Lasers in Manufacturing Conference 2023

Evaluation of failure modes on AM-processes

Christoph Wilsnack[a, *], Anne-Katrin Leopold[a], Lukas Stepien[a], Elena Lopez[a], Frank Brückner[a,c], Christoph Leyens[a,b]

[a]*Fraunhofer Institute for Material and Beam Technology, Dresden, 01277, Germany*
[b]*Technische Universität Dresden, Dresden, 01069, Germany*
[c]*Luleå University of Technology, Luleå, 971 87, Sweden*

Abstract

Additive Manufacturing (AM) has become increasingly popular in recent years, particularly in the aerospace industry, but still has challenges like ensuring high-quality parts and a reproducible process. This contribution presents an evaluation of failure modes in additive manufacturing (AM) processes. The scope of the study includes an overview of challenges in AM such as multivariate interaction and quality assurance.

A model for a generic process failure mode and effect analysis (PFMEA) is developed and applied in an industrial context, specifically in the aerospace industry. Recommendations are also derived to improve the speed, reproducibility, and stability of AM processes, with the goal of achieving first-time-right production. The study includes the demonstration of proposed recommendations on an exemplary application using laser powder bed fusion (LPBF).

Keywords: Laser Powder Bed Fusion; Additive Manufacturing; Quality Assurance; Process chains; Failure modes

---

1. Introduction

The emergence of additive manufacturing technologies in an industrial context like laser powder bed fusion in the last years is developing steadily. Alongside the scientific challenges connected with additive manufacturing of reliable structural parts with respect to process and material development their industrialization still requires work to achieve a broad application within some high demanding industrial branches.

Application areas like aerospace require a reliable process chain for the production of parts used in in their products. Due to the fact of the high process complexity for the majority of products, only small product batches are economically reasonable. Nevertheless, the manufacturing of such smaller batches for spare parts, functional prototypes or individualized parts is one of the most attractive opportunities for the industrialization of AM in an agile work area. Currently novel parts for AM-suppliers require extensive process studies to ensure the manufacturing by maintaining the demanded geometrical and dimensional accuracy and the structural properties in a reproducible way. This elongated process studies lead to an additional economical risk. Because of the multitude of challenges within the processes themselves, only highly tuned processes are common to prevent the production of insufficient part properties due to the process chain.

Yet, a comprehensive approach to overcome these obstacles is more or less unavailable today. It would require to sort all possible potential failure modes and to elaborate potential solution strategies for each of them. Within the strategies for the elaboration of the several root causes with a failure mode and effects analysis (FMEA) is attractive when trying to transfer research work into an industrial environment. Therefore, a generic process chain including the main influencing factors and the quality criteria in form of key process variable (KPV) is necessary (Brückner *et al.*, 2020).

2. Process Specific Classification of Failure Modes

As failure modes, all incidents, which lead to the failing of the process chain and having an impact on the resulting part quality or leads indirect to an irregular usage in the final application. The root causes could be categorized into the fields of material, geometrical and dimensional related insufficiencies. For a comprehensive discussion over the failure modes each step must be analyzed regarding their impact on the before mentioned criteria.

For the consideration about failure modes, this contribution focuses on the Laser powder bed fusion process (LPBF), but the general idea can be transferred to other AM-processes like laser metal deposition or binder jetting. For the representation of the process, a simple process chain diagram in form of a simplified BPMN-scheme (Business Process Model and Notation) is used (see Fig. 1). A BPMN scheme is a standardized way to document, analyze, and improve process chains. The subdivision into separate process steps. For the LPBF-process, this can be mainly categorized into material procurement, process preparation, processing and finishing. Each of these have several sub-steps, of which not all impact on the resulting part quality (Freund and Rücker, 2012).

The material procurement even though it is not directly part of the processing, but the feedstock properties in AM can have influence on the downstream performance of the process. For the majority of metal-based AM-methods materials are processed as metal powders with a large variety of properties including the general composition, the particle morphology and the flow ability/rheology. The combination of these properties determine the general process ability with respect on the general processing and the resulting part and material properties. Therefore, depending on the powder properties and part requirement processes might be sensitive to variations in the powder properties due to deviations of the production method, possible contamination or other extrinsic changes (e.g. deformation of particles, segregation). Other consumables like the used shielding gas and substrate material can also lead to a failure of the process chain and the resulting part (Hossain *et al.*, 2021; Attar *et al.*, 2015).

