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Machine Learning-enabled feedback loops for metal powder bed fusion additive manufacturing

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Abstract

Metal Powder Bed Fusion (PBF) has been attracting an increasing attention as an emerging metal Additive Manufacturing (AM) technology. Despite its distinctive advantages compared to traditional subtractive manufacturing such as high design flexibility, short development time, low tooling cost, and low production waste, the inconsistent part quality caused by inappropriate product design, non-optimal process plan and inadequate process control has significantly hindered its wide acceptance in the industry. To improve the part quality control in metal PBF process, this paper proposes a novel Machine Learning (ML)-enabled approach for developing feedback loops throughout the entire metal PBF process. A categorisation of metal PBF feedback loops is proposed along with a summary of the critical PBF manufacturing data in each process stage. A generic framework of ML-enabled metal PBF feedback loops is proposed with detailed explanations and examples. The opportunities and challenges of the proposed approach are also discussed. The applications of ML techniques in metal PBF process allow efficient and effective decision-makings to be achieved in each PBF process stage, and hence have a great potential in reducing the number of experiments needed, thus saving a significant amount of time and cost in metal PBF production.

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1. Introduction

Metal Additive Manufacturing (AM) refers to the manufacturing process in which metal parts are joined or solidified from a feedstock. In recent years, various types of metal AM technologies have been developed and some of them have been commercialised and applied in the production of fully functional parts. In general, AM technologies can be divided into seven categories, including binder jetting, direct energy deposition, material extrusion, material jetting, powder bed fusion (PBF), sheet lamination, and vat photopolymerization [1]. The fundamental theory and mechanism of each AM technology differ significantly from one another. The focus of this study is on the most mature and widely applied metal AM technology, i.e. metal PBF.

PBF is an AM process that uses a laser or electron beam to selectively melt and fuse areas of a layer of powders, after which the powder bed is moved downwards, another layer of powders is added and the process repeats until the part is built up. Widely used metal PBF techniques include Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS). Though metal PBF is a relatively new technology compared to traditional subtractive manufacturing, it has shown distinctive advantages in terms of the higher design flexibility, shorter development time, lower tooling cost, and less production waste. However, despite these advantages, its widespread adoption is significantly hindered by the variability in part quality with respect to the dimensional accuracy, surface roughness, mechanical and physical properties, porosity, and other defects [2,3]. A typical metal PBF process comprises several stages such as product design, process planning, PBF manufacturing, post-processing (optional), and product quality measurement. The inconsistent part quality can be caused by various reasons in different stages such as inappropriate product design, non-optimal process plan and inadequate process control. Therefore, part quality control remains a major challenge for metal PBF.

An ideal solution to address this issue is to establish feedback loops (or closed-loop manufacturing) throughout the entire metal PBF process, such that the product design, process planning and process control can be optimized either on-line or off-line based on process monitoring and product quality measurement. The development of feedback loops for metal PBF requires a collective effort from various PBF-related research areas such as in-situ process monitoring [3,4], process control and optimization [5], process simulation [6] and product quality measurement [7]. With the advancements in process monitoring and quality measurement technologies, large amounts and various types of manufacturing data become available to be utilized to develop the feedback loops. However, traditional statistical methods suffer from their poor capability of analysing the highly heterogeneous and non-linear data.

Recent advancements in Machine Learning (ML) provide advanced data analytics tools for processing and analysing the big manufacturing data. Nowadays, ML techniques have been increasingly applied in the manufacturing area as they allow to gain insights of the big manufacturing data and facilitate the decision-making processes [8,9]. The advantages of ML have shown a great potential in facilitating the development of feedback loops for metal PBF process.

This study investigates the opportunities and challenges for developing ML-enabled feedback loops for metal PBF process. A literature review on feedback loops and ML applications in PBF is provided in Section 2. The categorization of metal PBF feedback loops and the identification of the critical data are presented in Section 3. Section 4 introduces the ML-enabled feedback loops for PBF, including a generic framework of the ML-enabled feedback loops and some example applications. Section 5 discusses the opportunities and challenges for developing the ML-enabled metal PBF feedback loops. Section 6 concludes the paper.

2. Literature review

2.1. Feedback loops for metal PBF

Development of feedback loops is considered an ultimate goal of a large amount of PBF research, though most of the existing research works focus only on a specific part of the feedback loop such as in-situ process monitoring or process control. This subsection reviews some representative works that are most relevant to the development of PBF feedback loops.

