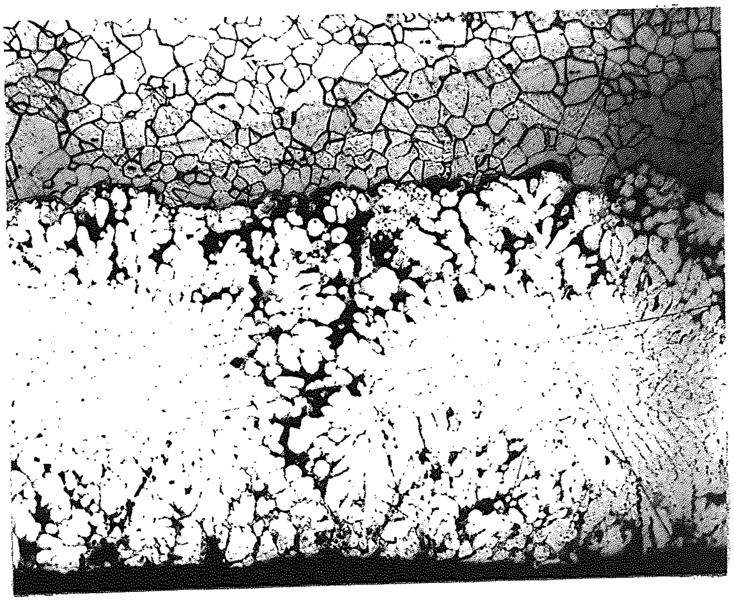


Figure 21

Tinned mild steel - aluminium (Al - 5% si filler)

Tin rich alloy concentration in underbead.

Etch 0.5% HF and 1% Nital x 150

In some instances, intergranular penetration of tin-rich material was noted extending from the steel/aluminium interface to the outside of the weld bead.

Where a similar combination of materials was employed except that an electroplated tin coating instead of hot-dip on the steel was used, quite reasonable tensile strength was recorded (Section 4.2.2. Table VI). Metallographic examination showed that the resulting fractures followed an intergranular path away from the aluminium-iron compound layer and through the aluminium-magnesium filler metal zone. Varying amounts of films and pools of tin-rich material were present but usually considerably less than observed with hot-dipped coated steel. These regions were frequently well away from the fracture region and could hardly have contributed to failure.

As might be expected, in the absence of the controlling influence of silicon in the filler rod, there was considerable variation in thickness of the intermetallic layer but this did not appear to have any effect on the fracture origin. For example, in several specimens the thickness ranged from 0.0007" - 0.0015", the change being gradual from the centre to the edge of the bead.

From appearance of the fracture after tensile testing, about 80 per cent. of the bonding failed, the rest remaining intact with filler metal adhering to it.

For comparison, microsections were examined of joints between commercially pure aluminium joined to mild steel coated by hot-dipping in tin and utilising the commercial aluminium-5% silicon filler rod.

The mechanical properties of such panels were already regarded as generally satisfactory (Table VI) but there remained some doubt as to the presence of films or areas of tin-rich material. Metallographic investigation confirmed that occasionally tin-rich liquid penetration had taken place under these circumstances but its presence did not apparently affect the extent or course of fracture under tensile or bending stresses. Apart from a few heavier zones of perhaps 0.0003", the aluminium-iron compound thickness averaged 0.00015".

Further comparison with welds between aluminium-magnesium sheet material (NS5) and aluminised mild steel, (aluminium-5% magnesium rod) revealed no cracks. Examination after tensile or bend testing showed that fracture had occurred mainly through the centre of the intermetallic compound, but sometimes at the steel-compound interface.

Hardness determination (including microhardness) for welds between hot-tinned steel and aluminium-magnesium alloy using the aluminium-5% magnesium filler rod produced average values of 73 V.P.N. for the filler metal zone, 540 V.P.N. at the centre of the intermetallic compound and 119 V.P.N. for the mild steel. The zone between the weld metal and compound centre was approximately 300 V.P.N. while between compound centre and steel it was slightly harder before rapidly falling to the mild steel value. In other words, peak hardness occurred nearer to the steel than the aluminium alloy and indicated that the intermetallic layer was not uniform. The absence of silicon as a softening agent on compound hardness is clearly marked in the above values when comparison is made with values obtained and reported under the section 10.1. dealing with aluminium as a coating material.

Microanalyser study of iron and tin diffusion indicated that the concentration of iron changed sharply at the boundary zone as the aluminium-5% silicon filler metal was entered in contrast to observations on similar systems but with other coatings. For example, with hot-tinned steel it reduced from approximately 92% to 38% over a distance of 0.0001" whereas with an aluminised steel it dropped from 79% to 42% over the same distance. On reaching the 38% iron content region further fall in iron content was much more gradual. Over a total length of 0.0004" from the steel interface the iron reduction was from 100% to 6%

The iron did not penetrate uniformly very far into the aluminium but tended to form isolated particles in addition to the intermetallic at the interface. The tin did not penetrate into the steel, neither did it migrate through the aluminium-silicon weld metal except to form isolated particles or areas of tin-iron and tin-aluminium.

The filler metal-steel boundary with tin coated specimens was much sharper, as shown by electron and X-ray scans, than with zinc or aluminium. Interpretation of the micrographs also resulted in the conclusion that the iron-rich particles were not so coarse as, for example, when zinc coatings were used on the steel. A slow scan for iron across the weld interface of a zinc coated steel specimen showed distinct peaks corresponding to coarse particles of iron-rich compounds whereas a similar scan across a tin coated sample produced hardly any peaks at all.

8.2. Discussion.

The coating thickness of the hot-dipped tinned steel was greater than that of the electroplated material (Section 4.1) and observations during the actual welding operation revealed that the hot-dip coating was more fluid than that of the alternative treatment. Liquid tin tended to drain towards the underbead region and through the underbead metal; this observation was associated with the evidence of intergranular penetration in this zone (Figure 21).

With the aluminium-magnesium alloy (NS5), using the aluminium-5% magnesium filler rod, the hot-tinned steel welds were severely cracked but electroplated specimens welded under similar conditions produced satisfactory mechanical properties (Table VI) and cracks were not observed. Metallographic examination showed that the tin-rich areas were considerably less in evidence with electroplated specimens, compared with hot-tinned steel, and that these areas were frequently well away from the fracture region and could hardly have contributed to failure. Again, with hot-tinned steel welded to aluminium (SIC) using the aluminium-5% silicon filler rod, failure during mechanical testing could not be attributed to fracture taking place through the tin-rich zones.

With the greater thickness of the hot-dipped finish, a great deal more tin was available than with the plated coating, and it is suggested that a considerable proportion of this became molten for a short period under the influence of the electric-arc and in combination with the aluminium-magnesium filler rod, conditions were created which resulted in severe hot-cracking. It would appear that as considerable amounts of the tin drained away from the steel, particularly from the underside, this process of gravity liquation restricted contact of filler metal with the steel so that the compound layer thickness was less in the underbead, compared with the top bead and steel edge zones.

In the absence of published information on the ternary system, aluminium-tin-magnesium, it was necessary to examine the binary equilibrium diagrams and make an assumption on the extent of the freezing range, as a wide range might well be responsible for the severe cracking which occurred.

In the binary system, aluminium-tin (Figure 18), the lowest temperature at which liquid may exist under equilibrium conditions is 228°C, whereas at the tin-rich end of the magnesium-tin system (Figure 22), liquid can exist down to 200°C. With the limited range of primary solid solution in both systems, it is very likely that the ternary system, certainly at the tin-rich end, will exhibit some form of isothermal reaction at temperatures below either of the two binary eutectic reaction temperatures, i.e. below 200°C. Consequently, it would be expected that the addition of small amounts of magnesium (from the aluminium-magnesium filler rod) would further extend the freezing range of aluminium-tin alloys.

It is likely that the wide freezing range of the liquid, predicted above, and the extensive intergranular penetration, might well be responsible for the severe cracking which occurred. The presence of films and/or pools of tin-rich material does not seem to promote cracking tendencies since negligible amounts were present in the weld metal zone at the point of fracture. At elevated temperatures, however, the force needed to produce fracture might be quite small (Section 6.1).

Finally in this section, it would seem appropriate to comment on the influence of groove geometry, as consideration shows that unsatisfactory dimensions might induce or increase hot-cracking tendencies during solidification of the more difficult material combinations. In many tests where cracking was experienced using hot-tinned steel and the aluminium-magnesium alloy sheet, the underbead was of $\frac{1}{4}$" radius and about $\frac{1}{8}$" deep. It is suggested that for material of about $\frac{1}{8}$" thickness, the groove depth should be less than that used in this investigation, therefore reducing the mass of metal solidifying during the metal joining process, and possibly overcoming hot-cracking difficulties. This is discussed further in Section 11, where the effect of bead geometry on strength is examined.