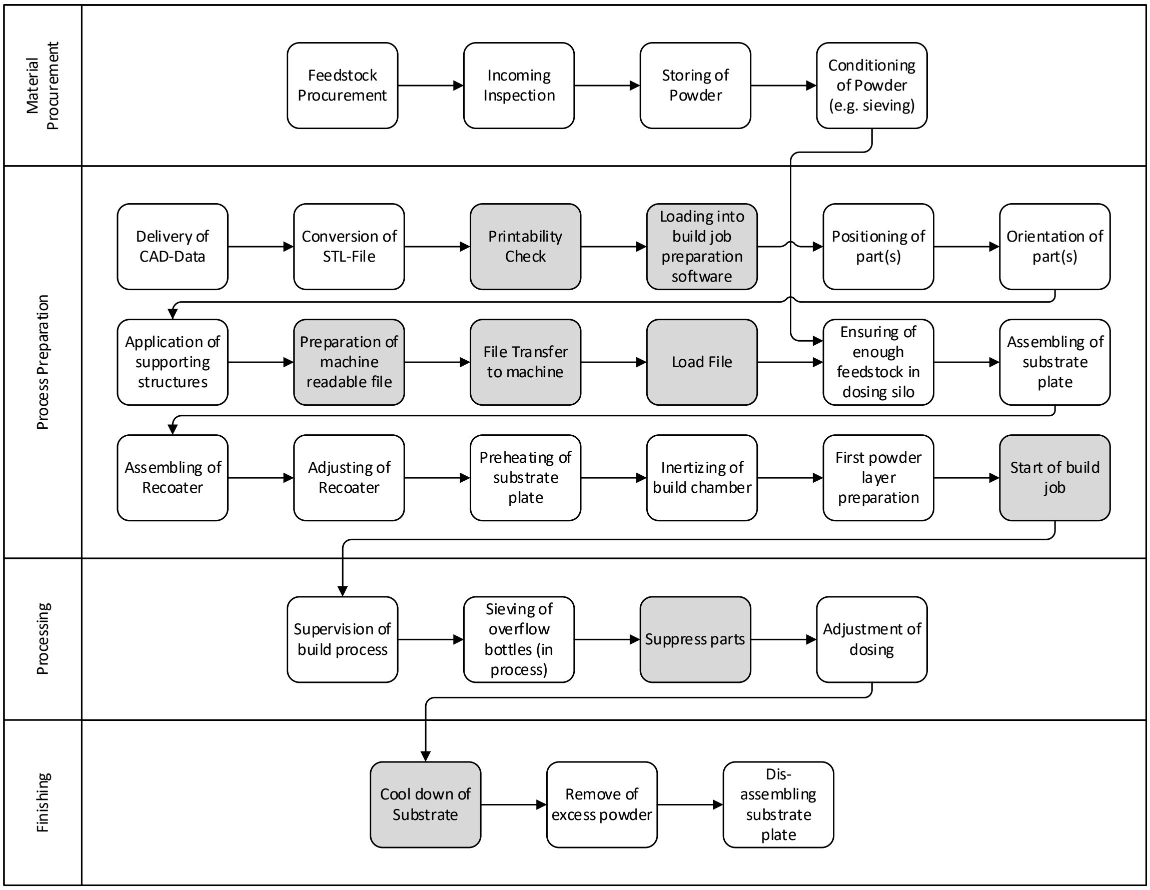

Fig. 1. Simplified BPMN-scheme for the LPBF process chain (grey – no influence on occurring failure modes).

The used machine and tools have to be considered regarding the root causes for potential failure modes. This includes the general capabilities of an AM machine like laser specifications, the atmospheric cycles, mechanics and peripherals. The variety of these capabilities of the different machines can lead to challenging transitions between build processes between different machines from various producers. Therefore, they need to be considered in process preparation, especially when adapting processes to new machines (Klingaa *et al.*, 2021).