Several conceptual PBF feedback loops have been proposed. Based on the hierarchy of PBF parameters, Vlasea et al. [10] proposed four types of PBF feedback control strategies: 1) pre-processing for predictive control, 2) in-situ

defect or fault detection and handling, 3) in-situ continuous feedback control, and 4) signature-derived control through plant models or simulations. Aiming to develop closed-loop PBF system, Chua et al. [11] proposed three approaches based on different stages of the inspection and monitoring system, i.e. 1) single layer inspection-based, 2) multi-layer inspection-based, and 3) final product inspection-based feedback loops. Upon the analysis of the control cascades of PBF, Renken et al. [12] proposed three types of feedback control strategies: 1) in-process (vector) control, 2) in-situ (vector sets) control, and 3) in-situ (layer) control.

Various types of in-situ process monitoring technologies have been utilized to support the development of feedback control of PBF. Renken et al. [13] applied an on-axis high-speed pyrometer on a PBF machine to detect the real-time radiation intensities at the melting point. This signal is used to control the laser power and speed in real time to minimize the temperature deviation. Their experimental results showed that closed-loop control could decrease the temperature deviation by up to 90%. Mireles et al. [14] implemented an infrared (IR) camera on an EBM machine to monitor the in-situ IR thermography of each printed layer. Defects detected in the IR thermography are used to trigger a re-melting process to correct the defect, such that an in-situ correction feedback loop is established.

Simulation-based (or model-based) feedback loops have been extensively studied. For instance, Wang et al. [15] developed an analytical and control-oriented model that simulates the dynamics of melt pool cross-sectional area during laser scanning. The simulation results are fed back to the controller which adjusts the laser power to regulate the melt pool cross-sectional area during the build process. The developed feedback loop reduces defects during the build such as keyhole formation and over-melting.

Off-line PBF feedback loops that aim to optimize the product design or process parameters have also been investigated. Based on off-line experimental data and quality measurement results of PBF processes, Brika et al. [16] developed a feedback loop that uses a genetic optimization algorithm to optimize the build orientation while simultaneously considering mechanical properties, surface roughness, support structure and build time and cost.

2.2. Machine Learning applications in metal PBF

Recently, ML techniques have been increasingly applied in metal PBF research to facilitate various types of decision-making processes. Based on the melt pool images captured by a high-speed camera during the PBF process, Yang et al. [17] developed a deep learning-based melt pool classification method to predict the melt pool size in real time. They claimed that the processing time of the developed Convolutional Neural Network (CNN) is reduced by 90% compared to traditional image analysis method. To gain insights of how process parameters affect the PBF process, Garg et al. [18] proposed a multi-gene genetic programming method to analyse the hidden relationships between the bead width and some important process parameters such as layer thickness, laser power and scan speed. Scime and Beuth [19] developed a multi-scale CNN that is capable of detecting and classifying seven types of powder bed anomalies based on the powder bed images taken after recoating. Their experimental results showed a 97% detection and classification accuracy, which is higher than traditional image processing methods. To analyse the complex relationships between single track morphology and dynamic process signatures, Zhang et al. [20] proposed two intelligent classification methods, i.e. CNN and support vector machine (SVM), to classify three types of track morphology based on the images of melt pool, plume and spatters captured by a high-speed camera. It is noted that their classification methods could only work off-line due to the high computational power requirement. Ye et al. [21] proposed a novel defect detection method for SLM process based on the acoustic signal captured by a microphone in the build chamber. A deep belief network (DBN) framework was developed to predict the melted state of the SLM process based on the acoustic signal.

It is noted that ML has been extensively utilised in metal PBF research to solve various types of data analytics problems. However, few studies have investigated ML-enabled feedback loops for metal PBF from a systematic perspective. Hence, this study attempts to bridge this research gap by analysing the types of feedback loops in metal PBF process, the critical manufacturing data involved in the feedback loops, and how to apply ML techniques to facilitate the development of the feedback loops.

3. Metal Powder Bed Fusion feedback loops

In general, a feedback loop refers to a system where the output of a system becomes the input for the next iteration of the system, such that the performance of the system can be improved. This section analyses the types of metal PBF feedback loops from a systematic perspective considering the entire PBF process and identifies the critical data in each type of feedback loop.

3.1. Categorisation of metal PBF feedback loops

In general, a complete PBF process contains five stages, including product design, process planning, PBF manufacturing, post-processing, and product quality measurement. To analyse the types of feedback loops, the PBF manufacturing stage needs to be broken into more detailed substages considering the process monitoring and control strategies. Since PBF uses a layer-by-layer building process, the control parameters can be adjusted either during recoating or during laser/beam scanning, while the process monitoring is performed at the same time. Furthermore, since there exist various distinctive post-processing technologies (powder removal, heat treatment, machining, etc.), the post-processing stage is not considered in the feedback loops for this study.