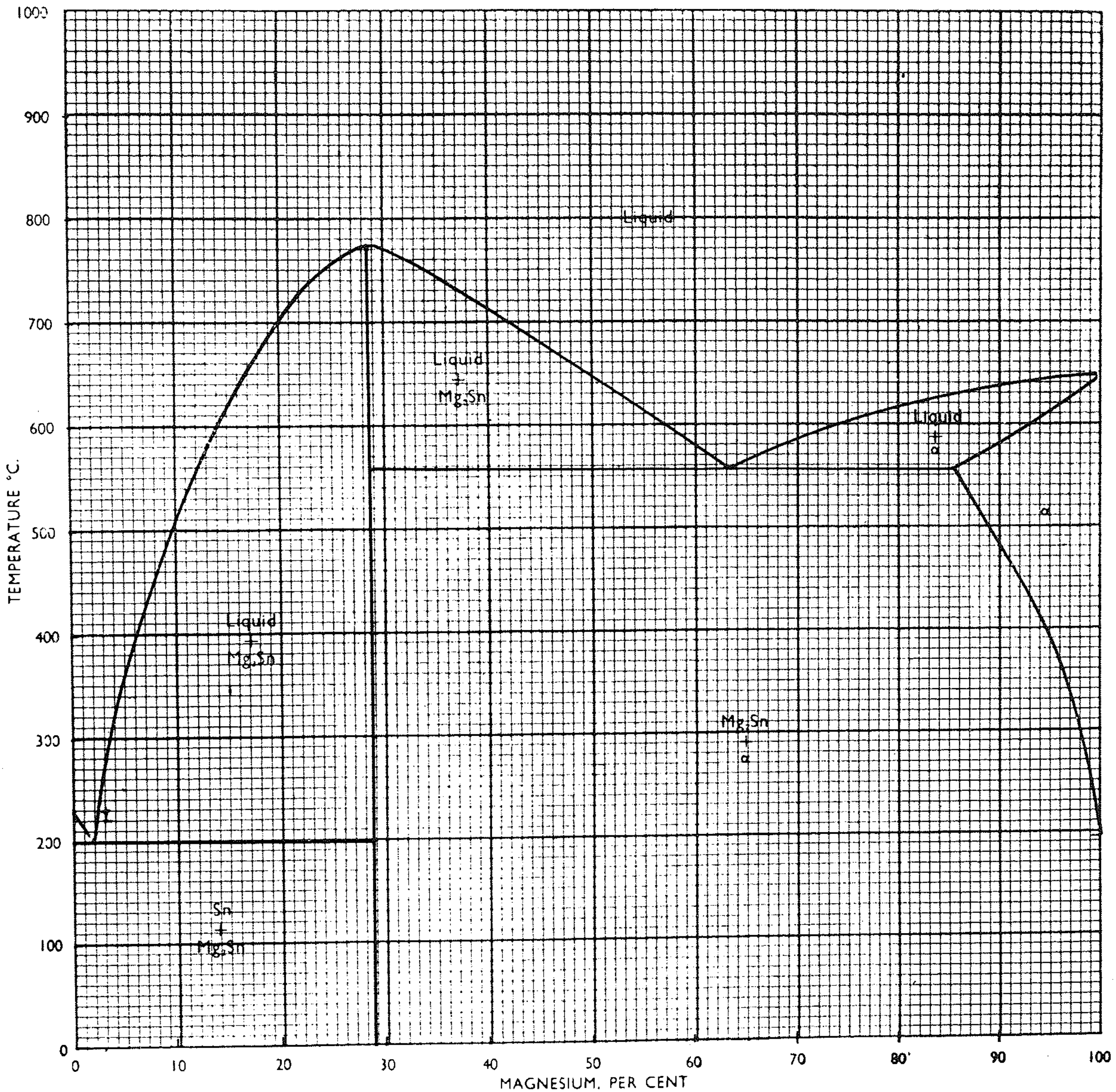


Figure 22

Tin - Magnesium Equilibrium Diagram

9. ZINC COATINGS.

9.1. Experimental Results.

During general examination of sheet butt joints between aluminium and hot-dipped zinc coated steel, it became apparent that sometimes the tensile and bending properties were abnormally low. Metallographic examination of a typical section taken from a panel of aluminium-manganese alloy (NS3) welded to galvanised mild steel using the aluminium-5% silicon filler rod showed that almost complete separation of weld metal and steel had occurred as a result of tensile loading. Fracture had also taken place through the weld metal, indicating that little difference existed between its strength and that of the interface between the steel and aluminium. Layers of compound existed outside of the normal region of the joint, often distributed in the top bead zone and one particular layer was just over 0.08 inch in length, and its width ranged from 0.0008 - 0.002 inch. It seemed that this layer, considered to be mainly composed of iron-zinc compounds, had been detached from the edge of the coated steel, almost intact, by the molten metal in the weld pool and swept upwards, to be trapped by the solidifying mass of metal at some distance from its original site.

This was an unusual microstructure and originally thought to be a phenomenon confined to steel coated by hot-dipping but subsequent investigation revealed its occasional appearance with electrodeposited zinc coatings, the affected regions were small compared with galvanised steel panels and the mechanical properties were apparently unaffected.

This feature has not been observed in welds where tin or aluminium coatings have been involved.

Again, in a section taken from a joint between the aluminium-magnesium alloy (NS5) and galvanised mild steel using the aluminium-5% magnesium filler rod, the tensile test resulted in fracture at the interface and through part of the top bead. The amount of compound distributed in the weld metal was considerable but particularly concentrated towards the upper section of the weld; the thickest section was almost 0.003 inch but generally the layers were less than 0.002 inch whether in long or short lengths.

Micrographs produced from the electron probe microanalyser investigation showed that in the weld between galvanised steel and the aluminium-manganese alloy (NS3) using the aluminium-5% silicon filler rod, iron diffused unevenly into the aluminium weld metal forming discrete particles of compound in the process. These particles were identified as iron-aluminium and iron-aluminium-silicon. A slow scan across the weld interface indicated these particles by distinct peaks in the iron concentration. Evidence of zinc diffusion was found right up to the specimen edge and it was also detected in some of the binary and ternary particles. The concentration of zinc in the particles was no greater than that in the matrix. The particles were coarser than those observed in joints where tin or aluminium had been employed as a coating on the steel.

It is apparent that the zinc from the galvanised steel had diffused to a considerable extent through the weld metal. Because of these observations and because of the importance of total zinc and magnesium content in the ternary aluminium-magnesium -zinc system (Section 6.2.), it was necessary to determine the amount of zinc by chemical analysis, in different regions, of the weld metal.

Table XVII.

Approx. distance from interface zone	Zinc content
1/16 inch	9.7% by weight
$\frac{1}{8}$ "	2.4% "
$\frac{1}{4}$ "	0.021% "
Average Magnesium content	4.8% "

As shown in Table XVII, the weld metal region surrounding the steel at a distance of approximately 1/16 inch from the compound layer contained at least 14% total zinc and magnesium, and closer to the interface the content must have been very much higher. Probably, similar amounts of diffusion would be revealed in welds produced from steel which had been coated with zinc by electrodeposition.

9.2. Discussion.

Of the elements normally present in steel sheet, silicon has the most pronounced effect on galvanising practice. Alloy growth rate is increased and the structure modified by silicon and this effect is clearly apparent when more than about 0.2% silicon is present. The effect of aluminium is to reduce the thickness of the alloy layer between the steel and the zinc coating. If silicon and aluminium are present in the steel, then the effect of silicon is reversed, in that less aluminium is required to reduce the thickness of the iron-zinc intermetallic compound layer.

These facts are relevant to the welding of galvanised steel to aluminium in view of the substantial remelting of the zinc which does take place. The thickness of the original zinc coating ranged between 0.003 - 0.004 inch, whereas the heaviest compound layer observed after welding, only just approached 0.003 inch and over the whole range of tests, for all the different coatings, the average thickness of the intermetallic layer was only 0.0005 inch.

Concerning removal of the iron-zinc compound layer from the steel edge and its effect on weld strength; if this is removed by the molten metal in the weld pool, then fresh molten metal will be unable to bond effectively to the uncoated steel. If adhesion is lacking in such regions then lower strength would be expected in certain instances; measurement showed that the effective area of adhesion was often reduced by as much as 30%. Bel'chuck[31] also observed that at least the zinc was driven back from the surface of the steel allowing direct contact of molten aluminium filler metal with the steel surface.