The main influencing factors for the process can be found within the geometrical and process parameters. The high degree of freedom in design for AM is one the main causes for the usage of the method, but with these, many challenges follow. Even though the freedom is limited to some geometrical boundaries. These include the general complexity of the part containing parameters like overhang angles, minimal structure sizes and producible aspect ratios of thin features. To ensure the manufacturing usually the orientation of the part in the build chamber needs to be optimized. This optimization usually takes all areas (triangles) of the CAD-file into account and reduces the amount of areas with an inclination lower than a specific surface angle threshold. A suitable orientation has to consider other factors like the functional surfaces and hollow. In addition, the positioning of the parts can affect the part quality through the interaction between multiple parts through the cross jet and the transported fumes, which could alter the surface morphology (Wilsnack *et al.*, 2021; Adam and Zimmer, 2015).

The process Laser parameters like power, scan speed and the scanning pattern (scanning strategy, hatch, offsets) are the main influencing factors for the part quality. These can be subdivided into several categories for volume, borders, contours and up-skin and down-skin parameters with different laser parameters regarding the thermal properties. To ensure dense parts with a minimum of porosity and defects the parameters usually have to be optimized for each material and machine via parameter studies (Oliveira *et al.*, 2020; Pfaff *et al.*, 2020).

Due to the wide range of used different machines, powders and applications, the process could be sensitive to slight deviations of the before mentioned parameters and lead to an overall failure of the process. The identification of the main influences requires a preceding systemization of the input and output parameters which can have an influence on the process quality or can be used to control the process quality (Grund, 2015). Therefore, an Ishikawa (Cause-Effect Diagram) can be used to visualize the input factors and link them to specific output factors later on as shown in Fig. 2.

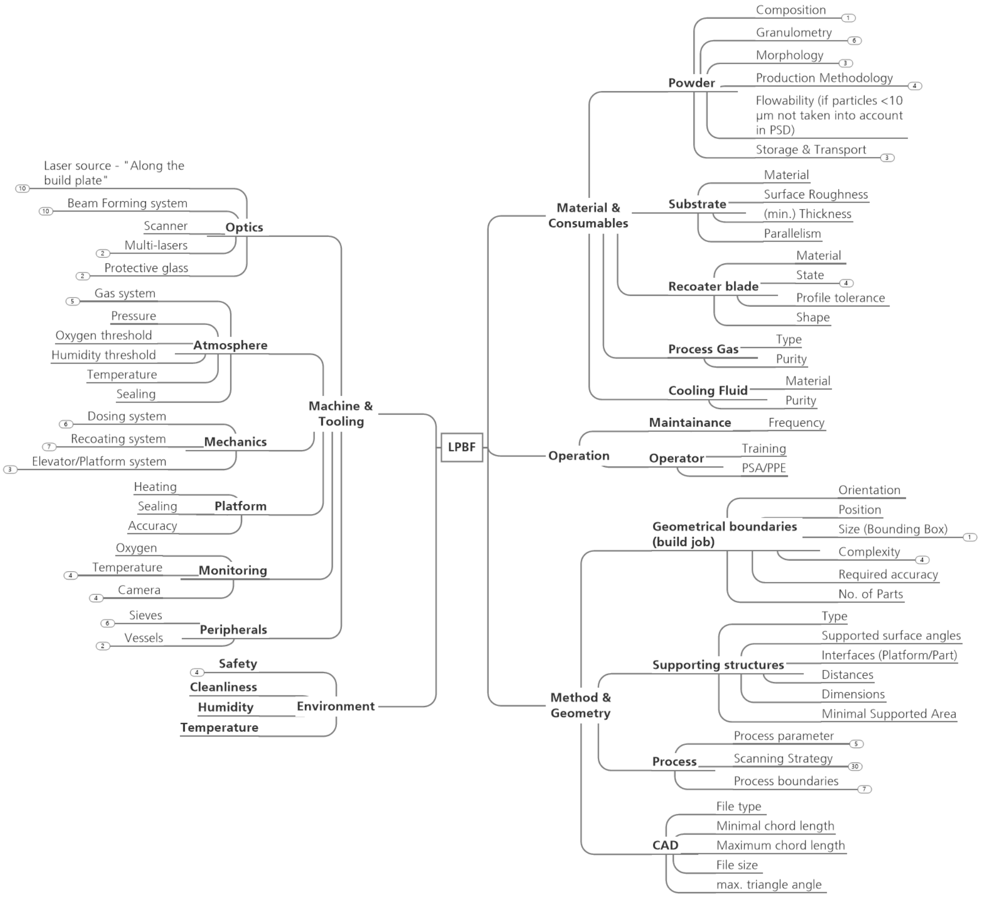

Fig. 2. Simplified Input Key Process variables with 3 levels for the LPBF-Process in form of an Ishikawa diagram.