Hence, in this work, the PBF process is further divided into six stages: 1) product design, 2) process planning, 3) recoating, 4) laser/beam scanning, 5) process monitoring, and 6) product quality measurement. Based on these PBF process stages, we categorise the metal PBF feedback loops into four types, including 1) ex-situ product design optimisation, 2) ex-situ process plan optimisation, 3) in-situ (layer-by-layer) feedback control, and 4) in-process feedback control, as shown in Figure 1. The first two feedback loops are performed off-line, while the last two are conducted during PBF manufacturing process.

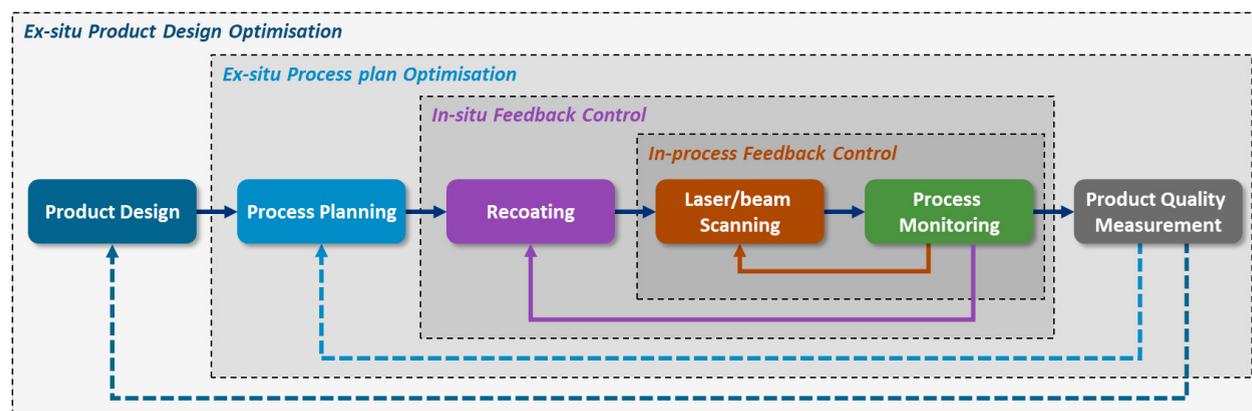


Fig. 1. Categorisation of metal PBF feedback loops

Product design is the initial step of PBF process that determines the material, geometry, and other requirements of the PBF product such as dimensional tolerances and surface roughness. Commonly, the product design cannot be modified in the following manufacturing stages. Hence, product design optimisation is always achieved off-line, where product designers compare the final results from the product quality measurement (sometimes also from the process monitoring) to find the design flaws that cause the product defects, and then perform design optimization to improve the product quality.

Process planning is a preparatory step before PBF manufacturing that determines support structures, build position and orientation, and various process parameters such as laser/beam power, scan speed, scan pattern, layer thickness and gas flow rate. In the ex-situ process plan optimisation feedback loop, process planners use data analytics tools to find the relationships between the final product quality (sometimes also the process signatures from process monitoring) and various process parameters to optimise the process plan off-line. Traditionally, process plan optimisation is achieved through the design of experiments or trial and error method.

In-situ feedback control is performed during the recoating process, i.e. before the printing of the next layer. Since PBF manufacturing follows a layer-by-layer process, some layerwise process signatures detected from the process monitoring (powder bed image, layerwise temperature distribution, etc.) can only be obtained after the layer is finished. Based on the monitored process signatures, some process parameters can be adjusted (depend on the control system) to improve the quality of the next layer or correct the defects of the previous layer. If fatal errors are detected in process monitoring, the operator can stop the process to prevent further damage of the machine components.

In-process feedback control is performed during the laser/beam scanning, where the real-time process signatures (such as melt pool radiation and plume and spatters) are used as the feedback to adjust the laser/beam power, scan speed and scan pattern. In-process feedback control is a very challenging task since it requires real-time data analytics as well as real-time control of the laser/beam power and scan speed. In addition, it is worth mentioning that most commercial PBF machines do not allow operators to adjust the process parameters during scanning.

3.2. Critical data in metal PBF feedback loops

Critical data in PBF feedback loops refer to the manufacturing data in the entire PBF process that can be adjusted, controlled, monitored, or measured to improve the product quality through the proposed four types of feedback loops (Figure 1). Identification of the critical data is a prerequisite for developing feedback loops for PBF process. A comprehensive list of specific metal PBF data in each product lifecycle stage has been reported in our previous work as a metal PBF product data model [22]. In this study, we summarise the critical data that could be monitored, controlled, or measured in each stage of the PBF feedback loops as a fishbone diagram shown in Figure 2.