When the mechanical test results of butt joints in sheet materials for aluminium-magnesium alloy and zinc coated steel are studied, there is no real evidence of brittle failure although the bending properties compared rather unfavourably with those obtained when the steel component of the weld was aluminised or tin electroplated.

It will be recalled that conditions arise for an age-hardening system, aluminium-zinc-magnesium, to occur near to the interface in these welds

(Table XVII). If solution treatment was carried out followed by natural ageing or artificial ageing, then no doubt, although the tensile strength and proof might be increased, ductility would decrease, with the possibility of intercrystalline and brittle fracture.

It is apparent that the removal of the iron-zinc compound layer from the steel edge, resulting in the absence of an effective buffer coating necessary to provide the right conditions for adhesion or alloying of filler metal to the steel, offers a possible reason for the observed lower strength of galvanised steel - aluminium welds, compared with, for example, aluminised steel. In addition, the high rate of zinc diffusion and the importance of total zinc and magnesium content in the system, aluminium-zinc-magnesium, indicates that there is a possibility of brittle fracture when an aluminium alloy is welded to a zinc coated steel using the aluminium-5% magnesium filler rod.

10. ALUMINIUM COATINGS.

10.1. Experimental Results.

Many of the interface structures in aluminium welded to aluminised steel exhibited columnar-shaped crystals, which were clearly defined when suitably etched by means of a 0.5% hydrofluoric acid solution followed by immersion in a 1% nital solution. Presumably, in other cases a relatively fine-grained structure existed but no direct evidence was obtainable. The boundary line between steel and compound and/or compound and filler metal was often irregular. Photomicrographs of sections taken through aluminised steel components frequently show a tongue-shaped configuration, the length of tongue varying considerably due to the aluminium diffusing rapidly into the steel on an irregular front. This irregularity indicates preferential diffusion along a certain crystallographic direction in the aluminised component. Although such irregularities existed at the interface of the dissimilar metal joints, no pronounced tongue-shaped crystals were observed. For example, with an aluminised mild steel welded to commercially pure aluminium (SIC), using the aluminium-5% silicon rod, the compound generally varied between 0.0004 - 0.0006 inch . In the main, the uneven boundary was on the steel side but occasionally it made an appearance on the light alloy side. Most of these observations compared favourably with the experimental results of Heumann and Dittrich[39].

Where an aluminium-silicon filler rod is used, the silicon atoms would be thought to modify the composition of the aluminium-iron compound layer. With aluminised steel of the aluminium-silicon coating type, dark grey acicular constituents are detected in the outer coating layer in a typical microstructure. Such needles are often considered to be rich in silicon with a small addition of aluminium and iron. The remainder of the outer layer appears to contain small zones of an aluminium-iron constituent in aluminium solid solution. Similar needles may occur in aluminium-steel welds. Usually they are found adjacent to the interface (Figure 23). From metallographic evidence it appeared that the aluminium-iron compound had been modified by the presence of silicon from the filler rod. The aluminium-silicon eutectic was absent from those areas immediately surrounding the needles.

Diffraction studies were therefore undertaken on a specimen from the compound layer adjacent to the weld metal, and a specimen from the acicular constituent, in a weld between aluminised steel and aluminium joined by means of the aluminium-5% silicon filler rod. The pattern in each case was indicative of a cubic structure with a parameter of 12.4 $\overset{o}{A}$, which suggests that the phase was probably α- $Al_{12}Fe_3Si$, which has a parameter of 12.523kX, (Table XVI).

Investigation by means of the microanalyser, of a normal cross-sectional specimen of hot-dipped aluminium coated steel welded to aluminium using the aluminium-5% silicon filler material, showed that there was no significant diffusion gradient of iron near the joint interface. Iron was present in the aluminium-silicon alloy as discrete particles of aluminium-iron and/or aluminium-iron-silicon. Iron had therefore diffused into the aluminium as well as aluminium into the steel

Figure 23

Appearance of acicular constituent extending into filler metal from normal compound layer

Etch 0.5% HF x 1000

but, in the former case the iron did not penetrate evenly into the aluminium but rather formed discrete intermetallic compounds.

Microhardness determinations were carried out using two different types of apparatus for all the specimens examined. Good agreement was obtained from both series of results. Apart from the known effect of silicon in reducing the thickness of the alloy layer, it was shown also to reduce the hardness. Microhardness tests confirmed this during investigation of commercially pure aluminium welded to aluminium, tin or zinc coated steel. These results (Table XVIII) can be compared with aluminised steel welded to aluminium-magnesium alloy (NS5) using the aluminium-5% magnesium filler metal. In contrast to that obtained with the silicon rod, the greatest hardness occurred in the zone intermediate between mild steel and the compound layer centre. Fracture rarely occurred, as a result of mechanical testing, in the softer region between weld metal and compound layer centre.

Table XVIII.

Metal combination	M. S.	Weld metal	Compound layer centre	Average values - V.P.N. Between -	
				M. S. and compound layer centre	Weld metal and compound layer centre
H. D. Sn steel/Al-5% Mg filler rod	119	73	540	310	300
Steel coated with Sn, Zn, or Al/Al-5% Si filler rod		72	400	243	245
H. D. Al steel/Al-5% Mg filler rod		73	535	709	255

Further information on the actual hardness values is given in the Appendix.

Joints between aluminium and mild steel produced by Friction Welding (Section 4.5.4.), provided an opportunity to examine an interface formed in the absence of silicon.

Comparison of the friction welded aluminium to steel interface, with interfaces produced using the aluminium-5% silicon rod, revealed no difference in the unetched state. However, using a double etch of 0.5% hydrofluoric acid followed by 1% nital, two constituent layers were visible in the weld prepared by means of the filler metal. That on the weld metal side was dark grey changing to a lighter grey layer towards the steel. Evidence of a columnar structure, as discussed by Heumann and Dittrich existed. Some areas in the adjacent weld metal contained the acicular constituent Al-Fe-Si and these needles were also dark grey in colour.

The friction weld specimens, on the other hand, showed a fairly uniform weld structure at low magnification. High magnification revealed that there were two constituents - a dark grey one dispersed in a light grey matrix. It is considered that the background constituent was the Fe_2Al_5 phase with particles of FeAl and/or Fe_3Al distributed within it. It seems unlikely that either $FeAl_3$ or Fe_2Al_7 existed (Section 6.3).

Some confirmatory evidence was obtained using the electron microscope. Commercially pure aluminium welded to aluminised steel by means of the aluminium-5% silicon filler rod, was selected for investigation. The sections were etched with the hydrofluoric acid and nital solutions, and carbon extraction replicas prepared from them.

Scanning the interface from the mild steel to the weld metal, showed that two distinct bands existed in the microstructure; thus confirming observations made using the optical microscope. The band existing on the steel side seemed to be smoother than that towards the weld metal where a large number of high spots appeared to occur. This might well be connected with the formation of an Al-Fe-Si compound near the weld metal but which is less in evidence adjacent to the mild steel.

It was also evident that in the case of aluminised steel, some of the original coating remained in contact with the parent metal, apparently undisturbed by the process of argon-arc welding (Figure 24). For example, in a specimen having a total width of compound between steel and weld metal of some 0.0006 inch, the suspected original layer of aluminium still intact, almost approached 0.0002 inch in width. From surface marking indications it was of much lower hardness than the centre region of intermetallic compound and those areas immediately on either side of this.

Other regions examined showed columnar structures but these mainly occurred at the centre of the interface.

10.2. Discussion.

The results of the diffraction study on the argon-arc welds where aluminium-5% silicon filler rod had been used in conjunction with aluminium parent metal (SIC), suggested that the acicular constituent and that part of the interface layer existing on the aluminium side of the joint was an aluminium-iron-silicon compound with a composition