Key process variables (KPV) can be categorized in different ways, depending on the industry, process, or system being analyzed. KPVs can be classified as input variables, which are the factors that go into the process, or output variables, which are the results or outputs of the process. KPVs can be annotated in various ways, such as controllable and uncontrollable variables. Controllable variables, which can be adjusted or controlled by the operator, are distinguished from uncontrollable variables, which are beyond the operator's control. Similarly, KPVs can be classified as critical variables, which significantly impact the quality, output, or efficiency of the process, or non-critical variables, which have a less significant impact.

Identifying critical KPVs is crucial for improving the quality, output, and efficiency of a manufacturing or production process. Methods for identifying critical KPVs include analyzing historical data, seeking expert judgment, mapping out the process flow, and conducting a failure mode analysis. Analyzing historical data can help identify which KPVs have the most significant impact on the process. Seeking expert judgment provides valuable insights into critical KPVs. Mapping out the process flow helps identify where critical KPVs occur. Conducting a process failure mode and effect analysis (PFMEA) helps identify which KPVs require close monitoring or control to prevent failures. By identifying and focusing on critical KPVs, operators and engineers can improve process outcomes, leading to increased efficiency, quality, and output (Maisano *et al.*, 2020).

PFMEA is a systematic approach utilized in manufacturing and production industries to identify and prevent potential failures in a process. PFMEA involves a team of experts who analyze the steps in a process to identify any potential failures that could occur and the potential effects of those failures. The team assigns a severity ranking and a probability ranking to each potential failure based on the potential impact and likelihood of occurrence. This is a widely used tool in various industries, including automotive, aerospace, and healthcare, among others. It is often included as a part of a larger quality management system and has been shown to be an effective method of improving product quality, reducing costs, and enhancing customer satisfaction (Fasolo and Elgh).

The mainly occurring failure mode classes for additive manufacturing can be categorized into material, surface, geometrical and dimensional related issues. The material related issues consist of defects (e.g. pores, cracks etc.), microstructural and chemical deviations from the targeted state (e.g. contaminations, grain coarsening) and mostly resulting irregularities in the mechanical properties of the final part. Surface-related issues in additive manufacturing can be categorized as surface finish or surface roughness failures. Surface finish failures refer to issues with the quality or smoothness of the surface, such as surface waviness, surface porosity, or surface defects. Surface roughness failures refer to issues with the roughness or texture of the surface, such as rough or jagged edges, ridges, or bumps. The geometrical failure modes refer to deviations from the targeted physical shape of the printed part like deformation through warping (thermally induced, mechanically induced). Dimensional failures refer to errors in the physical size or measurements of the printed object, such as incorrect thickness, width, or height.

This systemization of process KPV and failure mode categories for LPBF can then be utilized to facilitate the before mentioned PFMEA and do a ranking of the main root causes for failures. Without having a specific component as target this is firstly done in a generic way, which later can be applied and adapted for specific parts.

3. Phenomenological Classification of Failure Modes

Failure modes can be categorized in those that affect the overall process chain and those that result in defective final parts. Failures in the build process primarily occur during the process itself and can be attributed to inadequate process preparation, user mishandling, or machine deficiencies. Undesirable artifacts such as pores, cracks, and surface irregularities often cause defective parts.

Several critical failures in the build process can be identified, including warping of the built part and obstruction of mechanical machine parts, insufficient powder dosing, and failures of media. On the other hand, defective parts can exhibit a variety of artifacts. Balling occurs when irregularly shaped molten metal droplets fail to adhere properly to the substrate or previously deposited layers. This might be caused by factors such as excessive laser power or scanning speed, insufficient powder layer thickness, or improper laser beam focus.