Figure 2 does not aim to provide an exhaustive list of critical data in metal PBF feedback loops since there still exist many PBF parameters that have not been studied. However, it includes the most commonly mentioned parameters in existing literatures. Note that process parameters that affect the product quality can be divided into two categories, i.e. predefined and controllable. Predefined process parameters are the parameters that cannot be modified even in the process planning stage such as the powder material properties and some build environment parameters. Hence, for the process planning parameters, we only include the controllable parameters; the predefined parameters are omitted for the feedback loops in this study. For the details of each data item such as the description, data format, unit and methods/devices used to acquire the data, readers are recommended to refer to our previous work [22].

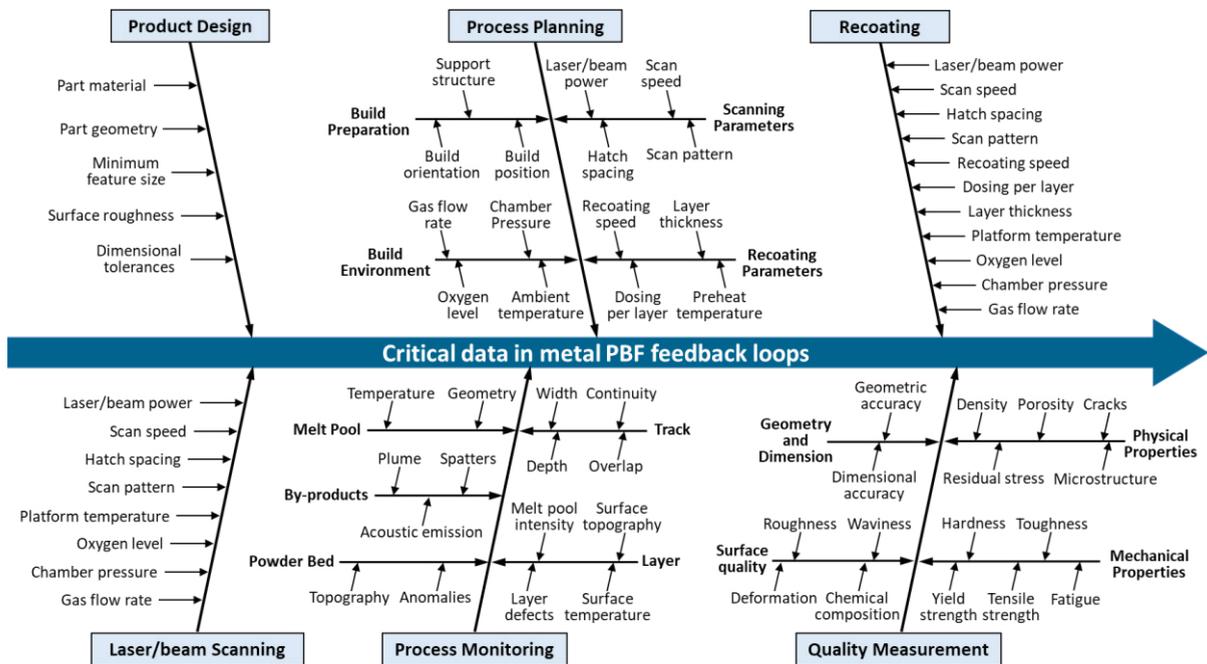


Fig. 2. Critical data in metal PBF feedback loops

4. Generic framework of Machine Learning-enabled metal PBF feedback loops

Figure 2 shows that metal PBF process involves large amounts of heterogeneous manufacturing data with highly complicated relationships. Analysing these data to establish metal PBF feedback loops requires advanced data analytics tools. As recent advancements in ML have shown great potential in solving complicated data analytics problems, this section proposes a ML-based approach to developing metal PBF feedback loops.

To explain how to apply ML to support the development of PBF feedback loops, we propose a generic framework of ML-enabled feedback loops for PBF system as shown in Figure 3. This framework is based on the analysis of the types of PBF feedback loops presented in Section 3.1.

