



Residual Stress Mitigation and Distortion Control in Laser Powder Bed Fusion Components for High-Reliability Engineering Applications

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[Doi: 10.63125/1b3nyj37](https://doi.org/10.63125/1b3nyj37)

Received: 03 July 2025; Revised: 28 July 2025; Accepted: 12 August 2025; Published: 26 September 2025

Abstract

This study examined residual stress mitigation and distortion control in Laser Powder Bed Fusion (LPBF) components for high-reliability engineering applications. The problem addressed was the limited quantitative evidence on how process instability, residual stress, distortion, post-processing, and inspection jointly influence LPBF component reliability. The purpose was to determine whether these control practices significantly predict reliability outcomes in demanding engineering cases such as aerospace, biomedical, automotive, energy, defense, and precision tooling applications. A quantitative, cross-sectional, case-based design was used with 150 valid responses from additive manufacturing engineers, materials engineers, quality assurance professionals, design engineers, reliability/process engineers, and academic specialists. The key variables were process parameter stability, residual stress mitigation, distortion control, post-processing treatment, quality assurance and inspection, and LPBF component reliability. Data were analyzed using descriptive statistics, Cronbach's alpha reliability testing, Pearson correlation, multiple regression, and hypothesis testing. The findings showed high agreement across all major constructs, with post-processing treatment recording the highest mean score ($M = 4.18$), followed by residual stress mitigation ($M = 4.11$), LPBF component reliability ($M = 4.07$), distortion control ($M = 4.03$), quality assurance and inspection ($M = 3.96$), and process parameter stability ($M = 3.89$). The research instrument was reliable, with an overall Cronbach's alpha of 0.892. Correlation results showed significant positive relationships between reliability and post-processing treatment ($r = 0.704$), residual stress mitigation ($r = 0.681$), distortion control ($r = 0.653$), quality assurance ($r = 0.625$), and process stability ($r = 0.603$), all at $p < 0.01$. Regression analysis confirmed that the model explained 59.7% of the variance in LPBF component reliability, $R^2 = 0.597$, $F(5,144) = 42.67$, $p < 0.001$. Post-processing treatment was the strongest predictor ($\beta = 0.312$), followed by residual stress mitigation ($\beta = 0.286$) and distortion control ($\beta = 0.241$). The study implies that reliable LPBF manufacturing requires integrated process control, stress reduction, distortion management, post-processing, and inspection systems.

Keywords

Laser Powder Bed Fusion; Residual Stress Mitigation; Distortion Control; Component Reliability; Additive Manufacturing.

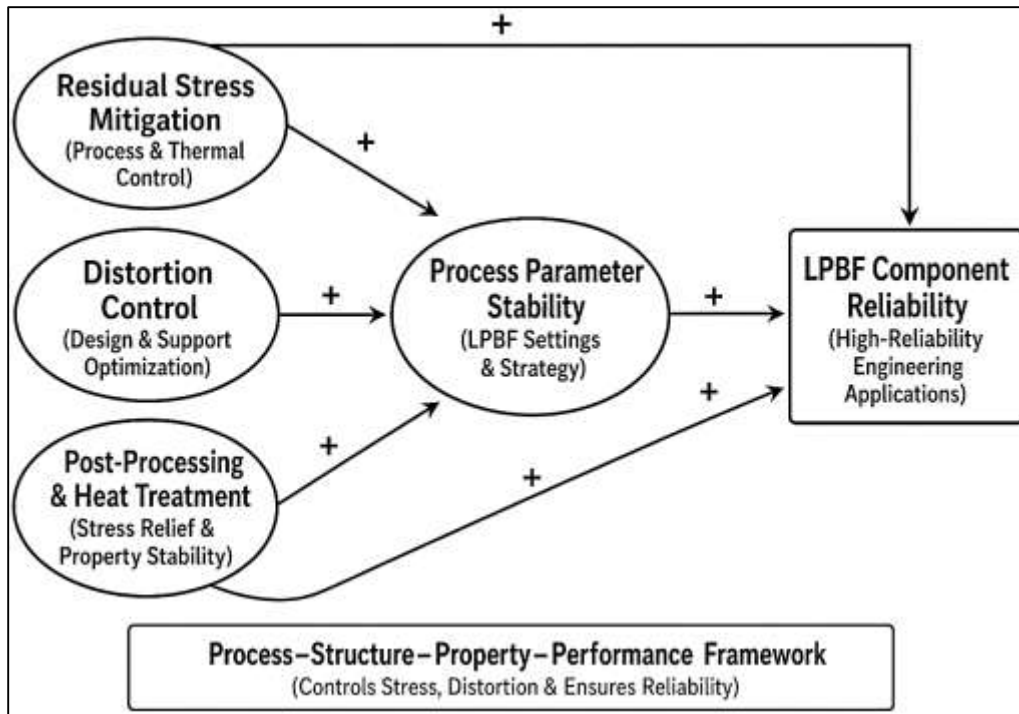
INTRODUCTION

Laser Powder Bed Fusion (LPBF) is a metal additive manufacturing process in which a high-energy laser selectively melts thin layers of metallic powder according to a digital three-dimensional model, allowing parts to be produced layer by layer with complex geometries that are difficult to fabricate through conventional subtractive or formative manufacturing routes (Masoomi et al., 2017). In engineering literature, LPBF is closely associated with selective laser melting, laser-based powder bed fusion, and powder bed fusion-laser beam/metal processes, although naming conventions differ across standards, machine vendors, and research communities. The process is internationally significant because it supports the production of lightweight, customized, topology-optimized, and high-performance components for aerospace, biomedical, automotive, energy, defense, tooling, and precision manufacturing sectors (DebRoy et al., 2018). LPBF allows designers to integrate internal channels, lattice structures, lightweight brackets, patient-specific implants, turbine-related components, and geometrically complex parts within a single build operation. This design freedom has made metal additive manufacturing a strategic technology for global advanced manufacturing, particularly in countries investing in digital manufacturing, Industry 4.0, aerospace modernization, medical implant innovation, and resilient supply chains (Ali et al., 2018). Metal additive manufacturing has been widely described as a process family capable of transforming component design, production logistics, and performance-oriented material development because it shifts manufacturing from tool-dependent fabrication toward digital, layer-wise production. Within this broader field, LPBF occupies a central role because it can process important engineering alloys such as Ti-6Al-4V, 316L stainless steel, Inconel 718, Inconel 625, AlSi10Mg, maraging steel, and cobalt-chromium alloys (Thijs et al., 2010). The international relevance of LPBF is further strengthened by its ability to reduce material waste, shorten development cycles, support part consolidation, and enable localized production of mission-critical parts. Research on LPBF has shown that the process is not only a manufacturing route but also a thermo-metallurgical system in which laser energy, scan strategy, layer thickness, powder properties, build geometry, and cooling behavior jointly determine microstructure and performance. For this reason, LPBF components must be understood through the interaction between process conditions, material structure, mechanical properties, and service performance (Vrancken et al., 2012).

Residual stress refers to internal stress that remains locked within a material or component after manufacturing, even when no external load is applied. In LPBF, residual stress is mainly generated by repeated localized heating, rapid melting, fast solidification, steep thermal gradients, constrained contraction, and successive thermal cycling across deposited layers (Fang et al., 2020). During laser scanning, the melt pool and surrounding material experience uneven temperature distribution; as the heated region expands and later contracts against cooler and more rigid surrounding material, tensile and compressive stresses develop. These stresses may remain after cooling and may redistribute when the component is removed from the build plate, heat treated, machined, or placed under service loading (Frazier, 2014). Distortion refers to unwanted geometric deformation, warping, bending, curling, dimensional deviation, or shape inaccuracy that occurs during or after LPBF processing. Residual stress and distortion are technically connected because internal stress fields can release through deformation, cracking, delamination, support failure, or build-plate separation. Residual stress has been established as a major limitation in selective laser sintering and selective laser melting through its connection with temperature gradients and part deformation (King et al., 2015). Residual stresses and deformations in selective laser melting have also been examined in relation to thermal-mechanical behavior and part accuracy. Later studies confirmed that laser power, scan speed, hatch spacing, scan rotation, build orientation, layer thickness, support structures, and preheating conditions can alter the magnitude and distribution of residual stress (Leuders et al., 2013). The global importance of this issue is high because LPBF is increasingly used in sectors where dimensional accuracy, fatigue resistance, fracture behavior, and long-term reliability are not optional quality attributes. In aerospace, for example, residual stress may influence crack initiation and fatigue life; in biomedical implants, distortion may affect anatomical fit and mechanical stability; in energy and high-temperature components, stress concentration may reduce resistance to cyclic loading and environmental degradation (Kruth et al., 2007). LPBF therefore requires more than successful part formation; it requires controlled thermal behavior, predictable stress evolution, and reliable dimensional outcomes.

The scientific foundation of LPBF residual stress formation is rooted in heat transfer, solidification, metallurgical transformation, and thermo-mechanical constraint (Read et al., 2015). A laser beam creates a small and highly transient melt pool that rapidly absorbs energy, melts powder particles, interacts with previously solidified layers, and cools under conditions that are far from equilibrium. Powder bed fusion has been described as a process governed by coupled physical phenomena, including laser absorption, powder-scale heat transfer, melt pool fluid flow, vaporization effects, and solidification. High-fidelity mesoscopic simulation has shown that melt pool dynamics can involve recoil pressure, surface tension, powder denudation, spatter, and complex flow behavior, all of which influence local thermal histories (Riemer et al., 2014).

Figure 1: Proposed LPBF Reliability Framework



These local thermal histories become important for residual stress because each layer is not thermally independent; it is deposited on a substrate and previous layers that constrain expansion and contraction. LPBF processing can produce distinctive microstructures and crystallographic textures in Ti-6Al-4V due to directional solidification and repeated thermal exposure. Heat treatment has also been shown to change the microstructure and mechanical properties of selectively laser melted Ti-6Al-4V, indicating that post-build thermal processing is directly connected to stress relief and property stabilization (Sames et al., 2016). The process-structure-property connection is therefore highly relevant to this research because process parameters influence thermal gradients, thermal gradients influence residual stress and microstructure, and residual stress and microstructure influence reliability-related performance. Internationally, this connection matters because LPBF adoption is expanding across engineering systems that operate under fatigue, vibration, pressure, thermal cycling, corrosion, and safety-critical loading. Studies on fatigue and mechanical behavior of additively manufactured metals have shown that defects, surface roughness, residual stress, and microstructural anisotropy can influence fatigue strength and scatter in performance data. As a result, residual stress mitigation cannot be treated as an isolated manufacturing preference; it is part of the broader engineering requirement for predictable structural performance (Simson et al., 2017).