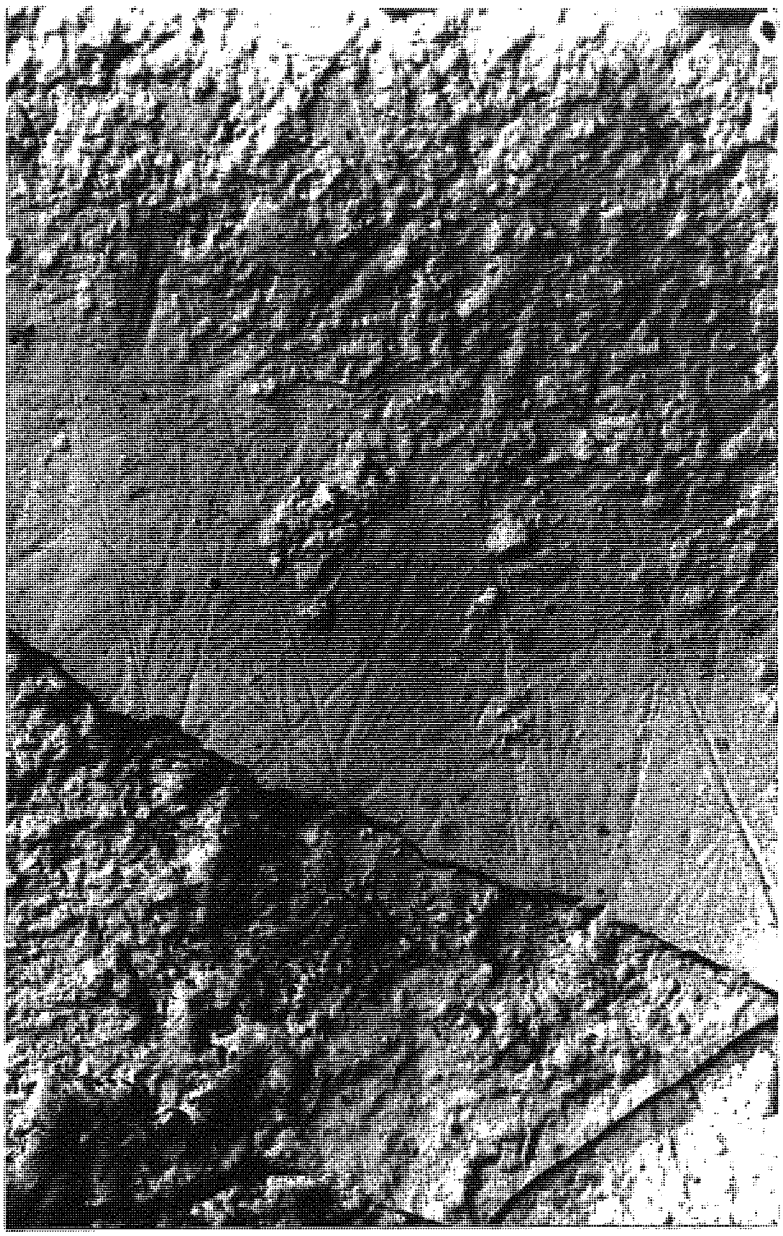


Figure 24

Aluminised mild steel - aluminium weld

(Al - 5% Si filler)

Interface region and mild steel (Bottom half of illustration)

Etch 0.5% H.F. and 1% Nital x 5,000
Carbon extraction replica x 2 enlargement.

corresponding to α-$Al_{12}Fe_3Si$. From various workers' results[39,40] and observations made during this research programme, the interface structure adjoining the mild steel is considered to be mainly composed of Fe_2Al_5. Figure 25 illustrates the columnar or tongue-shaped structure, indicating pronounced directionality, associated with this phase. The structure at the bottom of the illustration is that of the mild steel. Between the steel and the columnar structure is a band of the original aluminised coating. It is thought that in the case of the friction welded specimens the background constituent is Fe_2Al_5 with particles of FeAl and/or Fe_3Al distributed within it.

Although detailed electron microscope work has not been carried out on the aluminium-manganese (NS3) and aluminium-magnesium-silicon-manganese (HS30) alloys, it seems reasonable to assume that the type of structure described in connection with aluminium (S1C), would be substantially reproduced with NS3 and HS30 welded to aluminised steel by means of the aluminium-5% silicon rod. There is no evidence to suggest that a phase containing manganese occurs at the interface of welds involving NS3 or HS30.

On the other hand, where the aluminium-magnesium alloy (NS5) has been employed in conjunction with an aluminium-5% magnesium filler rod, the phase structure might well be quite different from that where commercially pure aluminium is involved. The absence of silicon in the filler rod eliminates the α-$Al_{12}Fe_3Si$ phase, and Barnick and Hanemann[47] did not discover any ternary phases in the aluminium-iron-magnesium system.

Microhardness tests indicated that when any filler rod material other than the aluminium-silicon is used, particular attention must be paid to the combination of metals to avoid, if possible, high hardness regions between compound centre and steel which may well lead to serious cracking problems.

It is apparent that the aluminium-5% silicon welding rod produced a superior joint compared with that obtained with a pure aluminium filler material. It is also important to note the considerable difference in intermetallic constituent layer thickness when comparing the two filler rods.

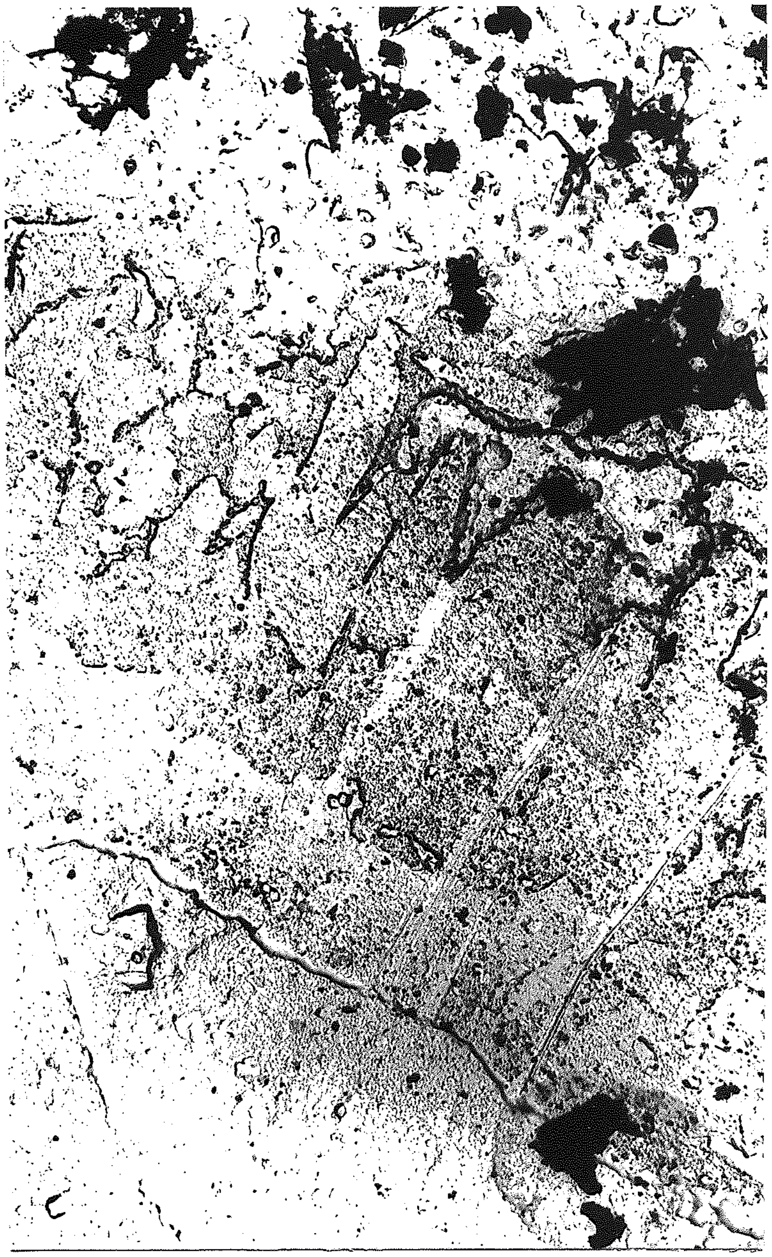


Figure 25

Aluminised mild steel - aluminium weld.

(Al - 5% Si filler)

Illustrating typical columnar structure occurring at centre of interface.

Etch. 0.5% H.F. and 1% Nital x 5000
Carbon extraction replica x 2 enlargement

11. BEAD GEOMETRY AND WELD STRENGTH.

In the previous sections, the investigation has been concerned with the development of a welding technique to enable aluminium to be satisfactorily joined to mild steel, and the metallurgy of the resultant joint. No data has been obtained, however, on the influence of weld reinforcement, or bond area, on joint strength. The scope of the work in this section is, therefore, directed towards establishing the relationship between bead geometry and the mechanical properties of the weld.

11.1. Experimental Techniques.

A series of butt welded test panels was prepared by means of manual inert-gas welding equipment. A welding current of 130 amperes was used with an argon flow of 14 and 2 litres/minute for torch and backing bar respectively.

As aluminised mild steel has proved to be the most satisfactory material to join to aluminium, attempts were made to obtain further samples of $\frac{1}{8}$ inch thickness. Unfortunately, the original supplier had ceased operating the batch plant in favour of a continuous unit producing 20 gauge aluminised steel, and an alternative supply was not available in this Country. It was considered that the 20 gauge coated steel did not lend itself to the type of experimental work envisaged, as the edge coating was of poor quality with rust spots being present. It was decided, therefore, to use galvanised $\frac{1}{8}$ inch steel sheet as the previous work had shown that a zinc coating was the best alternative to aluminium coated steel. Specimens having a coating thickness of 0.003-0.004 inch were obtained. During the galvanising operation, particular attention was paid to obtaining a smooth and dross free coating, and the resulting quality was much higher than that obtained for samples used in Part I of this investigation.