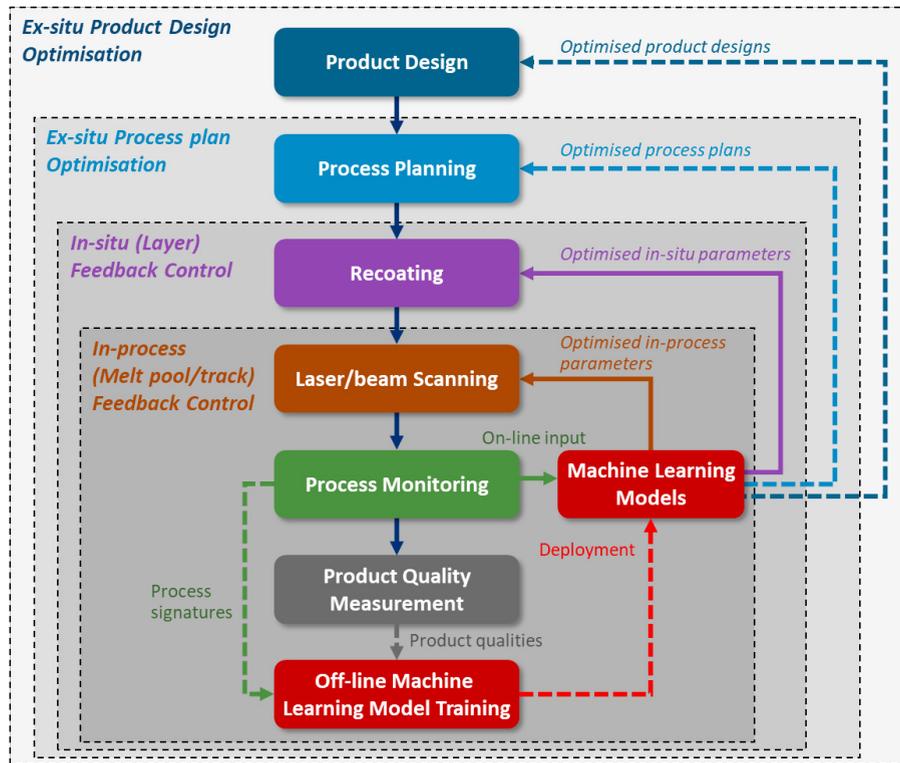


Fig. 3. Generic framework of Machine Learning-enabled feedback loops for PBF process

In general, ML techniques can be applied to support all the four types of PBF feedback loops by making use of critical manufacturing data mentioned in Section 3.2. The designed process parameters, the monitored process signatures, and the measured product qualities are used as the dataset for the off-line ML model training. The trained ML model is then deployed in the PBF process to predict either the in-situ process signatures or the final product qualities and provide the optimised parameters as the feedback to each PBF stage. Details of each ML-enabled feedback loop are explained along with some example applications as follows.

In the in-process (melt pool/track) feedback control loop, the melt pool/track signatures (melt pool radiation, track width, etc.) and the measured melt pool/track qualities (melt pool size, track geometry, etc.) are used as the dataset for the off-line ML model training. The trained ML model is then deployed as an in-process quality control model that uses the real-time process signatures to predict the quality of the melt pool/track and optimise the in-process control parameters in real time. Due to the real-time processing requirement, high-performance supervised ML models that can deal with image data such as various CNN models are commonly used to assist this feedback loop. An example is the work [17] mentioned in the literature review, where high-speed melt pool images are used to predict the melt pool size with a trained CNN model in real time. The predicted melt pool size can be used to provide optimised laser power and scan speed as the in-process feedback control.

The in-situ (layer) feedback control loop works in a similar way as the in-process feedback control loop, but uses the layer signatures (powder bed image, layer temperature distribution, etc.) and layer qualities (layer porosity, layer deformation, etc.) to train the ML model. After one layer is built, the trained ML model uses the in-situ layer signatures to predict the layer quality and optimise the laser power or scan speed for the next layer, or perform a re-melt to correct the defects of the previous layer. In this feedback loop, since the prediction is made layer-by-layer, the computational requirement of the ML model is as critical as the in-process feedback loop. Various types of supervised ML models that deal with image data can be applied. An example is from [23] where layerwise images and CT scans of the final part are used to train different ML models that predict the layer defects after one layer is built. The predicted defects can provide suggestions for optimising the control parameters for the next layer.

In the ex-situ process plan optimisation loop, ML models are developed to find the complicated relationships between the process plan (support structure, laser/beam power, scan speed, scan pattern, layer thickness, gas flow rate, etc.) and the final product qualities (density, geometry deformation, tensile strength, etc.). Since this is an off-line feedback loop, various types of supervised ML models can be applied. A typical example of this feedback loop is reported in [24], where the process parameters and the measured part density are used to train ML models to define a good process window for the scan speed. Moreover, since there is no well-developed simulation model for metal PBF process, ML techniques can also be integrated with physics-based simulation to achieve the process plan optimisation.

The ex-situ product design optimisation loop works in a similar way as the ex-situ process plan optimisation but focuses on finding the complex relationships between the product design features (material, geometry, feature size, etc.) and the final product qualities. Various types of supervised ML models can be applied to analyse the relationships between the heterogeneous manufacturing data. An example of this feedback loop is reported by Zhang et al. [25] in which they developed ML models for predicting the manufacturability of metal PBF parts with different materials, geometric structures, and sizes.

5. Opportunities and challenges

While ML-enabled metal PBF feedback loops provide various opportunities, a significant amount of challenges has also been recognised. This section discusses the opportunities and challenges for developing the proposed ML-enabled metal PBF feedback loops, based on the discussions of two promising application scenarios and the current limitations of the related technologies.