Residual stress mitigation in LPBF involves process-level, design-level, thermal-management, and post-processing strategies intended to reduce the formation, concentration, or harmful release of internal stresses (Yadollahi & Shamsaei, 2017). Common approaches include build platform preheating, optimized laser power, scan speed control, hatch spacing adjustment, layer thickness optimization,

scan vector rotation, island or chessboard scanning, stripe scanning, support structure optimization, part orientation planning, thermal simulation, stress-relief heat treatment, hot isostatic pressing, and surface finishing. Scan strategy is one of the most frequently investigated methods because it determines the direction, sequence, and distribution of heat input during fabrication. Thermo-mechanical simulation has shown that scan strategy can substantially influence residual stress patterns in selective laser melting (Yadroitsev et al., 2014). Experimental work on laser powder bed fusion has also shown that scan pattern selection changes stress distribution. Scan strategies have further been linked with residual stress and mechanical properties in selectively laser melted Ti-6Al-4V. Additional research has reported that scan strategy affects residual stress distribution in Ti-6Al-4V produced by selective laser melting. Preheating is another important strategy because it reduces the temperature difference between the melt pool region and the surrounding material, thereby lowering thermal gradients and thermal contraction mismatch (Mirkoohi et al., 2021). Modeling of the effect of preheating on residual stress in LPBF has shown that substrate temperature is relevant to stress prediction. Post-processing methods are equally important because residual stresses often remain after printing and may require stress-relief heat treatment or hot isostatic pressing before service. Heat treatment and post-processing can modify microstructure and mechanical behavior in Ti-6Al-4V parts. Residual stress in selective laser melting has also been reviewed in relation to experimental characterization, physical modeling, and active adjustment as major research directions within stress control. These studies collectively show that mitigation is not a single technique; it is a coordinated control system involving design, processing, thermal management, and post-build treatment (Herzog et al., 2016).

Distortion control is closely related to residual stress mitigation, but it focuses more directly on preserving dimensional accuracy, geometric stability, part tolerance, surface quality, and build success. In LPBF, distortion can occur when accumulated residual stresses exceed local resistance to deformation or when the part bends after being released from supports or the base plate. Distortion may also arise during the build itself, causing recoater interference, support fracture, poor layer deposition, or build failure. Support structures are therefore not only temporary mechanical attachments; they also act as heat conduction paths, geometric stabilizers, anchors against warping, and process-control features (Calignano, 2014). Design optimization of support structures in aluminum and titanium alloys produced by selective laser melting has shown that support design is relevant to manufacturability, heat transfer, and part quality. Additional work on geometric support design has shown that support characteristics may influence deformation, surface quality, and successful fabrication of overhanging structures (Mercelis & Kruth, 2006). Part orientation and geometry also matter because overhangs, thin walls, long unsupported spans, sharp transitions, and high aspect-ratio features can increase thermal imbalance and distortion risk. Simulation-based approaches have therefore become important for predicting distortion before printing. Inherent strain approaches for estimating residual stress and deformation in LPBF have been reviewed as useful part-scale modeling approaches when full thermo-mechanical simulation is computationally expensive (Mohammadtaheri et al., 2022). The effect of process parameters on residual stress evolution and distortion in laser powder bed fusion of Ti-6Al-4V has been examined, connecting process selection with geometric deformation. Residual stress measurements in 316L samples made by selective laser melting also show that stress evaluation is necessary for understanding part behavior after fabrication. The international significance of distortion control is particularly strong in industries where LPBF parts must fit assemblies, meet qualification requirements, undergo post-processing, or perform under cyclic loading. A part may have acceptable density and strength while failing dimensional requirements; therefore, distortion control is essential for linking manufacturability with reliability (Mercelis & Kruth, 2006).

High-reliability engineering applications are those in which component failure can create severe safety, financial, operational, regulatory, or mission-level consequences. LPBF components used in aerospace structures, aircraft engines, medical implants, pressure-containing systems, energy devices, defense systems, and critical tooling require confidence in dimensional accuracy, mechanical stability, fatigue life, fracture resistance, surface integrity, and repeatable production quality. In these contexts, reliability refers to the ability of a component to perform its intended function under specified conditions for a required period without failure (Jiang et al., 2019; Khairallah et al., 2016). LPBF reliability depends on more than one material property; it depends on process stability, defect control,

microstructural consistency, residual stress management, distortion control, post-processing, inspection, and qualification. Mechanical properties of metal additive manufacturing have been reviewed in relation to variability across materials, processes, and post-processing conditions. Additive manufacturing process conditions, microstructure, and resulting properties for metals have also been described as strongly connected (Song et al., 2018). Process–structure–property relationships in additively manufactured metallic components provide a strong theoretical basis for studying LPBF reliability as a function of process and quality-control factors. Parameter optimization in selective laser melting of AlSi10Mg has demonstrated that process settings affect part quality. Thermal modeling in laser powder bed fusion of Ti-6Al-4V has also been connected with mechanical considerations, reinforcing the relationship between heat flow and performance (Gu et al., 2012). Scanning strategy-induced microstructure has been shown to affect residual stress in LPBF Inconel 718, which is especially relevant to high-temperature engineering applications. These studies show that reliability in LPBF is produced through a chain of technical decisions, beginning with digital design and process planning and continuing through printing, stress relief, inspection, and service qualification. This chain provides the foundation for examining residual stress mitigation and distortion control as measurable predictors of component reliability (Parry et al., 2016).

The present research is positioned within this international body of LPBF scholarship by focusing on residual stress mitigation and distortion control in components intended for high-reliability engineering applications. A quantitative, cross-sectional, case-study-based design is appropriate because LPBF reliability challenges involve measurable professional judgments about process parameter stability, mitigation practices, distortion control methods, post-processing, inspection, and reliability outcomes. Existing studies provide strong experimental, numerical, and review-based evidence on residual stress formation, scan strategy, preheating, heat treatment, microstructure, support design, and distortion prediction. A survey-based quantitative approach allows these technical domains to be organized into variables that can be statistically tested using descriptive statistics, correlation analysis, and regression modeling (Serrano-Munoz et al., 2020). The five-point Likert scale is suitable for measuring professional perceptions of the extent to which LPBF process factors, mitigation strategies, distortion control practices, post-processing treatments, and quality assurance practices contribute to component reliability (Levkulich et al., 2019; Lewandowski & Seifi, 2016). The study is grounded in the Process–Structure–Property–Performance framework, where LPBF process conditions influence residual stress state, microstructural stability, dimensional accuracy, and mechanical performance. Under this framework, process parameter stability, residual stress mitigation, distortion control, post-processing, and inspection can be treated as independent or explanatory constructs, while LPBF component reliability can be treated as the dependent outcome. The research also introduces topic-specific result elements such as a Residual Stress–Distortion Risk Profiling Matrix and an LPBF Reliability Readiness Index, which are designed to connect statistical findings with engineering interpretation (Yadroitsev & Smurov, 2010; Zaeh & Branner, 2010). The introduction therefore establishes LPBF as an internationally significant manufacturing process, defines residual stress and distortion as central technical challenges, and positions reliability as the outcome of integrated process control, thermal management, dimensional stability, and quality assurance (Robinson et al., 2018).

Background of the Study

Laser Powder Bed Fusion has become one of the most important metal additive manufacturing processes for producing complex, lightweight, and high-performance engineering components. The process works by using a focused laser beam to selectively melt and fuse thin layers of metallic powder according to a digital design model. Through this layer-by-layer approach, LPBF allows manufacturers to create parts with intricate internal channels, lattice structures, optimized geometries, and customized designs that are difficult or impossible to achieve using conventional manufacturing methods. This makes LPBF especially valuable in high-reliability engineering sectors such as aerospace, biomedical engineering, automotive systems, energy production, defense, and precision tooling, where component performance, dimensional accuracy, and structural integrity are critical. However, the same thermal conditions that make LPBF effective also create major technical challenges. During printing, the material experiences rapid heating, melting, solidification, and cooling within a very short period.

These repeated thermal cycles create steep temperature gradients between the molten region and the surrounding solid material. As the heated material expands and later contracts, internal residual stresses are generated within the component. When these stresses accumulate, they may lead to distortion, warping, cracking, dimensional deviation, support failure, and reduced mechanical performance. In high-reliability applications, such defects can seriously affect fatigue life, load-bearing capacity, service stability, and overall component safety. Therefore, residual stress mitigation and distortion control have become central concerns in LPBF process development and quality assurance. Manufacturers and researchers use several strategies to control these problems, including process parameter optimization, build platform preheating, scan strategy modification, support structure design, build orientation planning, thermal simulation, post-processing heat treatment, hot isostatic pressing, and dimensional inspection. Although these strategies are widely recognized, there is still a need to understand how they collectively influence the reliability of LPBF components from a quantitative perspective. This study is therefore based on the need to examine the relationship between residual stress mitigation, distortion control, and component reliability in LPBF manufacturing. By using a quantitative, cross-sectional, case-study-based approach, the study aims to generate measurable evidence on how process control and quality improvement practices contribute to reliable LPBF production for demanding engineering applications.

Problem Statement

Laser Powder Bed Fusion has gained strong attention as a metal additive manufacturing process for producing complex and high-performance engineering components, yet residual stress and distortion remain major obstacles to its reliable industrial application. During LPBF processing, the repeated interaction between the laser beam and metallic powder produces rapid heating, melting, solidification, and cooling within a highly localized region. This repeated thermal cycling creates steep temperature gradients and uneven material contraction, which often generate internal residual stresses within the printed component. When these stresses are not properly controlled, they can lead to distortion, warping, cracking, dimensional deviation, support failure, poor surface quality, and reduced mechanical performance. These issues are especially serious in high-reliability engineering applications where components are expected to perform safely under demanding conditions such as fatigue loading, vibration, thermal cycling, pressure, and long-term service exposure. In such applications, even a small amount of distortion or internal stress can reduce dimensional accuracy, weaken structural integrity, and increase the risk of premature failure. Although several strategies are used to address these challenges, including process parameter optimization, scan strategy modification, build platform preheating, support structure design, build orientation planning, post-processing heat treatment, hot isostatic pressing, and inspection-based quality control, there is still a need to understand how these strategies collectively influence LPBF component reliability. Much of the existing technical discussion focuses on experimental testing, numerical simulation, or material-specific analysis, while fewer studies examine the combined relationship between residual stress mitigation, distortion control, process stability, post-processing, quality assurance, and reliability outcomes using a quantitative, survey-based approach. This creates a gap in understanding how LPBF professionals perceive and evaluate the effectiveness of these control strategies in real engineering contexts. Without such quantitative evidence, manufacturers may find it difficult to prioritize the most influential practices for improving dimensional accuracy, reducing residual stress risk, and strengthening component reliability. Therefore, the central problem addressed in this study is the insufficient quantitative understanding of how residual stress mitigation and distortion control strategies contribute to the reliability of LPBF-manufactured components used in high-reliability engineering applications.