The aluminium alloy NS3 was selected for butt welding to the galvanised steel on the basis of the test results of Part I and the fact that the aluminium-5% silicon filler metal could be used, thus ensuring maximum control of the intermetallic layer thickness by virtue of the silicon content. In addition, a test plate of aluminised steel joined to aluminium (S1C) by means of the silicon filler metal, and aluminium alloy NS5 joined to aluminised steel by means of the aluminium-5% magnesium filler metal, was utilised for the investigation. These were also butt welded test plates.

Sufficient test pieces of $\frac{1}{2}$ inch width were prepared so that tensile tests could be made in duplicate. The weld bead dimensions measured are shown in Figure 26, the lengths a and b being used to calculate face bond area, and c and d the amount of face reinforcement. A gauge length of two inches was chosen for the determination of elongation and measurement was made between the steel/aluminium interface and a mark on the parent aluminium material.

Except for control specimens left in the 'as-welded' condition, the test pieces were machined so that between 25 and 100 per cent. of the weld reinforcement thickness was removed. Alternatively, similar percentage reductions in bond area were made by machining away the

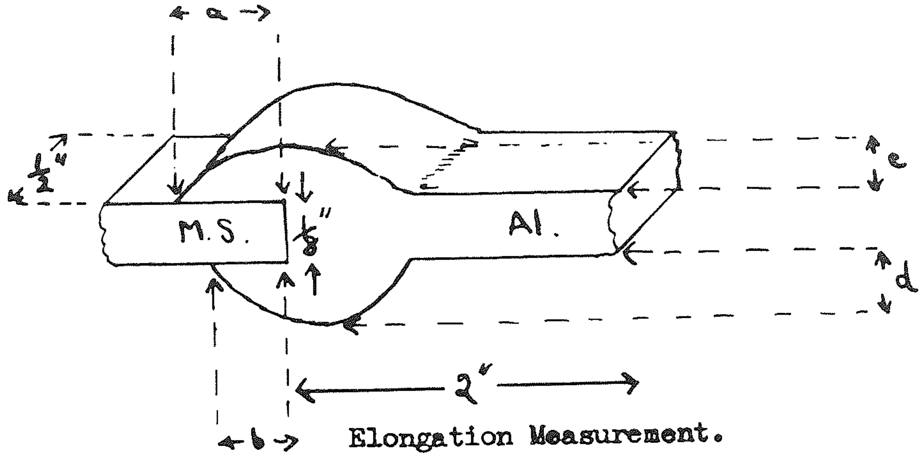


Figure 26. Weld Bead Dimensions.

aluminium filler metal from the top and bottom steel surfaces, leaving the edge bond intact.

With other specimens, the welded edge was carefully bored out by spark erosion equipment using copper or brass electrodes. This allowed the determination of strength due to the welding of aluminium filler metal to the top and bottom steel surfaces only. The removal of this interface was not an easy task, especially as dissimilar metals were involved, and it was necessary to prepare a number of specimens before three could be selected for testing. Selection was made on the basis of the lengths of a and b before and after spark erosion treatment.

11.2. Experimental Results.

Galvanised steel - Aluminium alloy NS3
(aluminium-5% silicon filler metal)

The breaking load was determined for the tensile test specimens and plotted against total bond area (using dimensions a and b - Figure 26) and total reinforcement (using dimensions c and d - Figure 26). The test results are shown in Figures 27 and 28 respectively. The effective bond bearing area, in this case, includes the bond between the aluminium and steel sheet edge in addition to the sheet face bonds. The reduction in bond area and reinforcement for the purposes of Figures 27 and 28 refers only to the top and bottom steel surfaces, so that with complete removal of the weld bead from these surfaces, the strength of the edge bond alone is determined.

With the 'area of bond' tests, all the specimens, with the exception

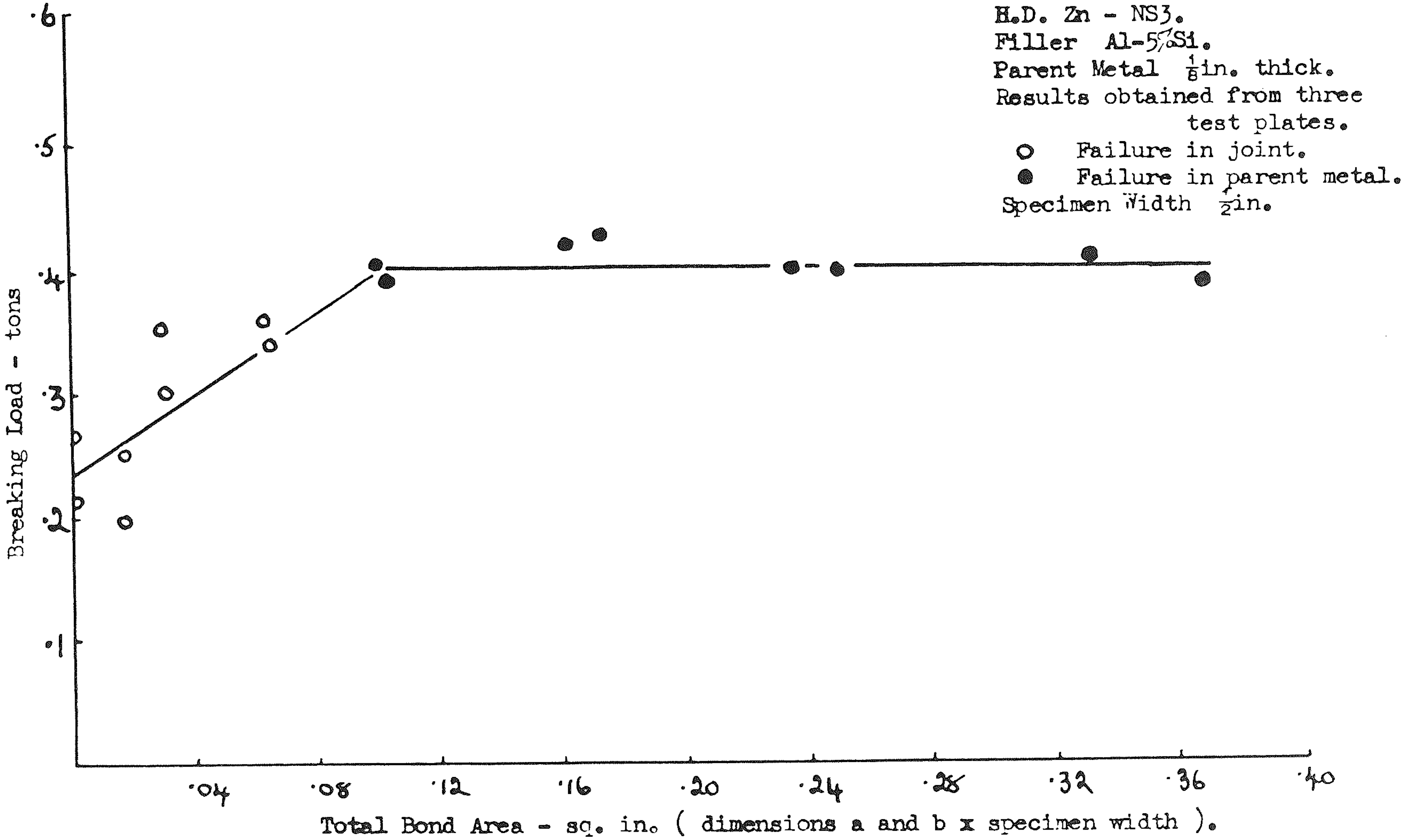


Figure 27. Effect of Bond Area on the Joint Strength.