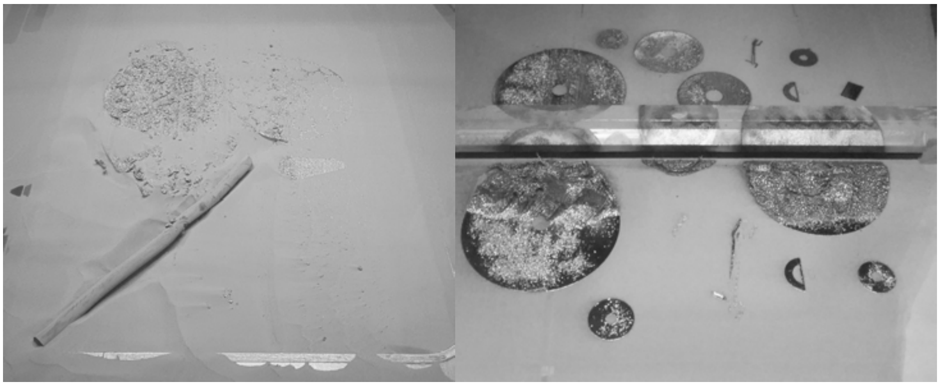

Fig. 3. Mechanical failures of a build process. Left: degraded and pulled out wiper silicon; Right: blocked recoating mechanism from warped parts.

Lack of fusion arises when the deposited powder particles fail to fully fuse with the previously deposited layer. Inadequate energy input, insufficient overlap between adjacent scan paths, or incorrect laser parameters like power or speed can contribute to this failure mode. Keyhole pores are elongated voids or cavities within the printed part, resulting from trapped gas bubbles or incomplete melting of the powder particles. They can weaken the mechanical properties of the part.

Spatter refers to the expulsion of molten metal particles during the LPBF process. Excessive laser power, improper shielding gas flow, or low-quality powder can cause spatter, leading to surface roughness, porosity, and reduced part accuracy. Warping and distortion frequently occur in LPBF, especially in large or complex geometries, due to non-uniform residual stresses during cooling. These issues can result in dimensional inaccuracies and compromised part quality.

Fig. 4. Defects in LPBF-process.

Porosity denotes the presence of voids or gas pockets within the printed part. Insufficient laser power, inadequate scanning strategies, or improper powder characteristics can contribute to porosity, negatively affecting the mechanical strength and overall integrity of the part. Thermal stress cracking arises from localized thermal gradients and rapid cooling, leading to the formation of cracks in the printed part. Improper laser scanning strategies, excessive temperature gradients, or inadequate preheating or post-heating procedures can be factors contributing to this failure mode.

4. Discussion

The linking of the multitude of possible failure modes, the process parameters and the corresponding process step leads to the challenging task to investigate it in depth. In Fig. 5, an exemplary schema is shown how the different levels are connected. This simplified schema summarizes the process steps and the KPV into fewer main categories, which allows a clearer overview. In future work these can also be subdivided more detailed. The connected nodes and interactions are not limited to work singularly. A lot of the failure modes and KPV interact (e.g., microstructural artefact can alter the mechanical material properties).

The schematic highlights three potential cases of usual failure modes and shows the logic between the three categories. While the material procurement and handling the powder could be contaminated by altering the chemical composition of the used powder with out of range elements, which leads then to the formation of artifacts in the material microstructure, which also might lead to decreased mechanical properties of the material and a subsequent failing of the part. The screening of powder quality with respect to chemical composition is a way to mitigate the influence of such failures. A failure mode caused in the process preparation is an insufficiently set orientation of the part, which leads to the deformation of the part in the process without aborting the process. Thermo-mechanical simulation can be used to prevent this deformation and ensure a good geometrical and dimensional accuracy. Deformation in process can lead to failures in process too. When warping up this could block the mechanical parts of the machine and lead to a critical failure of a build job. This could be very critical if the used hardware integrity is impacted by blocked parts. Ways to mitigate those is implementing sufficient monitoring methods, which allow an automatic control of the process and pauses the process in such critical failures.

By collecting a multitude of such failure modes in future more detailed this could be used for an evaluation of the impact of each KPV on the process failure modes, which then can be used for the establishing of control mechanisms and mitigation strategies at these nodes.