The main objective of this study is to quantitatively examine how residual stress mitigation and distortion control strategies influence the reliability of Laser Powder Bed Fusion components intended for high-reliability engineering applications. The study seeks to identify the major LPBF process factors that contribute to residual stress formation and distortion, including laser power variation, scan speed inconsistency, layer thickness selection, hatch spacing, build orientation, support structure design, thermal gradients, and cooling behavior. Another objective is to evaluate the perceived effectiveness of residual stress mitigation strategies such as platform preheating, scan strategy optimization, process parameter control, support structure improvement, stress-relief heat treatment, and hot isostatic

pressing. The study also aims to assess the role of distortion control methods in improving dimensional accuracy, geometric stability, build success, and overall component quality. In addition, the research intends to determine the relationship between process parameter stability, residual stress mitigation, distortion control, post-processing practices, quality assurance, and LPBF component reliability. Through descriptive statistics, the study will summarize the level of agreement among respondents regarding the importance and effectiveness of different LPBF control practices. Through correlation analysis, the study will examine the strength and direction of relationships among the major variables. Through regression modeling, the study will test the extent to which residual stress mitigation and distortion control practices predict reliability outcomes. The study further aims to develop a Residual Stress-Distortion Risk Profiling Matrix to classify LPBF factors according to their perceived risk levels and an LPBF Reliability Readiness Index to assess the overall preparedness of LPBF practices for producing reliable components. By achieving these objectives, the research will provide a structured quantitative understanding of how thermal management, process control, dimensional stability, post-processing, and inspection practices contribute to reliable LPBF production. The objective-based direction of the study is therefore centered on linking technical LPBF control strategies with measurable reliability outcomes in engineering environments where performance, safety, and dimensional precision are critical.

Research Hypotheses

The hypotheses of this study are developed to statistically examine the relationships among LPBF process parameter stability, residual stress mitigation, distortion control, post-processing practices, quality assurance, and component reliability. Since the study follows a quantitative, cross-sectional, case-study-based approach, the hypotheses are designed to be tested using correlation analysis and regression modeling based on five-point Likert-scale data. The first hypothesis proposes that LPBF process parameter stability has a significant positive relationship with residual stress mitigation effectiveness. This means that stable control of laser power, scan speed, hatch spacing, layer thickness, and build orientation is expected to support better management of internal stress formation. The second hypothesis states that residual stress mitigation strategies have a significant positive effect on LPBF component reliability. This assumes that practices such as platform preheating, scan strategy optimization, stress-relief heat treatment, and support design improvement can enhance mechanical stability, dimensional performance, and service confidence. The third hypothesis proposes that distortion control practices have a significant positive relationship with dimensional accuracy in LPBF components. This suggests that build orientation planning, support optimization, thermal simulation, compensation modeling, and in-situ monitoring may reduce warping, shrinkage, and geometric deviation. The fourth hypothesis states that post-processing treatment has a significant positive effect on reducing residual stress-related reliability risks. This is based on the assumption that heat treatment, hot isostatic pressing, surface finishing, and final inspection improve the structural readiness of LPBF components after printing. The fifth hypothesis proposes that residual stress mitigation and distortion control practices jointly have a significant predictive effect on LPBF component reliability. This means that the combined application of stress-control and distortion-control methods is expected to explain a meaningful portion of reliability outcomes. The sixth hypothesis states that quality assurance and inspection practices significantly strengthen the relationship between LPBF process control and component reliability. Together, these hypotheses provide a statistical foundation for examining whether LPBF reliability can be improved through integrated control of thermal behavior, process parameters, post-processing, dimensional accuracy, and inspection systems.

Significance of the Research

- i. **Significance to additive manufacturing knowledge:** This study is significant because it contributes to the growing body of knowledge on Laser Powder Bed Fusion by examining residual stress mitigation and distortion control from a quantitative perspective. It moves beyond general technical discussion by measuring how different control practices relate to component reliability using statistical techniques.
- ii. **Significance to LPBF manufacturers:** The findings may help manufacturers identify which process-control practices are most strongly associated with reliable LPBF production. This can support better decision-making in relation to scan strategy selection, platform preheating, support structure design,

post-processing, dimensional inspection, and quality assurance.

iii. **Significance to high-reliability engineering sectors:** The research is important for sectors such as aerospace, biomedical engineering, automotive systems, energy, defense, and precision tooling, where LPBF components must meet strict requirements for dimensional accuracy, fatigue strength, mechanical stability, and service performance.

iv. **Significance to quality assurance professionals:** The study can support quality assurance teams by showing how residual stress mitigation, distortion control, and inspection practices contribute to reliability outcomes. This may help improve qualification procedures, acceptance standards, and risk-based inspection planning for LPBF components.

v. **Significance to engineering designers:** The research may guide designers to consider stress risk, distortion sensitivity, build orientation, support requirements, and post-processing needs during the early design stage. This is important because LPBF reliability is influenced not only by printing conditions but also by design decisions made before production.

vi. **Significance to researchers and academics:** The study provides a useful framework for future academic work by combining the Process-Structure-Property-Performance logic with measurable survey constructs. The Residual Stress-Distortion Risk Profiling Matrix and LPBF Reliability Readiness Index also add originality to the research design.

vii. **Significance to industrial decision-making:** The study can help organizations prioritize resources toward the most effective LPBF reliability improvement practices. By using descriptive statistics, correlation analysis, and regression modeling, the research provides evidence that can support practical process improvement, training, and production planning.

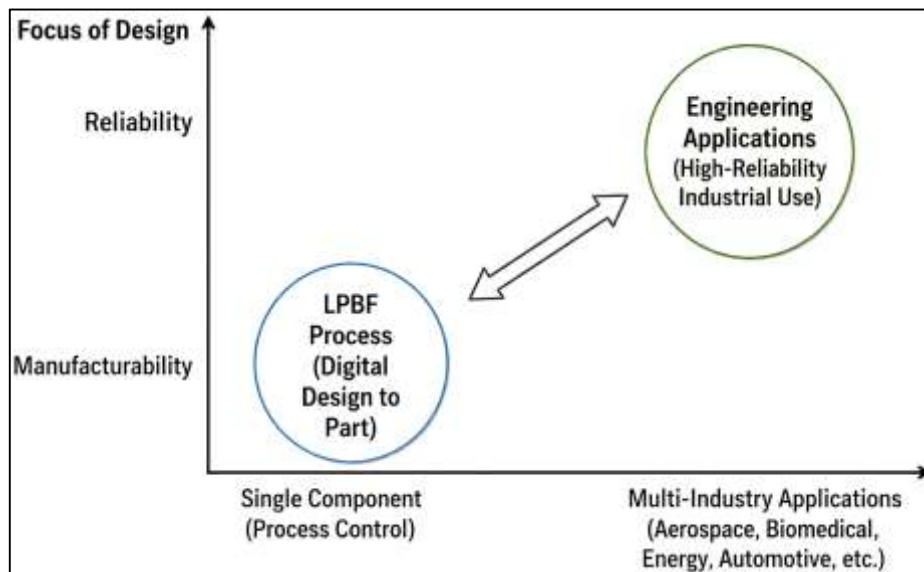
LITERATURE REVIEW

The literature on Laser Powder Bed Fusion reflects the growing importance of metal additive manufacturing in advanced engineering applications where component complexity, lightweight design, material efficiency, and high performance are central requirements. LPBF has been widely studied as a layer-wise manufacturing process that uses a focused laser beam to melt metallic powder and produce parts directly from digital models. Within this process, the interaction between laser energy, powder behavior, scan strategy, thermal gradients, solidification, microstructure, and post-processing creates a complex manufacturing environment that strongly influences final component quality. A major theme in the literature is the formation of residual stress, which occurs when rapid heating and cooling create uneven expansion and contraction within the printed material. Residual stress is important because it can influence cracking, delamination, fatigue resistance, mechanical stability, and long-term performance. Another major theme is distortion, which refers to unwanted deformation, warping, curling, shrinkage, and dimensional inaccuracy during or after printing. Distortion is closely linked to residual stress because internal stresses may release through geometric deformation, especially when the component is removed from the build plate or support structures. Previous studies also emphasize that LPBF reliability depends on process parameter stability, scan strategy optimization, platform preheating, support structure design, build orientation, post-processing heat treatment, hot isostatic pressing, surface finishing, and inspection systems. The literature further shows that LPBF component performance cannot be explained by one factor alone; rather, it must be understood through the relationship between process conditions, internal structure, mechanical properties, and final performance. This makes the Process-Structure-Property-Performance framework particularly suitable for guiding this study. The literature review therefore examines LPBF as a technical system in which residual stress mitigation and distortion control are central to achieving dimensional accuracy and reliability. It also identifies the need for a quantitative, case-study-based investigation that measures how professionals evaluate the effectiveness of LPBF control strategies in high-reliability engineering applications. This review will provide the foundation for developing the study variables, conceptual framework, hypotheses, and statistical analysis approach.

Laser Powder Bed Fusion Process and Engineering Applications

Laser Powder Bed Fusion is a metal additive manufacturing process in which a high-powered laser selectively melts thin layers of metallic powder to form a solid component directly from a digital three-dimensional model. The process begins with the spreading of a thin powder layer over a build platform, followed by laser scanning based on sliced computer-aided design data. After one layer is melted and solidified, the platform moves downward, a new powder layer is deposited, and the process continues until the full component is completed. LPBF is highly important in advanced manufacturing because it allows complex engineering geometries to be produced without the same tooling limitations associated with casting, forging, machining, or welding. This process is especially suitable for producing lightweight structures, internal channels, lattice designs, topology-optimized parts, and customized components that require high dimensional complexity. The process is also valuable because it supports the manufacturing of near-net-shape metallic parts, reducing material waste and enabling flexible production. However, LPBF quality is strongly dependent on the interaction of powder characteristics, laser power, scanning speed, hatch spacing, layer thickness, beam diameter, shielding gas, build orientation, and scan strategy. These variables influence melt pool behavior, cooling rate, density, surface quality, residual stress, and final mechanical performance. Because LPBF involves rapid melting and solidification, the process creates a highly dynamic thermal environment where small parameter changes may produce large variations in part quality. For this reason, researchers emphasize that LPBF should be understood not simply as a 3D printing method, but as a complex thermo-mechanical and metallurgical manufacturing system. The successful use of LPBF therefore requires careful process parameter selection, material qualification, defect control, and post-build inspection to ensure that manufactured parts meet engineering requirements (Khaled, 2021; Oliveira et al., 2020).