5.1. Hybrid modelling for metal PBF process

An emerging idea in computer-aided engineering science is hybrid modelling, or physics-informed machine learning. The premise is to make use of a simplified representation of the physics involved in the engineering process to be controlled, and to complement this representation by machine learning, using data acquired on-the-fly to further increase the predictive capabilities of the digital system.

This can be achieved in many ways. For instance, inputs of physics-based PBF simulators such as inherent strains or convection coefficients may be linked to machining parameters through a non-parametric regression, leading to a hybrid model represented by a neural network whereby the last layer is made of the physical models. Advanced differentiation techniques developed in the field of modelling with partial differential equations may subsequently be used to obtain the quantities required to perform back propagation. Similarly, physical measurements such as porosities or microstructure states may be predicted via a neural network that takes the output of a physical model as input, for instance the solution predicted by a transient thermal problem. Finally, hybridisation may also be obtained by allowing the parameters of the physical model to change with time, using time filtering approaches.

For such advanced digital twinning approaches to be feasible, robust data-to-simulation pipelines must be constructed so that inference algorithms may be deployed to compare simulated outputs and measurements so that the corresponding error may be minimised during the calibration or manufacturing process. This pipeline must also be able to provide real-world feedback to control the manufacturing process inputs thus numerically optimised, or to automatise the acquisition of new data, in an active learning fashion.

5.2. On-line process parameter optimisation with Reinforcement Learning

Optimising parameters from massive amount of data collected is typically tackled by offline learning, i.e. supervised or unsupervised learning. However, it has always been an interesting subject to explore how a model can be established for on-line PBF process control optimisation. One promising approach is to deploy the technique of deep reinforcement learning (DRL) that models the sequential decision-making problem by an agent, which determines the next action to interact with the environment given the observation (i.e. state) with the goal of maximising long term rewards towards an optimal solution. The most well-known application with DRL is the success of AlphaGo, which beats the world champion of the GO game and several recent publications, especially the work reported by DeepMind, claiming human-level intelligence for game environment such as Atari [26].

For PBF process control specifically, the problem is considerably more complicated. First, the Go or Atari environments are represented in discrete space, where Deep Q-Learning Network (DQN) can be used directly. However, for real-world metal PBF processes, we need to operate the manufacturing processes in a continuous space, i.e. parameters of laser power, exposure time, scan path, and so on. Many attempts have been made for learning in continuous space and the most prominent method is the Deep Deterministic Policy Gradient (DDPG) network. DDPG is an actor-critic-based network, allowing, on one hand, DQN-like off-policy learning for efficient updating of the value functions from experience buffer and, on the other hand, train a policy network simultaneously [27]. Second, a compact representation of the states will be required. With the Atari games, raw pixel-wise state representations are used. However, it is still considered less challenging than the PBF processes, considering the possible state space of the environment with not only 3D geometric information, but also all the relevant dynamic physical attributes of the process. Abstracted parameters of the product, such as dimensions, densities, statistical information of defects or quality and so on, could be potentially considered for representing the states. Another challenge is that the simulation is highly time-consuming and learning meaningful rewards from such a reward-sparse environment will be very difficult. Thus, how to accelerate the process of learning needs to be addressed. Such mechanisms may include providing human demonstrations from experts with prior expert knowledge.

5.3. Limitations of related technologies

Challenges for the development of ML-enabled metal PBF feedback loops have also been recognised from the current limitations of the related technologies.

It is noted that most of the commercial metal PBF machines provide very limited controllability for the users. As a result, the on-line process control feedback usually cannot be achieved due to the closed control system. Another issue with current metal PBF machine is the poor data interoperability. While traditional subtractive manufacturing has taken advantage of open and unified data communication standards such as MTConnect and OPC UA [28,29], there is currently no unified data communication protocol for metal PBF machines. This not only poses challenges for the field-level manufacturing data acquisition, but also limits the transferability of the developed feedback loops between different metal PBF machines.

Development of ML models usually requires large amounts of manufacturing data. For metal PBF process where manufacturing data is obtained from practical experiments, the time and cost for the experiments have to be taken into account. The poor interpretability, explainability and trustability of some deep learning models may also limit their application in the manufacturing environment. Moreover, the on-line ML models usually require very high computation capability in the field level, which is also a challenge for current shop floors.

The limitations of current process monitoring and quality measurement technologies also hinder the development of ML-enabled metal PBF feedback loops. Though various types of in-situ monitoring techniques have been developed in the past several decades, detecting the real-time process signature accurately, efficiently, and cost-effectively has always been a major challenge. Besides, the limitations of current non-destructive testing (NDT) technologies also pose challenges for labelling the PBF manufacturing data. For example, measurement and localisation of internal defects such as porosity of a large-sized high-density metal part remains a critical challenge.