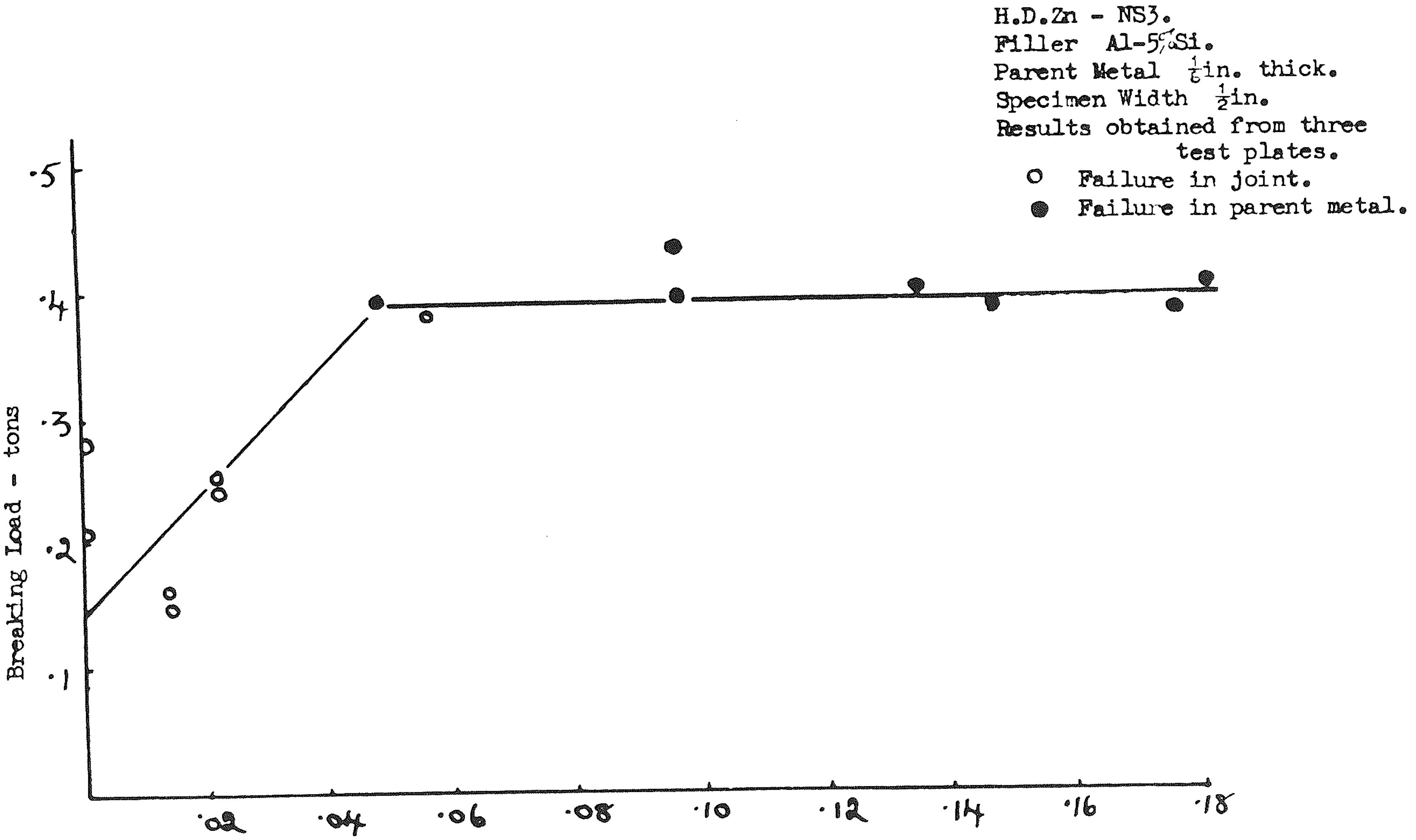


Figure 28. Effect of Weld Reinforcement on the Joint Strength.

of those where the top and bottom beads were completely or nearly completely machined away, failed in the parent aluminium at between 6.0 and 7.0 ton/in^2 and 12-15 per cent. elongation. Steel edge bonding alone resulted in a tensile strength of 3.4 and 4.0 ton/in^2 with an elongation (measured as shown in Figure 26) of 1.5 per cent., failure taking place at the steel-aluminium interface.

Similar results were obtained for the weld reinforcement tests except that, at 75% reduction of the bead, one specimen failed in the parent aluminium and the duplicate at the steel-aluminium interface.

In an attempt to determine the maximum load which the joint could withstand, test pieces were inserted into the wedge grips of the tensile testing machine so that, although the steel was held normally, the aluminium was gripped at the weld zone. A breaking load of 0.56 and 0.57 ton (9.0 and 9.1 ton/in^2) was recorded.

The specimens from which the edge-edge interface had been removed by spark erosion were tensile tested with a) top and underbead intact, b) 50 per cent. of the bond area removed, and c) after heat treatment at 400°C for twenty-four hours. The results are shown in Table XIX. For these specimens, the bead dimensions given in the table indicate that the spark erosion operation did not markedly reduce the lengths of a and b (Figure 26).

Table XIX.

Dimensions inches				Condition	Breaking load tons	T.S. ton/in^2	Elong. per cent.
before boring		after boring					
* a	b	a	b				
.404	.350	.400	.340	'as-welded' - total bond area 0.37 sq. in.	0.39 Failure in parent metal.	6.2	12
.408	.336	.402	.321	50% reduction of bond area (0.18 sq. in.)	0.18 Failure in joint	2.8	1.5
.355	.367	.340	.360	H. T. 400°C 24 hrs. (bead dimensions as welded)	0.16 Failure in joint.	2.5	1.5

* Dimensions a and b as in Figure 26.

In addition to the heat treated spark eroded test piece detailed in Table XIX, several other specimens were machined and then subjected to heat treatment. The specimen preparation and results are given in Table XX.

Table XX.

Effect of heat treatment at 400°C for 24 hrs.

Preparation	Breaking load - tons	T.S. ton/in^2	Elong. per cent.	Position of failure
Complete removal of reinforcement	0.04	0.64	1.5	Joint
"	0.075	1.2	1.0	"
0.05 inches total reinforcement	0.225	3.6	1.5	"
0.09 sq. inches total bond area	0.38	6.0	15	P.M.
Parent metal - NS3	0.38	6.0	20	-

Aluminised steel - Aluminium S1C (aluminium-5% silicon filler metal)

This test plate was welded under the conditions given for test number 166, Table VI - Section 4.2.2.

Figure 29 is a plot of breaking load against total weld reinforcement. The curve shows the decline in strength after the reinforcement had been reduced below 0.09 inches. It is shown that even with complete removal of the reinforcement, the weld strength is equal to half that of the parent aluminium.

Aluminised steel - Aluminium alloy NS5. (aluminium-5% magnesium filler metal)

This test weld was prepared under the conditions given for test number 284, Table VI - Section 4.2.2.

Reduction in bond area brought about a marked decrease in strength. With complete removal of the bead from the top and bottom surfaces of the steel, two of the four specimens broke without giving any measurable strength, indicating a weak edge bond. As shown in Figure 30, there was considerable scatter in the results and all the specimens failed at the steel-aluminium interface.

11.3. Discussion.

Most of the experimental work was concerned with the galvanised steel, and there is no doubt that the superior surface coating on the steel, particularly with regard to adherence at the steel edge, was responsible for the absence of the low tensile strength results sometimes observed in the previous work on this system, described in Part I. The