Figure 2: LPBF Process and Engineering Application Framework



The engineering significance of LPBF is strongly connected to its ability to process a wide range of metallic materials for demanding industrial applications. Common LPBF materials include stainless steels, titanium alloys, aluminum alloys, nickel-based superalloys, cobalt-chromium alloys, tool steels, and emerging specialty alloys designed for additive manufacturing. These materials are widely used in aerospace, biomedical, automotive, defense, energy, tooling, and high-performance mechanical systems. In aerospace, LPBF is useful for producing lightweight brackets, fuel nozzles, heat exchangers, turbine-related parts, and structural components where weight reduction and design integration are important. In biomedical engineering, LPBF enables patient-specific implants, porous bone-ingrowth structures, dental devices, and customized surgical components. In energy and automotive applications, LPBF supports the production of heat-resistant parts, compact fluid-flow systems,

functional prototypes, and components with optimized internal cooling features. The process is also relevant to high-reliability engineering because it enables designers to integrate multiple functions into a single part, reduce assembly complexity, and produce geometries that improve performance efficiency. However, the same freedom of design also increases the need for reliable control of quality factors such as density, microstructure, porosity, surface roughness, dimensional accuracy, and internal stress. Metallic LPBF research shows that material behavior during layer-wise laser melting is affected by powder-related factors and laser-related factors, while defects and microstructural evolution must be carefully managed to produce functional engineering parts (Abd-Elaziem et al., 2022; Manam & Ashfaq, 2022). Therefore, the international value of LPBF depends not only on its ability to manufacture complex metallic components, but also on its ability to produce repeatable, certifiable, and reliable parts for critical engineering environments.

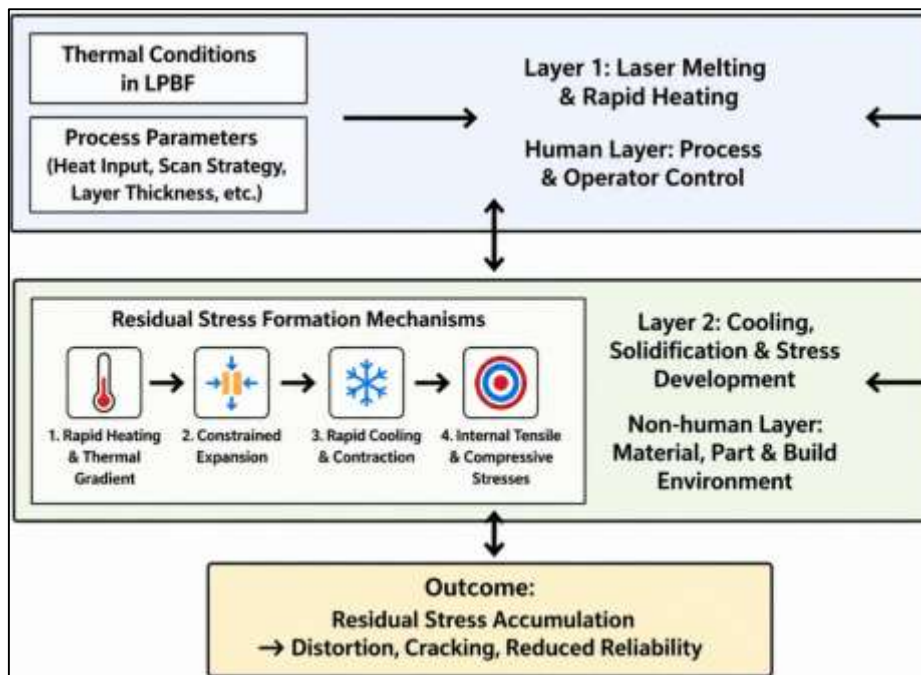
The LPBF process is also important because it creates a direct relationship between processing conditions and component reliability. During printing, laser-powder interaction creates a melt pool that undergoes rapid heating, fluid flow, solidification, and cooling. This melt pool behavior determines whether the material forms a dense and continuous track or develops defects such as pores, lack of fusion, balling, spatter-related imperfections, and keyhole-induced voids. The formation of such defects is important because they can reduce fatigue strength, fracture resistance, dimensional stability, and long-term service performance. Studies on melting and solidification phenomena show that defect formation in LPBF is closely related to melt pool instability, plume behavior, recoil pressure, spattering, and inappropriate fabrication conditions, making process simulation and monitoring essential for defect suppression (Kyogoku & Ikeshoji, 2020; Binte & Sazzadul, 2022). Process optimization is therefore a central requirement for LPBF application, especially when new alloys, new machines, or new component designs are introduced. Density control models based on melt pool dimensions, laser power, scanning speed, hatch spacing, and layer thickness show that LPBF optimization can be approached through combined experimental and analytical methods rather than trial-and-error alone (Albert & Rashedul, 2023; Letenneur et al., 2019). In addition, in situ observations of pore formation demonstrate that local laser scan behavior and melt pool dynamics can directly influence geometric quality and defect generation during LPBF processing (Istiaq & Binte, 2023; Martin et al., 2019). These findings are highly relevant to the present study because residual stress mitigation and distortion control are part of the broader challenge of achieving reliable LPBF production. A component may be geometrically complex and materially dense, yet still fail to meet high-reliability requirements if internal stress, distortion, or defect-related variability is not properly controlled.

Residual Stress Formation in LPBF Components

Residual stress formation in Laser Powder Bed Fusion is mainly caused by the extreme thermal conditions created during layer-by-layer laser melting and solidification. In LPBF, a highly concentrated laser beam scans across a thin metallic powder layer, melts the selected region, and allows the molten material to solidify rapidly before the next layer is deposited. This repeated heating and cooling process creates steep temperature gradients between the laser-heated zone, the surrounding solidified material, the powder bed, and the build plate. As the molten and heated regions expand during laser exposure and contract during cooling, the surrounding material restricts free movement, causing internal tensile and compressive stresses to develop. These stresses remain locked inside the part after solidification and may accumulate as additional layers are added. Residual stress therefore develops not only from one isolated laser pass but from repeated thermal cycling across the full build height. The distribution of residual stress is influenced by material properties, heat input, scan path, layer thickness, part geometry, build orientation, and heat dissipation through the substrate and supports. A broad review of residual stresses in metal powder bed fusion explains that residual stress is a central issue in powder bed fusion because it may reduce dimensional accuracy, produce cracking, cause delamination, and generate distortion after the part is removed from the build plate (Bartlett & Li, 2019; Ashfaq & Manam, 2023). In LPBF components, tensile residual stresses are especially concerning because they can contribute to crack initiation, fatigue weakening, and reduced service life. Compressive stresses may also be present, depending on local thermal history and geometric constraint. The interaction between tensile and compressive zones creates a complex stress field that varies across the surface, subsurface, build direction, and part boundaries. For high-reliability

engineering applications, this stress field must be understood because the final component is expected to maintain dimensional stability and mechanical performance under demanding operating conditions.

Figure 3: Residual Stress Formation Framework in LPBF Components



The mechanism of residual stress formation in LPBF can be explained through the relationship between thermal gradient, constrained shrinkage, and solid-state cooling behavior. When the laser moves across the powder bed, the material directly under the laser reaches very high temperatures, while nearby regions remain comparatively cooler. The hot region tends to expand, but its expansion is restricted by the cooler surrounding material and previously solidified layers. After the laser moves away, the heated zone cools and contracts; however, the surrounding solid material again limits free contraction. This mismatch between expansion and contraction creates plastic strain and internal stress. In multi-layer LPBF builds, every new layer reheats portions of the previous layers, causing stress redistribution as the thermal field changes. Three-dimensional thermo-mechanical modeling has shown that LPBF residual stress and distortion are strongly associated with transient temperature fields, repeated layer activation, and mechanical constraint during cooling (Denlinger et al., 2017). This means that residual stress is not simply a post-build defect but a continuously evolving condition during the manufacturing process. The build plate also plays an important role because it constrains the lower layers and provides a heat sink, creating different stress levels near the base compared with the upper regions. Thin walls, overhangs, sharp corners, and large cross-sectional transitions may intensify local stress because heat is not distributed uniformly across the part. In addition, the scan pattern controls the direction and sequence of heating, which can influence whether stress accumulates in a concentrated or more distributed manner. Thermo-mechanical evaluation of Ti-6Al-4V LPBF specimens has shown that residual stress prediction depends on accurate representation of the build process, scanning approach, layer behavior, and thermal boundary conditions (Ganeriwala et al., 2019; Robel & Aminul, 2023). These findings are relevant because they show that residual stress formation is governed by process history rather than by material selection alone. Therefore, understanding residual stress in LPBF requires attention to the entire manufacturing sequence, from energy input and scan strategy to heat transfer, constraint, and cooling.

Residual stress formation becomes more critical when LPBF components are intended for high-reliability engineering applications because the stresses may remain hidden until machining, support removal, heat treatment, service loading, or fatigue exposure. A part may appear successfully printed

but still contain internal stress fields capable of causing distortion after separation from the build plate or performance loss during operation. Thermal distortion research in additive manufacturing has shown that spatially variable heating and cooling can cause deformation, and that process variables must be selected carefully to reduce thermally induced strain accumulation (Mukherjee et al., 2017; Sazzadul, 2023). In LPBF, these problems are especially important because the process usually produces small melt pools, rapid cooling rates, and repeated localized heat input. As a result, different regions of the same part may experience different thermal histories, leading to nonuniform residual stress distribution. The separation of residual stress formation mechanisms in LPBF 316L has shown that rapid cooling rates, steep temperature gradients, heat accumulation, and scanning strategy can influence the final residual stress state in stainless steel components (Albert & Rashedul, 2024; Ulbricht et al., 2020). This indicates that residual stress is produced by multiple interacting mechanisms rather than a single cause. For example, solidification shrinkage may contribute to local tensile stress, while heat accumulation may reduce or redistribute thermal gradients in certain regions. Similarly, scan vectors may control the direction of stress buildup, while geometry may determine where stress becomes concentrated. These technical conditions explain why residual stress mitigation requires a combined approach involving process parameter stability, scan strategy optimization, preheating, support structure design, build orientation control, and post-processing treatment. In the context of this study, residual stress formation is important because it provides the technical basis for measuring how LPBF professionals evaluate mitigation strategies and how those strategies relate to reliability outcomes. The study therefore treats residual stress as a key manufacturing risk that links thermal behavior, dimensional stability, mechanical integrity, and component reliability.