6. Conclusions

Metal PBF has been attracting an increasing attention as an emerging metal AM technology. Despite its distinctive advantages compared to traditional subtractive manufacturing such as high design flexibility, short development time, low tooling cost, and low production waste, the inconsistent part quality caused by inappropriate product design, non-optimal process plan and inadequate process control has significantly hindered its broad acceptance in the industry.

To improve the part quality control in metal PBF process, this study proposes a novel ML-enabled approach for developing metal PBF feedback loops. First, a categorisation of the types of metal PBF feedback loops is proposed based on the metal PBF process stages. The critical manufacturing data that affect the final product quality in each stage are identified. Second, a generic framework of ML-enabled metal PBF feedback loops is proposed and each feedback loop is explained in detail with some practical examples. Finally, the opportunities and challenges of the proposed approach are discussed.

The proposed ML-enabled feedback loops enable the vision of closed-loop manufacturing for metal PBF processes, in which the in-situ process signatures monitored during the manufacturing stage and the measured product qualities are fed back to product design, process planning and on-line process control stages to ensure the process stability and optimise the final product quality. The applications of ML techniques in metal PBF process allow efficient and effective decision-makings to be achieved in each PBF process stage, and hence have a great potential in reducing the number of experiments needed, thus saving a significant amount of time and cost in metal PBF production.

The proposed ML-enabled feedback loop approach is also in line with the emerging concepts in Industry 4.0 and Smart Manufacturing such as Digital Twin [30] and Cyber-Physical Machine Tool [31]. It can be applied as a generic ML-enabled feedback loop solution for other types of manufacturing systems to facilitate the development of the envisioned Cyber-Physical Production System (CPPS) and Smart Factory in the era of Industry 4.0.

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References

- [1] ISO/ASTM. (2015) “International Standard ISO/ASTM 52900 Additive manufacturing – General principles – Terminology.” *International Organization for Standardization*.
- [2] Mani M, Lane B, Donmez MA, Feng SC, Moylan SP, Fesperman R. (2015) “Measurement Science Needs for Real-time Control of Additive Manufacturing Powder Bed Fusion Processes.” *NIST Interagency/Internal Report (NISTIR) - 8036*.
- [3] Grasso M, Colosimo BM. (2017) “Process defects and in situ monitoring methods in metal powder bed fusion: A review.” *Measurement Science and Technology*: **28**:044005.
- [4] Everton SK, Hirsch M, Stavroulakis PI, Leach RK, Clare AT. (2016) “Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing.” *Materials and Design* **95**:431–45.
- [5] Fleming, T. G., Nestor, S. G., Allen, T. R., Boukhaled, M. A., Smith, N. J., & Fraser, J. M. (2020). “Tracking and controlling the morphology evolution of 3D powder-bed fusion in situ using inline coherent imaging.” *Additive Manufacturing* **32**:100978.
- [6] King W, Anderson AT, Ferencz RM, Hodge NE, Kamath C, Khairallah SA. (2015) “Overview of modelling and simulation of metal powder bed fusion process at Lawrence Livermore National Laboratory.” *Materials Science and Technology (United Kingdom)*.
- [7] Taheri H, Shoaib MRBM, Koester LW, Bigelow TA, Collins PC, Bond LJ. (2017) “Powder-based additive manufacturing - a review of types of defects, generation mechanisms, detection, property evaluation and metrology.” *International Journal of Additive and Subtractive Materials Manufacturing* **1**(2): 172-209.
- [8] Wang, J., Ma, Y., Zhang, L., Gao, R. X., & Wu, D. (2018) “Deep learning for smart manufacturing: Methods and applications.” *Journal of Manufacturing Systems* **48**: 144-156.
- [9] Razvi SS, Feng S, Narayanan A, Lee YTT, Witherell P. (2019) “A review of machine learning applications in additive manufacturing.” *Proceedings of the ASME Design Engineering Technical Conference*.
- [10] Vlasea ML, Lane B, Lopez F, Mekhontsev S, Donmez A. (2015) “Development of powder bed fusion additive manufacturing test bed for enhanced real-time process control.” *26th Annual International Solid Freeform Fabrication Symposium* 13-15.