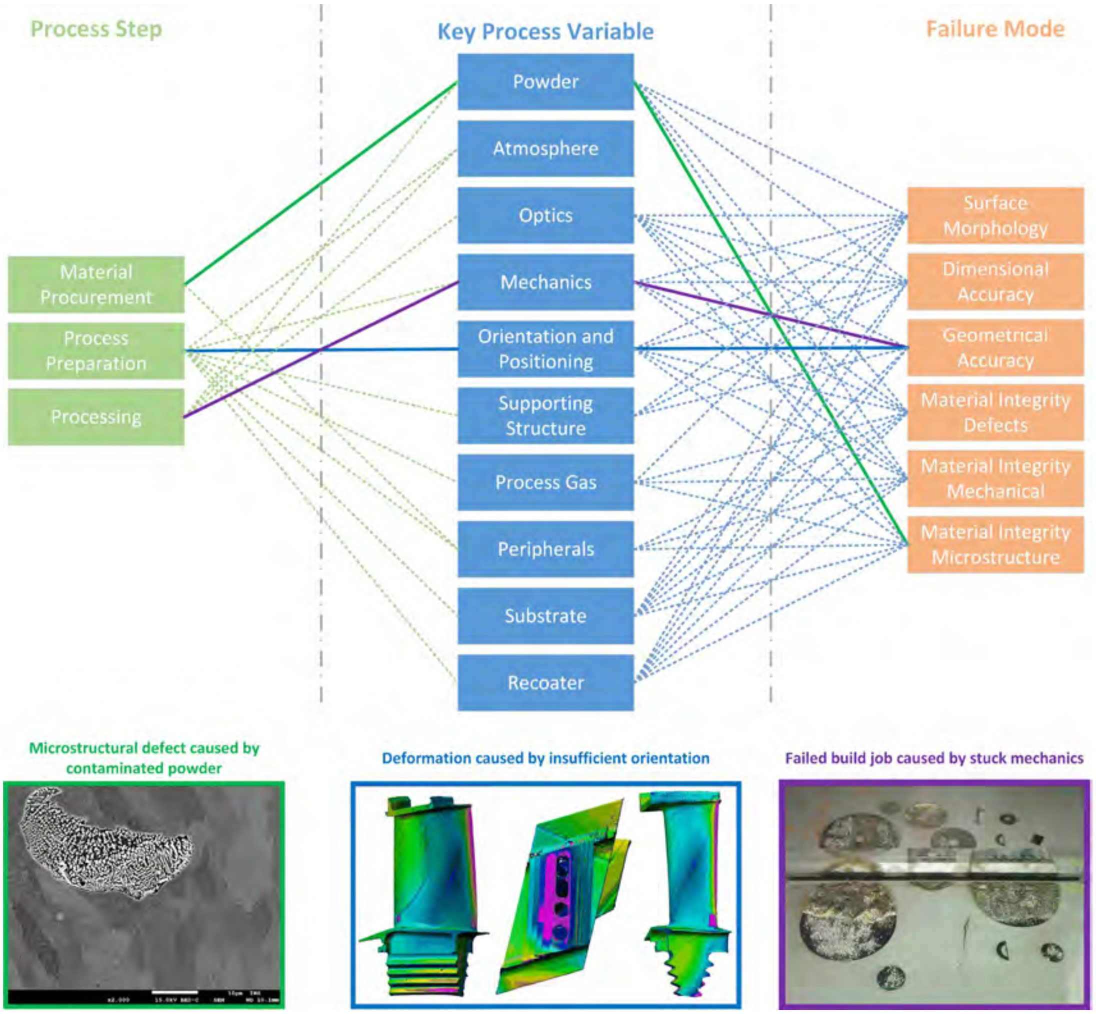

Fig. 5. Linking of process steps, key process variables and the possible failure mode class, with highlighted exemplary failure modes.

5. Conclusion and Outlook

In conclusion, the industrialization of additive manufacturing (AM) technologies, such as laser powder bed fusion (LPBF), is steadily progressing. However, achieving a broad application of AM in high-demanding industrial sectors, like aerospace, requires overcoming scientific challenges and ensuring a reliable process chain for producing parts. Failure modes and their root causes, including material, geometrical, dimensional, and process-related factors, pose significant obstacles to the successful implementation of AM in industrial production.

To address these challenges, a comprehensive approach is needed, which involves a visualization of the individual process steps as well as sorting and analyzing potential failure modes and developing corresponding solution strategies. Tools like Failure Mode and Effects Analysis (FMEA) and Phenomenological Classification of Failure Modes provide systematic frameworks for understanding the causes and effects of failures in the

AM process chain. Identifying critical Key Process Variables (KPVs) and implementing control mechanisms for these variables is crucial for improving process outcomes, enhancing efficiency, and ensuring high-quality output.