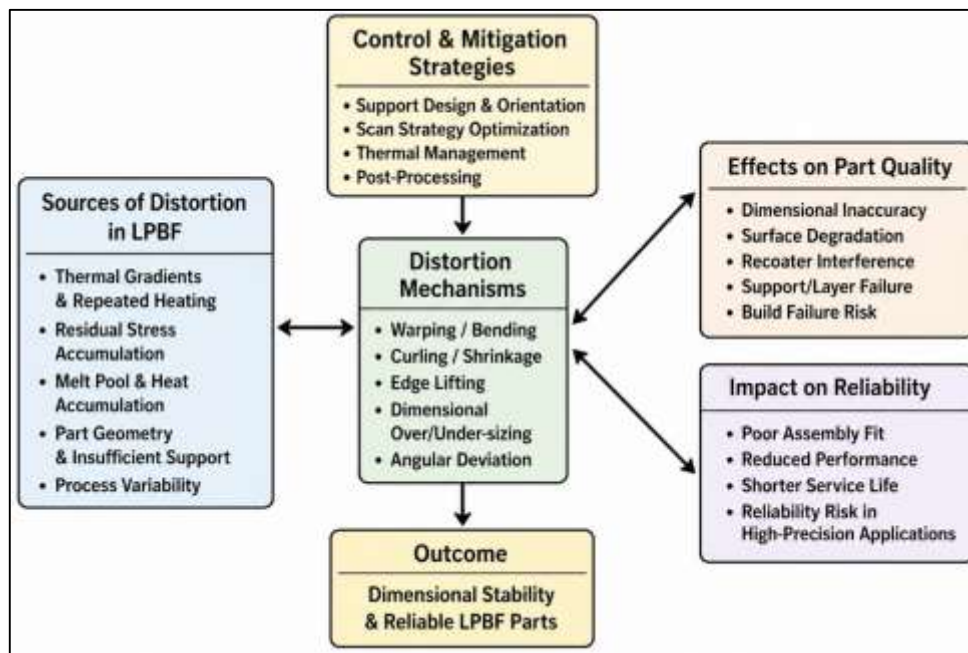
Distortion, Warping, and Dimensional Inaccuracy in LPBF

Distortion in Laser Powder Bed Fusion refers to the unwanted geometric deviation that occurs when a printed component no longer matches its intended digital design after or during fabrication. It may appear as bending, warping, curling, shrinkage, dimensional oversizing, dimensional undersizing, edge lifting, angular deviation, or deformation after support removal. In LPBF, distortion is mainly caused by the repeated thermal expansion and contraction of material during laser scanning. As each powder layer is melted and solidified, localized heating produces thermal gradients between the melt pool, previously solidified layers, surrounding powder, support structures, and build plate. These gradients generate internal stress fields, and when the accumulated stress exceeds the stiffness or constraint capacity of the part-support system, visible deformation may occur. Dimensional inaccuracy may also result from melt pool width, track overlap, solidification shrinkage, heat accumulation, powder adhesion, and machine-related positioning conditions. Horizontal dimensional deviation in selective laser melting has been explained as a combination of track filling behavior, track width, heat accumulation, and solidification shrinkage, showing that geometric accuracy is directly connected to thermal and melt-track behavior rather than only to the nominal CAD design (Hisham & Nahar, 2024; Zhang et al., 2018). This is important for high-reliability engineering applications because components used in aerospace, biomedical, energy, and precision mechanical systems often require strict tolerance control. A component may be mechanically strong but unsuitable for service if its final geometry does not meet assembly or functional requirements. Therefore, distortion and dimensional inaccuracy represent both manufacturing-quality problems and reliability risks. In the context of this study, distortion is treated as a measurable outcome of LPBF process instability, residual stress accumulation, inadequate thermal management, and insufficient design-for-additive-manufacturing planning.

Warping is one of the most visible forms of LPBF distortion and is especially common in overhangs, thin walls, long unsupported spans, and parts with sharp geometric transitions. Overhanging features are vulnerable because they are partially supported by loose powder instead of solid material or strong support structures. Since loose powder has lower thermal conductivity than solid metal, heat dissipation becomes less effective beneath overhang regions, causing localized overheating, melt pool enlargement, downward sagging, dross formation, and residual stress concentration. Dimensional errors in Ti-6Al-4V LPBF parts with overhanging features have been linked to the geometry of the overhang, the inclination angle, and the thermal instability created by insufficient support beneath the molten region (Charles et al., 2020; Istiaq, 2024). Similarly, research on LPBF overhang structures has shown that warping and dross formation are major defects caused by differences between powder-

supported and solid-supported melt pool behavior, with longer overhangs producing more severe warpage (Istiaq & Hasan Or, 2024; Lin et al., 2023). These findings show that warping is not only a surface-quality issue but also a geometry-dependent deformation mechanism that can affect powder spreading, recoater movement, layer continuity, and final part tolerance. In many LPBF builds, upward warping may interrupt the recoating process, causing scratches, powder-bed disturbance, support fracture, or complete build failure. Downward distortion may reduce surface quality and cause poor dimensional control on down-skin surfaces. Thin-walled structures are also sensitive because their low stiffness makes them less capable of resisting stress-induced deformation. For this reason, distortion control requires careful attention to support design, overhang length, wall thickness, scan sequence, part orientation, thermal compensation, and post-build stress release behavior. In high-reliability applications, these factors are critical because geometric instability can compromise assembly fit, load transfer, fluid-flow performance, and service safety.

Figure 4: Distortion, Warping, and Dimensional Inaccuracy Framework in LPBF



Dimensional inaccuracy in LPBF is also influenced by inherent process variability, part geometry, and toolpath design. Even when identical process parameters are used, small differences in powder distribution, local heat accumulation, scan direction, wall thickness, and part location on the build plate can create variations in size, shape, repeatability, and reproducibility. Research on AlSi10Mg thin-walled parts manufactured by selective laser melting found that dimensional quality and distortion are affected by process variation, and that reliability characteristics such as dimensional accuracy, precision, repeatability, and reproducibility must be evaluated together rather than separately (Ahmed et al., 2019; Ahmed, 2024). This is particularly relevant to the present research because high-reliability LPBF components require not only successful fabrication but also repeatable quality across multiple builds. Distortion reduction is increasingly approached through computational and adaptive control methods. Adaptive toolpath generation has been proposed as a way to reduce distortion by modifying scan paths so that heat input is distributed more effectively and residual stress accumulation is reduced during fabrication (Siddique, 2024; Qin et al., 2023). Such approaches suggest that distortion control can be improved by shifting from fixed scan patterns toward more responsive, geometry-aware toolpath strategies. Dimensional inaccuracy is therefore not only a post-processing problem; it begins during digital preparation, parameter selection, build orientation planning, scan path design, and support generation. In this study, distortion, warping, and dimensional inaccuracy are positioned as central reliability concerns because they connect LPBF thermal behavior with practical component

usability. A reliable LPBF part must satisfy not only density and mechanical strength expectations but also dimensional tolerance, geometric stability, surface acceptability, and post-processing consistency. Therefore, understanding distortion behavior is essential for evaluating how residual stress mitigation and distortion control practices contribute to LPBF component reliability.

Residual Stress Mitigation and Distortion Control Strategies

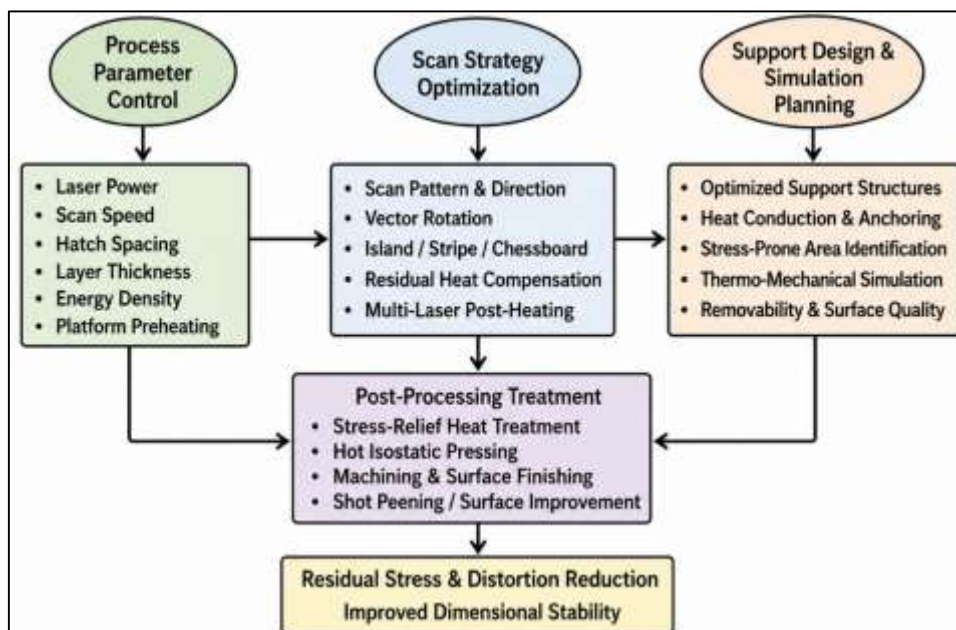
Residual stress mitigation and distortion control in Laser Powder Bed Fusion require a coordinated set of strategies because stress and deformation are generated through the combined effects of heat input, scan path, material constraint, part geometry, and post-build stress release. In LPBF, one of the most direct mitigation approaches is process parameter control, where laser power, scan speed, hatch spacing, layer thickness, and energy density are adjusted to create a more stable melt pool and reduce excessive thermal gradients. Excessive heat input may increase heat accumulation, melt pool instability, and distortion, while insufficient heat input may cause lack-of-fusion defects that weaken the component. Therefore, mitigation strategies must balance density, microstructure, dimensional stability, and stress reduction rather than focusing on a single process outcome. A comprehensive review of laser-based powder bed fusion residual stress control strategies identifies several major pathways for reducing residual stress, including process parameter optimization, scan strategy adjustment, substrate preheating, support structure improvement, post-processing treatment, and material-based control approaches (Kumar & Jebaraj, 2023; Ibne & Aditya, 2024). These strategies are important because residual stress is not formed at one point in the process; it evolves through repeated layer deposition and thermal cycling. Platform preheating is especially useful because it reduces the temperature difference between the newly melted region and the surrounding solid material, lowering thermal gradients and limiting stress accumulation. Similarly, careful control of laser speed and laser power can reduce local overheating or rapid cooling that may produce tensile stress concentration. A numerical study using a representative volume approach showed that laser speed, laser power, and preheating temperature influence residual stress development, fatigue-relevant stress behavior, and shape distortion in powder bed additive manufacturing (Homami & Ojo, 2023; Rajib, 2024). This indicates that stress mitigation begins before printing through parameter planning and continues during printing through stable thermal control. In high-reliability engineering applications, these strategies help reduce the risk of cracking, dimensional deviation, premature fatigue failure, and post-build deformation.