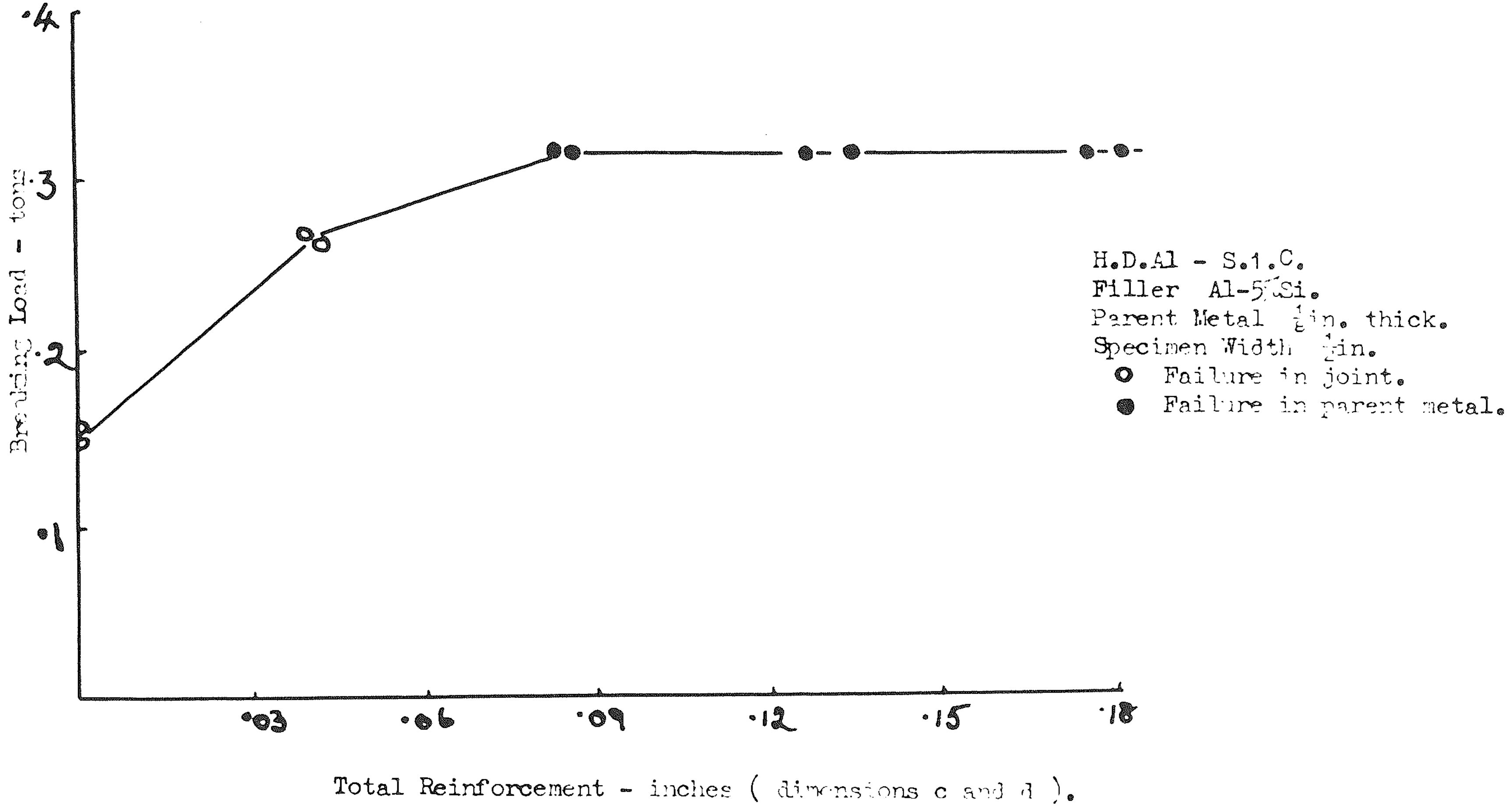
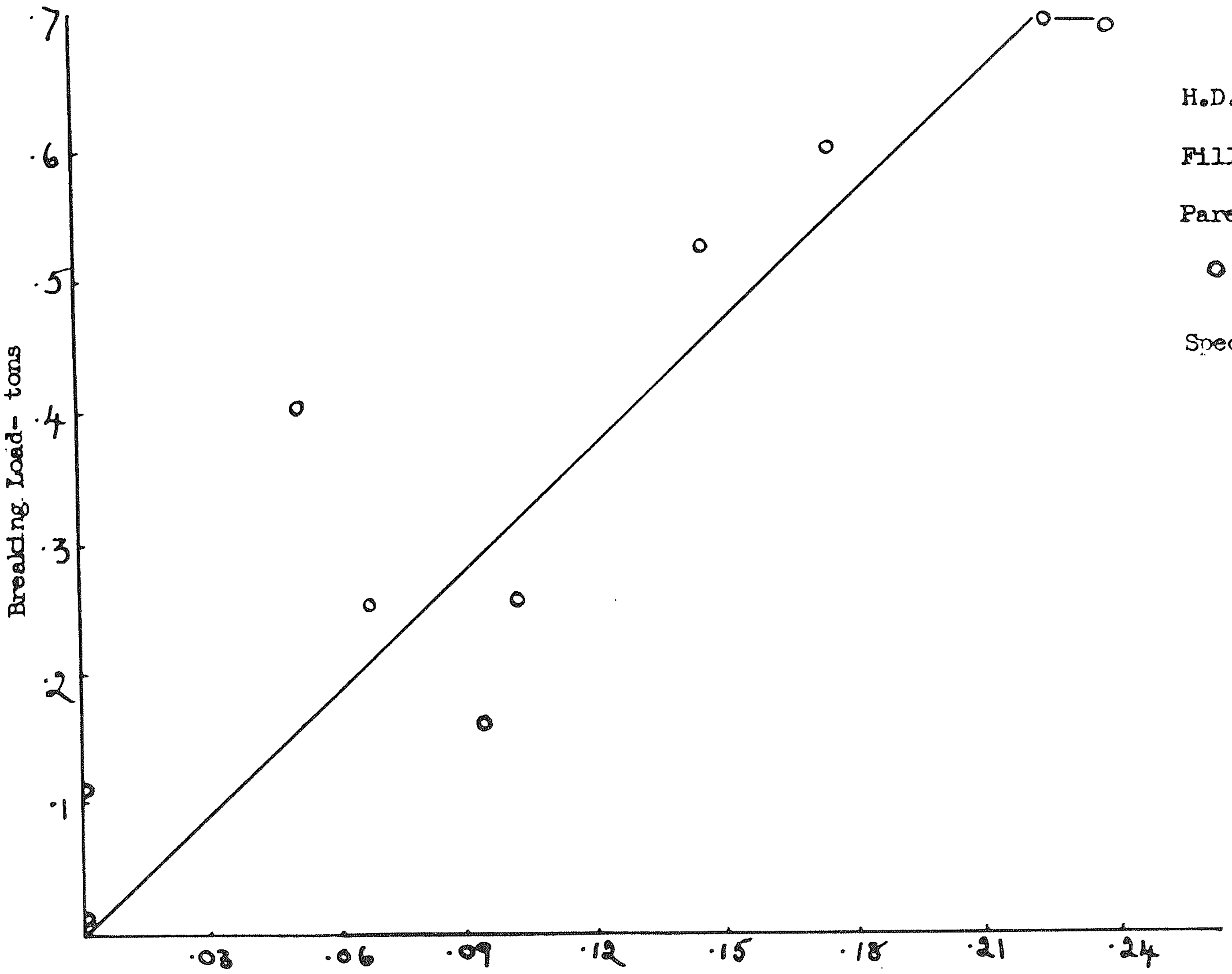


Figure 29. Effect of Weld Reinforcement on the Joint Strength.



H.D. Al - NS5.

Filler Al-5%Mg.

Parent Metal $\frac{1}{8}$in. thick

○ Failure in joint.

Specimen Width $\frac{1}{2}$in.

Figure 30. Effect of Bond Area on the Joint Strength.

buffer layer was not swept away by the flow of molten metal in the weld pool as had occurred in other cases (Section 9.1.).

The welded specimens for tensile testing were taken at random from a number of panels, and, as shown in Figures 27 and 28, the results were very consistent. The flat portion of the curve in Figure 27 (bond area vs breaking load) and in Figure 28 (reinforcement vs breaking load) does not indicate the maximum strength of the joint, as failure occurred in the parent aluminium alloy in all but one of the specimens. The only specimen which failed in the joint at this load is indicated by an open circle in Figure 28.

The fact that, with duplicate specimens, one failed in the parent metal and the other in the joint, clearly shows that the total weld reinforcement should not be less than about 0.06 in. for material of $\frac{1}{8}$ in. thickness as, otherwise, the weld strength will be less than that of the aluminium alloy. Again, if the total bond area (excluding the edge bond and bearing in mind that a $\frac{1}{2}$ inch wide test specimen was used for these calculations) is less than about 0.12 sq. in., weld strength will be decreased. On the other hand, there is no advantage in having an excessive amount of reinforcement or bond area and, in fact, as already mentioned in Section 8.2, bead geometry, which results in a relatively large mass of metal having to solidify, may increase hot-cracking tendencies.

On the basis of these results, it is suggested that for material up to $\frac{1}{8}$ in thickness, a groove of $\frac{1}{4}$ in. radius and 1/16 in. deep, in the backing bar, is most suitable. Ideally, there should be similar dimensions for the top bead as well.

If the metal to be joined is correctly centred over this groove, these dimensions will produce a total bond area of at least 0.16 sq. in. (again excluding the edge bond) and a total reinforcement of 0.09 in. Should the operator not centre the material reasonably accurately, for example, if a greater amount of aluminium extends over the groove compared with the steel, then sufficient margin has been allowed to provide adequate bond and reinforcement metal to avoid weld strength falling below the parent aluminium material.

It will be observed from Figures 27 and 28 that even with complete removal of the weld bead a strength of at least 0.15 tons (2.4 ton/in^2) was obtained. This figure can be added to that obtained after coring out the edge interface, (specimen tested in the 'as-welded' condition - Table XIX). Thus a total breaking load of at least 0.54 tons (8.6 ton/in^2) is obtained. This figure compares reasonably well with the breaking load of 0.56 and 0.57 tons obtained for specimens tested with the aluminium filler metal held in the wedge grips of the tensile testing machine.

As shown in Table XIX, the removal of the steel edge-aluminium interface by spark erosion, leaving the reinforcement intact, made no difference to the test result as failure still occurred in the aluminium. A fifty per cent. reduction in bond area produced a large decrease in strength and on this occasion failure did occur in the weld. A similar reduction in bond area, with the edge bond intact, was not sufficient to reduce the strength of the weld below that of the aluminium. These facts indicate the importance of obtaining a sound bond at the steel edge to counteract the effects of any defective areas in the bond on the top or bottom steel surfaces.