The failure modes in AM can lead to defective final parts or impact the overall process chain. Defects such as warping, lack of fusion, keyhole pores, spatter, porosity, and thermal stress cracking can compromise part quality, mechanical properties, and dimensional accuracy. Addressing these failure modes requires a combination of process optimization, parameter studies, and quality control measures, such as monitoring systems and suitable material procurement practices.

Looking ahead, further research and development efforts should focus on detailed investigations of the interconnections between failure modes, process parameters, and process steps. By evaluating the impact of each KPV on failure modes and implementing control mechanisms at critical nodes, the AM process can be optimized and failure risks mitigated. Additionally, advancements in simulation techniques, materials characterization, and process monitoring technologies will contribute to the continuous improvement and industrialization of AM. Therefore methods like machine learning can be applied to the made systemization (Sing *et al.*, 2021).

Overall, with a comprehensive understanding of failure modes and their underlying causes, along with effective control strategies and ongoing research and development, the industrial adoption of AM technologies can be accelerated, enabling their widespread application in various high-demanding industries and unlocking the full potential of additive manufacturing.

References

Adam, G.A.O. and Zimmer, D. (2015), “On design for additive manufacturing. Evaluating geometrical limitations”, Rapid Prototyping Journal, Vol. 21 No. 6, pp. 662–670.

Attar, H., Prashanth, K.G., Zhang, L.-C., Calin, M., Okulov, I.V., Scudino, S., Yang, C. and Eckert, J. (2015), “Effect of Powder Particle Shape on the Properties of In Situ Ti–TiB Composite Materials Produced by Selective Laser Melting”, Journal of Materials Science & Technology.

Brückner, F., Leyens, C., López, E. and Wilsnack, C. (2020), “Qualitätssicherung in der additiven Fertigung”, in Steven, M. (Ed.), SMART FACTORY: Einsatzfaktoren - Technologie - Produkte, KOHLHAMMER Verlag, Stuttgart, pp. 142–165.

Fasolo, C. and Elgh, F., “Integration of DFMEA and PFMEA for Enhanced Co-development of Product and Production”, in 2022 IEEE International Conference, pp. 1546–1550.

Freund, J. and Rücker, B. (2012), Praxishandbuch BPMN 2.0, 3., aktualisierte Auflage, Hanser, Carl, München.

Grund, M. (Ed.) (2015), Implementierung von schichtadditiven Fertigungsverfahren, Springer Berlin Heidelberg, Berlin, Heidelberg.

Hossain, M.S., Silva, D.F., Vinel, A., Liu, J. and Shamsaei, N. (2021), Powder Features Affecting Structural and Mechanical Properties of Additively Manufactured Inconel 718: A Machine Learning Analysis, University of Texas at Austin.

Klingaa, C.G., Mohanty, S., Funch, C.V., Hjermitslev, A.B., Haahr-Lillevang, L. and Hattel, J.H. (2021), “Towards a digital twin of laser powder bed fusion with a focus on gas flow variables”, Journal of Manufacturing Processes, Vol. 65, pp. 312–327.

Maisano, D.A., Franceschini, F. and Antonelli, D. (2020), “dP-FMEA: An innovative Failure Mode and Effects Analysis for distributed manufacturing processes”, Quality Engineering, Vol. 32 No. 3, pp. 267–285.

Oliveira, J.P., LaLonde, A.D. and Ma, J. (2020), “Processing parameters in laser powder bed fusion metal additive manufacturing”, Materials & Design, Vol. 193, p. 108762.

Pfaff, A., Jäcklein, M., Schlager, M., Harwick, W., Hoschke, K. and Balle, F. (2020), “An Empirical Approach for the Development of Process Parameters for Laser Powder Bed Fusion”, Materials, Vol. 13 No. 23, p. 5400.

Sing, S.L., Kuo, C.N., Shih, C.T., Ho, C.C. and Chua, C.K. (2021), “Perspectives of using machine learning in laser powder bed fusion for metal additive manufacturing”, Virtual and Physical Prototyping, Vol. 16 No. 3, pp. 372–386.

Wilsnack, C., Cubillo, A.A., Robiner, V., Melzer, C., Richter, J., Paul, E.C., Zaltron, P., Riede, M., Stepien, L., Lopez, E., Frank, Brückner and Leyens, C. (2021), “Realization and verification of a compliant mechanism produced by Additive Manufacturing”.