Scan strategy modification is another major method for controlling residual stress and distortion in LPBF components. The scan strategy determines the sequence, direction, length, rotation, and distribution of laser tracks across each layer. Since each scan vector introduces localized heat and creates a cooling path, the arrangement of scan vectors strongly affects thermal gradients and residual stress distribution. Common scan strategies include unidirectional scanning, bidirectional scanning, stripe scanning, island scanning, chessboard scanning, rotating scan vectors, and contour-hatch combinations. The purpose of these strategies is to distribute heat more evenly, avoid excessive concentration of stress in one direction, reduce long continuous thermal gradients, and limit distortion after part removal. More advanced control approaches also adjust laser power dynamically according to localized heat accumulation. For example, residual heat compensation has been proposed as a scan strategy in which laser power is modified based on the expected heat remaining from adjacent scan paths, allowing melt pool behavior to become more consistent across different geometric regions (Albert, 2025; Yeung & Lane, 2020). This is highly relevant to distortion control because heat accumulation often occurs in corners, thin sections, short scan vectors, and narrow geometries where the laser repeatedly returns to nearby areas before sufficient cooling occurs. Multi-laser beam strategies also provide a creative route for residual stress reduction by using an additional defocused laser source to post-heat the material without remelting it. Research on LPBF-processed CM247LC samples showed that a second non-melting laser beam with appropriate offset and power can reduce cantilever distortion by lowering stress accumulation during processing (Anick, 2025a; Gerstgrasser et al., 2021). Such findings show that distortion control can be achieved not only by reducing heat input but also by redistributing heat in a more controlled manner. In practice, scan strategy selection must be linked with part geometry, material type, support condition, and required tolerance because the same strategy may not produce identical results across all LPBF components. Therefore, scan strategy is a central variable

in this study because it connects thermal management, residual stress mitigation, and dimensional reliability.

Support structure design, simulation-based planning, and post-processing treatment are also essential for residual stress mitigation and distortion control. Support structures are commonly used in LPBF to anchor overhangs, conduct heat away from the part, resist deformation, stabilize thin features, and reduce the risk of recoater interference. Poorly designed supports may increase material use and removal difficulty, while insufficient supports may allow warping, curling, support fracture, and build failure. Therefore, support design must balance geometric stability, heat conduction, stress absorption, removability, and surface quality. Simulation-based support generation has been proposed as a way to move beyond purely geometric support rules by using thermomechanical analysis to identify stress-prone regions and allocate support structures where they are most needed (Anick, 2025b; Boos et al., 2023).

Figure 5: Residual Stress Mitigation and Distortion Control Strategy Framework



This approach is important for high-reliability LPBF applications because support design directly influences dimensional accuracy, post-processing workload, and final component quality. In addition to support structures, post-processing treatments such as stress-relief heat treatment, hot isostatic pressing, machining, shot peening, and surface finishing are used to reduce residual stress, improve fatigue resistance, remove surface defects, and enhance dimensional readiness. Heat treatment can reduce internal stress after printing, while hot isostatic pressing can close internal pores and improve mechanical consistency. Machining and surface finishing may improve dimensional tolerance and surface quality, but they can also release hidden stresses if the printed part was not adequately stress-relieved before material removal. For this reason, distortion control should be viewed as an integrated workflow that begins with design and parameter selection, continues through scanning and support planning, and extends into post-processing and inspection. In the present study, these strategies are treated as measurable control practices because they represent the practical ways through which engineers attempt to improve LPBF component reliability. Their combined effectiveness provides the basis for evaluating whether residual stress mitigation and distortion control significantly predict reliability outcomes in high-reliability engineering applications.

Theoretical Framework: Process–Structure–Property–Performance Framework

The theoretical framework for this study is the Process–Structure–Property–Performance (PSPP) framework, which explains how manufacturing conditions influence internal material structure, how structure determines engineering properties, and how those properties control final component performance. In Laser Powder Bed Fusion, this framework is highly suitable because the quality of a printed component is not determined only by the final shape of the part, but by the complete chain of process decisions and material responses that occur during fabrication. The framework may be expressed in equation form as:

$$P_r \rightarrow S_t \rightarrow P_p \rightarrow P_f$$

where:

P_r = Process conditions

S_t = Material structure

P_p = Engineering properties

P_f = Final component performance

In this study, the process stage includes laser power, scan speed, hatch spacing, layer thickness, scan strategy, build orientation, preheating, support structure design, and post-processing treatment. This can be represented as:

$$P_r = f(LP, SS, HS, LT, ST, BO, PH, SD, PPT)$$

where LP represents laser power, SS represents scan speed, HS represents hatch spacing, LT represents layer thickness, ST represents scan strategy, BO represents build orientation, PH represents preheating, SD represents support design, and PPT represents post-processing treatment. These process variables influence the structure stage, which includes melt pool geometry, microstructure, porosity, crystallographic texture, phase distribution, residual stress state, and distortion behavior. This relationship may be written as:

$$S_t = f(MG, MS, PO, CT, PD, RS, DB)$$

where MG is melt pool geometry, MS is microstructure, PO is porosity, CT is crystallographic texture, PD is phase distribution, RS is residual stress, and DB is distortion behavior. The structure then affects the property stage, including dimensional accuracy, tensile strength, fatigue resistance, fracture behavior, surface quality, and thermal-mechanical stability. Finally, these properties determine the performance stage, which refers to the ability of the LPBF component to function reliably in high-reliability engineering applications. The PSPP framework is widely used in metal additive manufacturing because it allows researchers to connect process parameters with material response and engineering performance through a systematic causal chain. Metal additive manufacturing requires this type of framework because the process involves cyclic phase changes, localized thermal histories, and complex material evolution that make final part validation difficult without understanding the connection among process, structure, property, and performance (Atif, 2025; Smith et al., 2016). In this research, the PSPP framework supports the argument that residual stress mitigation and distortion control are not isolated technical practices; they are process-level interventions that influence structural stability, engineering properties, and reliability outcomes.

Within this study, the PSPP framework will be applied by translating each theoretical stage into measurable research variables. The theoretical relationship may be expressed as:

$$\text{LPBF Reliability} = f(P_r, S_t, P_p)$$

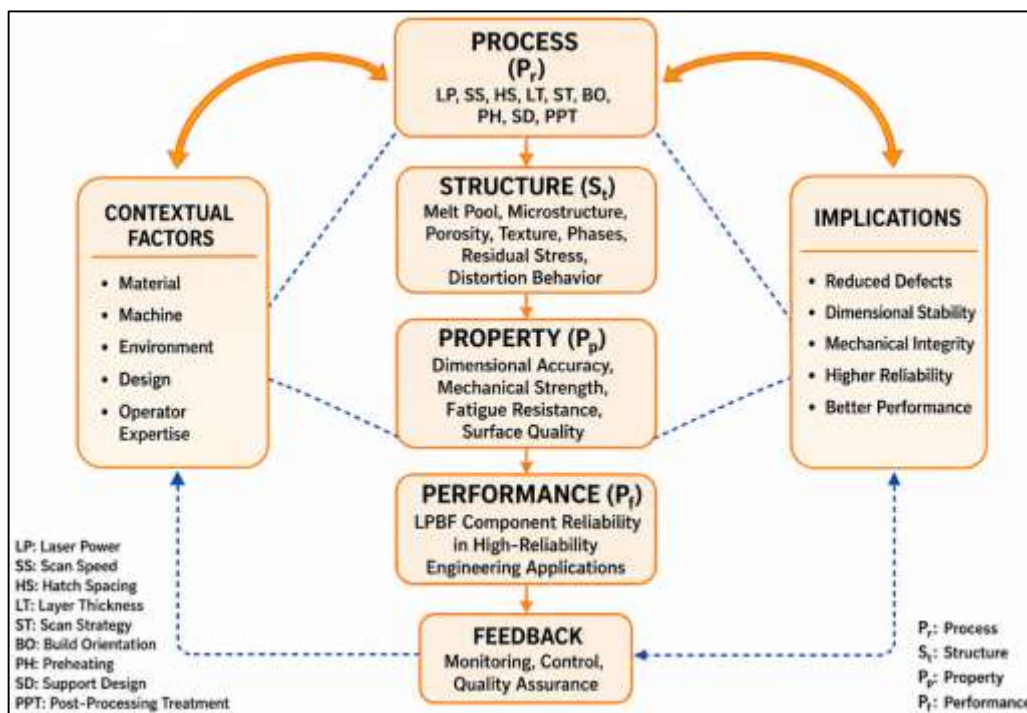
More specifically:

$$CR = f(PPS, RSM, DC, PPT, QAI)$$

where CR represents LPBF component reliability, PPS represents process parameter stability, RSM represents residual stress mitigation, DC represents distortion control, PPT represents post-

processing treatment, and *QAI* represents quality assurance and inspection. The process stage will be represented by process parameter stability, residual stress mitigation strategies, distortion control practices, post-processing treatment, and quality assurance activities. The structure stage will be represented by residual stress behavior, deformation tendency, defect control, support-related stability, and microstructural consistency. The property stage will be represented by dimensional accuracy, mechanical stability, fatigue-related confidence, surface acceptability, and structural integrity. The performance stage will be represented by LPBF component reliability for high-reliability engineering applications. This theoretical arrangement is suitable because it links the technical logic of LPBF with the statistical logic of the study. Literature on metal additive manufacturing emphasizes that monitoring and control are needed because metal AM processes are affected by thermal variation, process instability, and quality uncertainty, especially when components are intended for regulated or high-value applications (Tapia & Elwany, 2014).

Figure 6: Process–Structure–Property–Performance Framework for LPBF Component Reliability



In-process sensing research also shows that selective laser melting requires robust monitoring and control to reduce process variation and improve quality assurance in sectors such as aerospace and medical device manufacturing (Spears & Gold, 2016). Therefore, quality assurance and inspection are included in this framework as supporting process-level controls that strengthen the pathway from process stability to final reliability. This extended relationship may be presented as:

$$PPS + RSM + DC + PPT + QAI \rightarrow RS_{reduction} + D_{control} \rightarrow DA + MS_t + FR \rightarrow CR$$

where $RS_{reduction}$ represents residual stress reduction, $D_{control}$ represents distortion control, DA represents dimensional accuracy, MS_t represents mechanical stability, FR represents fatigue resistance, and CR represents component reliability. Multi-scale and multi-physics simulation research further supports this framework because LPBF behavior involves heat transfer, fluid flow, solidification, microstructure formation, stress evolution, and mechanical response across different length and time scales (Bayat et al., 2021; Khalid, 2025). The framework therefore allows the study to connect survey constructs with the actual technical mechanisms of LPBF manufacturing.