The heat treatment results (Tables XIX and XX) confirm the undesirability of exposing a welded structure to temperatures of 400°C and above. Although the specimen having a total bond area of 0.09 sq. in. possessed adequate strength, in the light of the other results, it is considered that any further slight reduction in bond area would cause a marked decrease in strength.

With aluminised steel joined to aluminium, the plot of total reinforcement vs breaking load (Figure 29) showed a similar trend to that obtained for the galvanised steel welds. In this case, weld strength falls below that of the aluminium when the reinforcement is less than 0.09 in.

Only with the aluminised steel/aluminium-magnesium alloy weld does the flat part of the curve (Figure 30) indicate actual joint strength since, in this instance, a much stronger aluminium alloy material was used and premature failure in the aluminium alloy was prevented. The maximum joint strength recorded was 0.7 tons (11.2 tons/in^2). There was considerable variation in the breaking load results as the bead was machined away. A progressive decline in strength occurred untill, with complete reinforcement removal, little or no measurable strength was recorded.

The edge bond with this combination of material is undoubtedly weak and this weakness is thought to be due to the increased hardness, brittleness and thickness of the intermetallic layer compared with the layer properties obtained when an aluminium-silicon filler rod is used. Having to use an aluminium-magnesium filler material is, therefore, a definite disadvantage because, unlike the element silicon, magnesium does not have a controlling influence on compound thickness and hardness.

Coupled with the weaker intermetallic layer there is the fact that the edge bond was tested under tensile loading conditions, whereas the bond between filler metal and top and bottom steel surfaces was tested under shear loading conditions with a certain amount of stress being carried by the reinforcement.

Graphs such as Figures 27 and 28 are useful for the guidance of the designer, technologist and operator in indicating the necessary bead dimensions to produce maximum strength, and assist in determining suitable dimensions for the backing bar groove.

Due to the unusual nature of the weld, it would seem inadvisable to use the existing graphs to predict correct bead geometry for material much thicker than $\frac{1}{8}$ inch. With thicker material an increase in reinforcement and bond area would be unlikely to produce a proportionate increase in strength. An increase in bead height would not contribute any additional strength as the author has shown in this investigation that the load bearing capacity of the bead is mainly limited to the lower portion of the reinforcement. In fact, a steep sided bead introduces a stress concentration at the toe of the weld.

A number of factors must be considered before deciding on the correct welding procedure for heavier gauge metals. Certainly in the case of the tungsten inert-gas welding process, the welding speed will be decreased while the current and argon flow will have to be increased.

The heat input, expressed as the arc power in watts divided by the travel speed of the electrode, will be increased, but the heat output will be determined by the mass of metal surrounding the weld. For example, if the component design is such that the deposit is laid towards a corner where several members intersect, the chilling effect will be substantial compared with the start of the weld. The maintenance of an even balance between heat input and output is important, especially from the point of view of the steel coating, as overheating of the steel will encourage growth of the intermetallic layer. On the other hand, a pronounced chilling action will have the opposite effect.

If the material thickness is such that the bevelling of the edge is necessary, then this would have to be carried out before coating the steel, as the necessity for edge coating has been demonstrated during this investigation.

12. CONCLUSIONS.

It has been shown that an inert-gas welding technique can be employed to join aluminium and its alloys to mild steel. A satisfactory weld cannot be produced, however, unless the following conditions are complied with:-

a) The steel must be coated, and aluminium is considered to be the most satisfactory metal for this purpose.

b) The aluminium must be applied by hot-dipping or cladding.

c) The coating should be 0.002-0.004 inch thick, smooth and free from inclusions. The surface coating process should also ensure that the intermetallic layer thickness is not allowed to exceed 0.0005 inch.

d) A secondary flow of inert-gas along the backing-bar groove is essential in most cases.

e) A butt weld design is generally preferable to that of a lap weld.

f) With fillet welds, preliminary surfacing of the coated steel, followed by the welding of the aluminium component to the steel, is the best technique to use.

The weld bead cannot be completely removed so as to obtain a thickness at the joint equal to the parent metals because a certain minimum reinforcement and bond area is necessary for the weld to possess maximum strength. When this requirement is met, for aluminium and the lower strength aluminium alloys, the joint strength is in excess of that of the parent aluminium metal. With these materials, even the edge to edge bond between the coated mild steel and aluminium is capable of a strength equal to half that of the aluminium or aluminium alloy.

Considerable differences in weld structure and strength exist when joints produced by means of either tin, zinc or aluminium coatings on the steel are compared. It is apparent that the fluidity of the tin coating needs very careful control during the welding process, also the degree of zinc diffusion through the weld metal may considerably alter the metal composition adjacent to the interface; a factor of some importance when joining an aluminium-magnesium alloy to steel. Attention must be drawn to the lower strength of galvanised steel welds compared with the use of, for example, aluminised steel, which has been observed during this research work and also recently reported by Bel'chuk and colleagues. Such difficulties do not appear to be associated with the use of aluminium or aluminium-silicon alloy processed by hot-dipping or cladding, although in the latter case investigation has been somewhat limited. It is clear, however, that if the hot-dipping procedure is very carefully controlled so as to produce a zinc coating on the steel of a higher quality than generally available commercially, then galvanised steel is an excellent alternative to aluminised steel.

Basically, the joining of these dissimilar metals has been accomplished by, (a) the formation of binary and ternary intermetallic compounds, depending on the system, and (b) diffusion without compound formation; the diffusion processes being induced by heat from the electric-arc except in the case of the friction welds.

It has been shown that the interface structure is not uniform and, for example, with aluminised steel joined to aluminium using the aluminium-5% silicon filler material, the structure adjacent to the mild steel is mainly composed of the Fe_2Al_5 phase, whereas adjacent to the weld metal it is mainly the ternary phase α- $Al_{12}Fe_3Si$. In those cases where an acicular constituent has been observed extending into the weld metal, the compound is also considered to be α- $Al_{12}Fe_3Si$. The outstanding example of diffusion without compound formation is that of the high rate of zinc diffusion through the aluminium-5% silicon and aluminium-5% magnesium weld metals, when zinc coated steel is joined to aluminium or its alloys by means of the argon-arc welding process.

All the work in this investigation has been carried out with mild steel, but future work might be directed towards determining the effect of increased carbon on the steel-aluminium joint and how it affects, for instance, the amount and constitution of the intermetallic phase. Again, the effect of alloying elements such as might be expected when using stainless steel, could be studied.

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APPENDIX.

HARDNESS VALUES.

	Vickers Pyramid Hardness Testing Machine.	Vickers Microhardness Testing Apparatus
Steel	20kg load – 127 126 118 108 106 125 Average 118 V.P.N.	100 gm load – 108 125 106 128 127 126 Average 120 V.P.N.
Al-5% Si Weld Metal	10 kg load – 77 79 74 73 Average 75 V.P.N.	100 gm load – 76 74 67 67 66 Average 70 V.P.N.
Al-5% Mg Weld Metal	– –	100 gm load – 74 73 75 69 Average 73 V.P.N.

Metal combination. – Vickers and Kentron Microhardness Testing Apparatus.

H.D.Sn steel/Al-5% Mg filler rod

Compound layer
centre.

100gm load 485, 599, 450, 585
50gm " 575, 500, 571, 561 Average 540 V.P.N.

Between M.S. and compound centre.

100gm load 312, 330, 288, 316
304, 314, 306 Average 310 V.P.N.

Between weld metal and compound centre

100gm load 270, 290, 345, 295 Average 300 V.P.N.

Steel coated with
<u>Sn, Zn or Al/Al-5%Si filler rod.</u>

Compound layer
centre

50 gm load 390, 412, 435,
380, 393, 390 <u>Average</u> 400 V.P.N.

Between M.S. and compound centre

50gm load 249, 203, 249, 237
100gm load 218, 267, 261, 265 <u>Average</u> 243 V.P.N.

Between weld metal and compound centre

50 gm load 254, 250, 243, 212
100 gm load 257, 252, 250 <u>Average</u> 245 V.P.N.

<u>H.D. Al steel/Al-5% Mg filler rod</u>

Compound layer centre

50gm load 488, 498, 532, 530
25gm load 629, 460, 561, 542, 581 <u>Average</u> 535 V.P.N.

Between M.S. and compound centre

50gm load 780, 642, 648, 822, 703, 660 <u>Average</u> 709 V.P.N.

Between weld metal and compound centre

50 gm load 250, 310, 320, 202, 180, 270 <u>Average</u> 255 V.P.N.

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