- [11] Chua, Z. Y., Ahn, I. H., & Moon, S. K. (2017). "Process monitoring and inspection systems in metal additive manufacturing: Status and applications." *International Journal of Precision Engineering and Manufacturing-Green Technology* **4**(2): 235-245.
- [12] Renken, V., Albinger, S., Goch, G., Neef, A., & Emmelmann, C. (2017). "Development of an adaptive, self-learning control concept for an additive manufacturing process." *CIRP Journal of Manufacturing Science and Technology* **19**: 57-61.
- [13] Renken, V., von Freyberg, A., Schünemann, K., Pastors, F., & Fischer, A. (2019). "In-process closed-loop control for stabilising the melt pool temperature in selective laser melting." *Progress in Additive Manufacturing* **4**(4): 411-421.
- [14] Mireles, J., Ridwan, S., Morton, P. A., Hinojos, A., & Wicker, R. B. (2015). "Analysis and correction of defects within parts fabricated using powder bed fusion technology." *Surface Topography: Metrology and Properties* **3**(3): 034002.
- [15] Wang, Q., Michaleris, P. P., Nassar, A. R., Irwin, J. E., Ren, Y., & Stutzman, C. B. (2020). "Model-based feedforward control of laser powder bed fusion additive manufacturing." *Additive Manufacturing* **31**: 100985.
- [16] Brika, S. E., Zhao, Y. F., Brochu, M., & Mezzetta, J. (2017). "Multi-objective build orientation optimization for powder bed fusion by laser." *Journal of Manufacturing Science and Engineering* **139**(11).
- [17] Yang, Z., Lu, Y., Yeung, H., & Krishnamurty, S. (2019). "Investigation of Deep Learning for Real-Time Melt Pool Classification in Additive Manufacturing." In *2019 IEEE 15th International Conference on Automation Science and Engineering (CASE)* 640-647.
- [18] Garg, A., Tai, K., & Savalani, M. M. (2014). "Formulation of bead width model of an SLM prototype using modified multi-gene genetic programming approach." *The International Journal of Advanced Manufacturing Technology* **73**(1-4): 375-388.
- [19] Scime, L., & Beuth, J. (2018). "A multi-scale convolutional neural network for autonomous anomaly detection and classification in a laser powder bed fusion additive manufacturing process." *Additive Manufacturing* **24**: 273-286.
- [20] Zhang, Y., Hong, G. S., Ye, D., Zhu, K., & Fuh, J. Y. (2018). "Extraction and evaluation of melt pool, plume and spatter information for powder-bed fusion AM process monitoring." *Materials & Design* **156**: 458-469.
- [21] Ye, D., Hong, G. S., Zhang, Y., Zhu, K., & Fuh, J. Y. H. (2018). "Defect detection in selective laser melting technology by acoustic signals with deep belief networks." *The International Journal of Advanced Manufacturing Technology* **96**(5-8): 2791-2801.
- [22] Liu C, Le Roux L, Korner C, Tabaste O, Lacan F, & Bigot S. (2020) "Digital Twin-enabled Collaborative Data Management for Metal Additive Manufacturing Systems." *Journal of Manufacturing Systems* (in press), <https://doi.org/10.1016/j.jmsy.2020.05.010>.
- [23] Gobert, C., Reutzler, E. W., Petrich, J., Nassar, A. R., & Phoha, S. (2018). "Application of supervised machine learning for defect detection during metallic powder bed fusion additive manufacturing using high resolution imaging." *Additive Manufacturing* **21**: 517-528.
- [24] Aoyagi, K., Wang, H., Sudo, H., & Chiba, A. (2019). "Simple method to construct process maps for additive manufacturing using a support vector machine." *Additive Manufacturing* **27**: 353-362.
- [25] Zhang, Y., Dong, G., Yang, S., & Zhao, Y. F. (2019). "Machine Learning Assisted Prediction of the Manufacturability of Laser-Based Powder Bed Fusion Process." In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* 59179: V001T02A008.
- [26] Mnih, V., Kavukcuoglu, K., Silver, D., Rusu, A. A., Veness, J., Bellemare, M. G., ... & Petersen, S. (2015). "Human-level control through deep reinforcement learning." *Nature* **518**(7540): 529-533.
- [27] Lillicrap, T. P., Hunt, J. J., Pritzel, A., Heess, N., Erez, T., Tassa, Y., ... & Wierstra, D. (2015). "Continuous control with deep reinforcement learning." *arXiv preprint arXiv:1509.02971*.
- [28] Liu, C., Vengayil, H., Zhong, R. Y., & Xu, X. (2018). "A systematic development method for cyber-physical machine tools." *Journal of manufacturing systems* **48**: 13-24.
- [29] Liu, C., Vengayil, H., Lu, Y., & Xu, X. (2019). "A cyber-physical machine tools platform using OPC UA and MTConnect." *Journal of Manufacturing Systems* **51**: 61-74.
- [30] Lu, Y., Liu, C., Kevin, I., Wang, K., Huang, H., & Xu, X. (2020). "Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues." *Robotics and Computer-Integrated Manufacturing* **61**: 101837.
- [31] Liu, C., & Xu, X. (2017). "Cyber-physical machine tool-the era of machine tool 4.0." *Procedia Cirp* **63**: 70-75.