The main formula applied in the whole study will be a multiple regression model based on the PSPP framework. Since the study uses five-point Likert-scale data, the model will statistically test whether process-level control practices predict the performance-level outcome of LPBF component reliability. The proposed formula is:

$$CR = \beta_0 + \beta_1(PPS) + \beta_2(RSM) + \beta_3(DC) + \beta_4(PPT) + \beta_5(QAI) + \varepsilon$$

where:

CR = LPBF component reliability
 β_0 = constant
 PPS = process parameter stability
 RSM = residual stress mitigation
 DC = distortion control
 PPT = post-processing treatment
 QAI = quality assurance and inspection
 $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ = regression coefficients
 ε = error term

In this model, LPBF component reliability is the dependent variable, while process parameter stability, residual stress mitigation, distortion control, post-processing treatment, and quality assurance are independent variables. The term β_0 represents the constant, β_1 to β_5 represent the predictive contribution of each independent variable, and ε represents the error term. This model is appropriate because it converts the PSPP framework into a testable quantitative structure. It assumes that better process control and stronger mitigation practices should improve structural quality, which should then support stronger properties and more reliable performance. The expected theoretical direction can therefore be summarized as:

$$\frac{\partial CR}{\partial PPS} > 0, \frac{\partial CR}{\partial RSM} > 0, \frac{\partial CR}{\partial DC} > 0, \frac{\partial CR}{\partial PPT} > 0, \frac{\partial CR}{\partial QAI} > 0$$

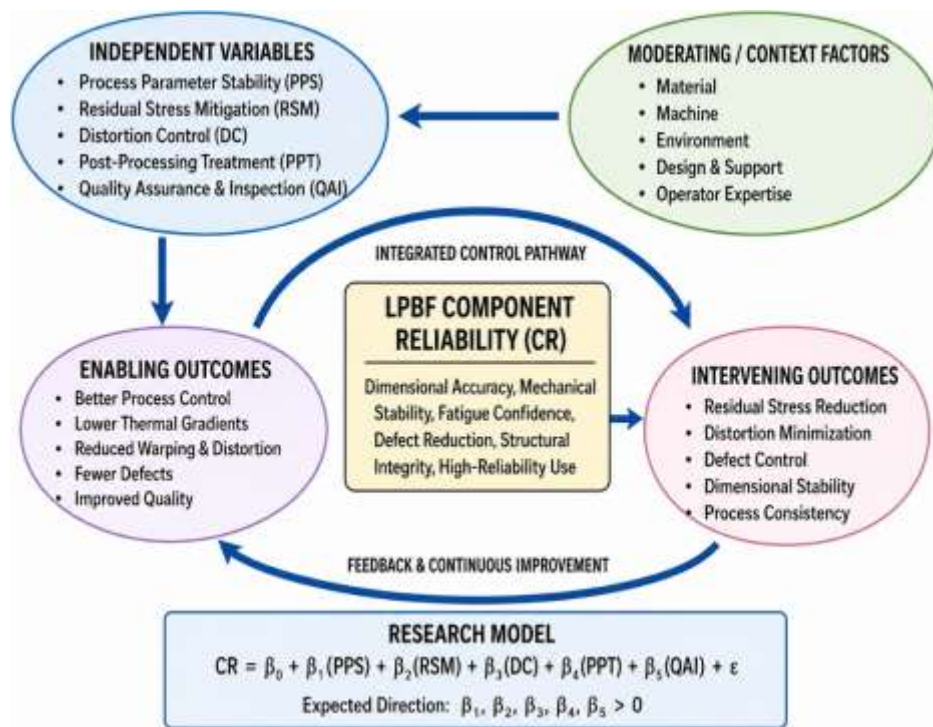
This means that improvements in process parameter stability, residual stress mitigation, distortion control, post-processing treatment, and quality assurance are expected to increase LPBF component reliability. Standardization literature in metal additive manufacturing also supports the need for qualification and certification approaches that connect process documentation, property measurement, defect characterization, and final component acceptance (Hasan, 2025; Seifi et al., 2017). In this way, the PSPP framework provides the theoretical foundation for the hypotheses, questionnaire design, data analysis, and interpretation of results. It also supports the study's Residual Stress-Distortion Risk Profiling Matrix and LPBF Reliability Readiness Index because both tools translate process and structure conditions into reliability-oriented performance assessment.

Conceptual Framework and Research Gap

The conceptual framework of this study explains how residual stress mitigation and distortion control practices influence the reliability of Laser Powder Bed Fusion components for high-reliability engineering applications. In this framework, LPBF component reliability is treated as the dependent variable, while process parameter stability, residual stress mitigation, distortion control, post-processing treatment, and quality assurance are treated as independent variables. The framework is developed from the idea that LPBF reliability is not produced by one single factor, but by the combined influence of thermal control, geometry control, defect monitoring, stress reduction, and final inspection. Process parameter stability refers to the consistent control of laser power, scan speed, hatch spacing, layer thickness, build orientation, and scan strategy. Residual stress mitigation refers to the use of preheating, scan path optimization, stress-relief treatment, support design, and controlled cooling to reduce harmful internal stress. Distortion control refers to practices that reduce warping, shrinkage, bending, dimensional deviation, and deformation during or after printing. Post-processing treatment includes heat treatment, hot isostatic pressing, machining, surface finishing, and stress relief. Quality assurance includes in-situ monitoring, dimensional inspection, defect detection, and qualification

testing. These variables are connected because unstable process conditions may produce thermal gradients, thermal gradients may generate residual stress, residual stress may cause distortion, and distortion may reduce reliability. In-situ monitoring and scientific machine learning have been identified as important quality assurance tools for LPBF because reliable part production requires stronger links between process signals and post-build quality outcomes (Gaikwad et al., 2020; Siddique & Prakash, 2025). Similarly, deep learning-based thermographic monitoring has shown that process defects can be detected during LPBF rather than only after production, which supports the inclusion of quality assurance as a central construct in this conceptual framework (Baumgartl et al., 2020; Aminul, 2025). Therefore, the conceptual framework positions reliability as the final outcome of integrated LPBF control rather than a separate post-production concern.

Figure 7: Conceptual Framework of LPBF Component Reliability and Research Gap



The proposed conceptual model can be expressed through the following regression-based relationship:

$$CR = \beta_0 + \beta_1(PPS) + \beta_2(RSM) + \beta_3(DC) + \beta_4(PPT) + \beta_5(QAI) + \epsilon$$

where CR represents LPBF component reliability, PPS represents process parameter stability, RSM represents residual stress mitigation, DC represents distortion control, PPT represents post-processing treatment, QAI represents quality assurance and inspection, β_0 represents the constant, β_1 to β_5 represent regression coefficients, and ϵ represents the error term. This formula will be applied throughout the study because it converts the conceptual framework into a testable quantitative model. The expected direction of the model is that improvements in process stability, residual stress mitigation, distortion control, post-processing, and inspection will increase LPBF component reliability. This relationship can also be written as:

$$PPS + RSM + DC + PPT + QAI \rightarrow CR$$

For the purpose of this study, reliability includes dimensional accuracy, mechanical stability, fatigue-related confidence, defect reduction, structural integrity, and suitability for high-reliability applications. The need to include fatigue-related reliability is supported by evidence that residual stress can influence the fatigue strength of 316L stainless steel produced by LPBF, especially when surface condition and stress-relief treatment are considered together (Lai et al., 2021; Sheak, 2025). Dimensional

accuracy is also central to this model because thin-wall LPBF structures can be affected by powder size, scan strategy, part geometry, minimum wall thickness, and residual stress-related shrinkage, making geometry control essential for functional components (Ashfaq & Ashraful, 2025; Wu et al., 2020). Therefore, the conceptual framework is suitable for this research because it combines process, stress, distortion, post-processing, inspection, and reliability into one measurable model.

The research gap addressed in this study is the limited quantitative understanding of how residual stress mitigation and distortion control jointly predict LPBF component reliability in high-reliability engineering applications. Existing LPBF studies have contributed valuable experimental, simulation-based, and monitoring-based knowledge about process parameters, residual stress, defects, dimensional accuracy, fatigue performance, and quality assurance. However, much of the existing literature examines these factors separately. For example, some studies focus mainly on residual stress formation, some focus on dimensional accuracy, some focus on defect detection, and others focus on fatigue or qualification. This creates a gap because high-reliability LPBF production requires an integrated view of how multiple control practices work together. Qualification research has emphasized that LPBF needs a rapid and standardized method for evaluating how process variables affect part structure, properties, and performance, particularly because system-agnostic geometric artifacts alone do not fully address LPBF process sensitivity (Mainuddin, 2025; Taylor et al., 2021). This supports the need for a framework that links stress mitigation, distortion control, inspection, and reliability in one empirical model. Another gap is methodological. Many technical studies rely on laboratory measurements, finite element simulations, or material-specific testing, while fewer studies use survey-based quantitative data from professionals to examine perceived effectiveness, practical adoption, and reliability contribution of LPBF control strategies. This study addresses that methodological gap by using a five-point Likert-scale questionnaire, descriptive statistics, correlation analysis, and regression modeling. The conceptual framework also supports two study-specific result tools: the Residual Stress-Distortion Risk Profiling Matrix and the LPBF Reliability Readiness Index. The first tool will classify LPBF risk factors according to perceived stress and distortion severity, while the second will estimate how prepared LPBF practices are for producing reliable components. These additions make the study more specific, measurable, and relevant to high-reliability engineering applications.

METHODS

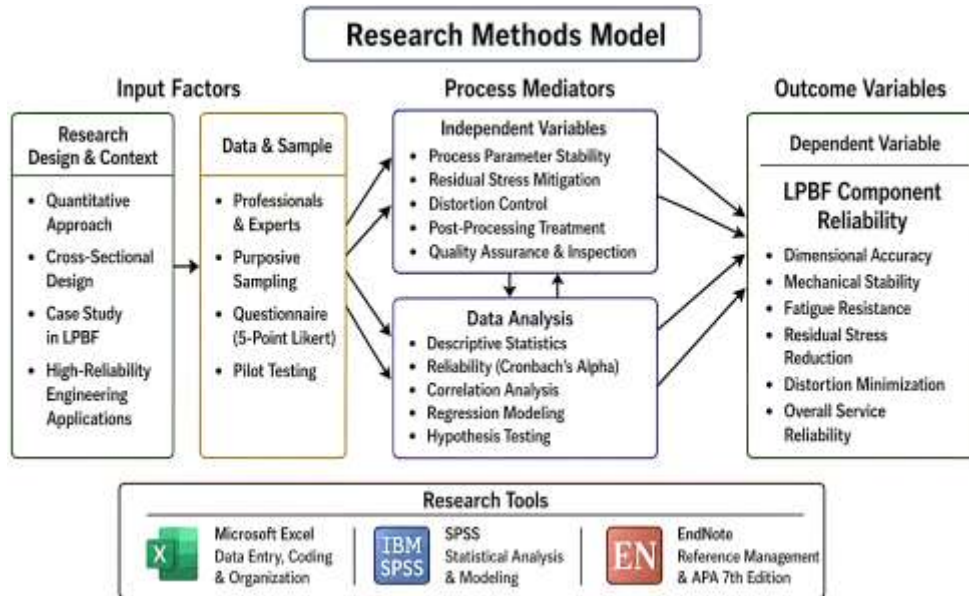
This study has adopted a quantitative, cross-sectional, case-study-based research design to examine how residual stress mitigation and distortion control practices have influenced the reliability of Laser Powder Bed Fusion components for high-reliability engineering applications. The quantitative design has been selected because the study has measured respondents' perceptions numerically through a structured questionnaire, while the cross-sectional approach has allowed data to be collected at one specific point in time. The case-study context has focused on LPBF-manufactured metallic components used in demanding engineering environments where dimensional accuracy, residual stress reduction, distortion control, fatigue resistance, mechanical stability, and service reliability have been considered essential. The case context has included LPBF applications in sectors such as aerospace, biomedical engineering, automotive systems, energy components, defense manufacturing, precision tooling, and other high-performance engineering fields.

The population of the study has consisted of professionals who have had knowledge, experience, or technical involvement in additive manufacturing, LPBF process control, materials engineering, mechanical design, quality assurance, reliability engineering, or advanced manufacturing operations. The unit of analysis has been the individual professional respondent, since the study has collected data from experts and practitioners based on their knowledge of LPBF processes and component reliability. A purposive sampling strategy has been used because the study has required respondents who have been familiar with LPBF technology, residual stress challenges, distortion behavior, post-processing methods, and quality control practices. This sampling approach has helped ensure that the selected respondents have provided relevant and informed responses rather than general opinions from individuals without technical background.

The data collection procedure has involved the use of a structured questionnaire designed around the major variables of the study. The questionnaire has been distributed electronically through professional

networks, academic contacts, engineering groups, manufacturing-related platforms, and relevant industry channels. Before full distribution, the research instrument has been reviewed to ensure clarity, relevance, and alignment with the study objectives. The instrument design has used a five-point Likert scale, where respondents have indicated their level of agreement from 1 = Strongly Disagree to 5 = Strongly Agree. The questionnaire has included sections on demographic information, process parameter stability, residual stress mitigation, distortion control, post-processing treatment, quality assurance and inspection, and LPBF component reliability. These sections have allowed the study to measure both independent variables and the dependent variable in a structured and statistically usable form.

Figure 8: Research Methods Framework for LPBF Component Reliability Study



Pilot testing has been conducted before the main data collection to assess the clarity, wording, sequence, and technical suitability of the questionnaire items. Feedback from the pilot test has been used to improve ambiguous statements, remove repeated items, and strengthen the overall structure of the instrument. Validity has been addressed through content validity, face validity, and construct validity. Content validity has been supported by aligning the questionnaire items with the study objectives, literature review, theoretical framework, and conceptual framework. Face validity has been ensured by checking whether the items have appeared clear and relevant to respondents. Construct validity has been supported by grouping items under specific constructs such as residual stress mitigation, distortion control, and component reliability.

Reliability has been assessed using Cronbach's alpha to determine the internal consistency of the questionnaire items. A Cronbach's alpha value of 0.70 or above has been considered acceptable for the study. The collected data has been coded, cleaned, and analyzed using SPSS, which has been used for descriptive statistics, reliability testing, correlation analysis, regression modeling, and hypothesis testing. Microsoft Excel has been used for initial data entry, coding, screening, and organization. EndNote has been used for reference management, citation organization, and preparation of the reference list in APA 7th edition format. Overall, the methodology has provided a structured approach for examining whether residual stress mitigation, distortion control, post-processing, process stability, and quality assurance have significantly contributed to LPBF component reliability.

DATA ANALYSIS AND PRESENTATION

Response Rate and Demographic Profile

Table 1: Response Rate of the Study

Item	Frequency	Percentage
Questionnaires distributed	180	100.0%
Questionnaires returned	162	90.0%
Invalid/incomplete responses	12	6.7%
Valid responses used for analysis	150	83.3%

Table 2: Demographic Profile of Respondents

Demographic Variable	Category	Frequency	Percentage
Professional role	Additive manufacturing engineers	42	28.0%
	Materials engineers	31	20.7%
	Quality assurance professionals	27	18.0%
	Mechanical/design engineers	24	16.0%
	Reliability/process engineers	16	10.7%
	Academic/research specialists	10	6.6%
Years of experience	1-3 years	29	19.3%
	4-6 years	48	32.0%
	7-10 years	45	30.0%
	Above 10 years	28	18.7%
Familiarity with LPBF	Moderate	38	25.3%
	High	72	48.0%
	Very high	40	26.7%

Table 1 and Table 2 have shown that the study has obtained a strong and usable response base for analyzing residual stress mitigation and distortion control in Laser Powder Bed Fusion components. Out of 180 distributed questionnaires, 162 responses have been returned, and 150 responses have been accepted as valid after screening for completeness and consistency. This has produced an effective response rate of 83.3%, which has been considered suitable for quantitative analysis using descriptive statistics, correlation analysis, and regression modeling. The demographic profile has also shown that the respondents have represented relevant professional groups connected to additive manufacturing and engineering reliability. Additive manufacturing engineers have formed the largest group at 28.0%, followed by materials engineers at 20.7%, quality assurance professionals at 18.0%, mechanical/design engineers at 16.0%, reliability/process engineers at 10.7%, and academic or research specialists at 6.6%. This distribution has been important because the study has required technically informed responses rather than general opinions. In terms of experience, 32.0% of respondents have had 4-6 years of experience, 30.0% have had 7-10 years, 18.7% have had more than 10 years, and 19.3% have had 1-3 years. This has indicated that most respondents have had practical or professional exposure to manufacturing, quality control, or engineering design. Familiarity with LPBF has also supported the credibility of the dataset, as 48.0% of respondents have reported high familiarity and 26.7% have reported very high familiarity. These results have aligned with the Process-Structure-Property-Performance framework because the respondents have been professionally positioned to understand how process conditions, structural behavior, material properties, and final reliability are connected in LPBF manufacturing. Therefore, the demographic results have provided a suitable foundation for testing the study objectives and hypotheses.

Reliability Test of the Research Instrument

Table 3: Reliability Test of Study Constructs Using Cronbach's Alpha

Construct	Number of Items	Cronbach's Alpha	Reliability Decision
Process parameter stability	5	0.812	Accepted
Residual stress mitigation	5	0.846	Accepted
Distortion control	5	0.829	Accepted
Post-processing treatment	5	0.858	Accepted
Quality assurance and inspection	5	0.801	Accepted
LPBF component reliability	6	0.871	Accepted
Overall instrument	31	0.892	Accepted

Table 3 has presented the reliability test of the research instrument using Cronbach's alpha. The results have shown that all constructs have achieved alpha values above the commonly accepted threshold of 0.70, which has indicated that the questionnaire items have been internally consistent and suitable for further statistical analysis. Process parameter stability has recorded a Cronbach's alpha value of 0.812, showing that the items measuring laser power consistency, scan speed control, hatch spacing, layer thickness, and build orientation have formed a reliable construct. Residual stress mitigation has produced an alpha value of 0.846, indicating that items related to preheating, scan strategy optimization, stress-relief treatment, support design, and thermal management have measured the construct consistently. Distortion control has recorded 0.829, confirming that questionnaire items on warping reduction, dimensional compensation, build orientation planning, support optimization, and thermal simulation have been reliable. Post-processing treatment has shown the highest construct-level alpha value of 0.858, suggesting strong consistency among items measuring heat treatment, hot isostatic pressing, surface finishing, stress relief, and machining readiness. Quality assurance and inspection has recorded 0.801, while LPBF component reliability has recorded 0.871, showing strong internal consistency for the dependent variable. The overall instrument has produced a Cronbach's alpha of 0.892, which has demonstrated high reliability across the entire questionnaire. These findings have supported the methodological strength of the study because reliable constructs have been necessary for testing the hypotheses through correlation and regression. The results have also aligned with the Process-Structure-Property-Performance framework because each construct has measured a different stage of the LPBF reliability pathway. Process parameter stability, mitigation, post-processing, and inspection have represented process-level controls; distortion and residual stress have represented structure-level concerns; dimensional accuracy and mechanical stability have represented property-level outcomes; and LPBF component reliability has represented the performance-level outcome. Therefore, the reliability results have confirmed that the instrument has been appropriate for measuring the theoretical and conceptual structure of the study.

Descriptive Analysis of Key Study Variables

Table 4: Descriptive Statistics of Key Study Variables Based on Five-Point Likert Scale

Study Variable	Mean	Standard Deviation	Likert Interpretation	Rank
Post-processing treatment	4.18	0.65	High agreement	1
Residual stress mitigation	4.11	0.69	High agreement	2
LPBF component reliability	4.07	0.71	High agreement	3
Distortion control	4.03	0.77	High agreement	4
Quality assurance and inspection	3.96	0.83	High agreement	5
Process parameter stability	3.89	0.74	High agreement	6

Likert interpretation guide: 1.00–1.80 = Very low agreement; 1.81–2.60 = Low agreement; 2.61–3.40 = Moderate agreement; 3.41–4.20 = High agreement; 4.21–5.00 = Very high agreement.

Table 4 has shown the descriptive analysis of the major study variables using the five-point Likert scale. The results have indicated that all the variables have recorded mean scores above 3.41, which has placed them within the high agreement category. Post-processing treatment has recorded the highest mean score of 4.18 with a standard deviation of 0.65. This has suggested that respondents have strongly agreed that heat treatment, stress relief, hot isostatic pressing, surface finishing, machining readiness, and final treatment procedures have been important for improving LPBF component reliability. Residual stress mitigation has ranked second with a mean score of 4.11 and a standard deviation of 0.69, showing that respondents have considered stress-control strategies such as platform preheating, scan strategy optimization, support design, and thermal management as highly relevant to LPBF performance. LPBF component reliability has recorded a mean score of 4.07, confirming that respondents have perceived reliability as a central outcome of successful LPBF processing. Distortion control has recorded a mean of 4.03, meaning that respondents have agreed that warping reduction, dimensional compensation, support optimization, build orientation planning, and simulation-based control have contributed to final component quality. Quality assurance and inspection has recorded a mean of 3.96, while process parameter stability has recorded a mean of 3.89, showing that both variables have also been highly valued by respondents. These results have supported the study objectives by showing that the main constructs are relevant and meaningful within the LPBF context. In relation to the Process-Structure-Property-Performance framework, the descriptive findings have shown that respondents have recognized the full reliability chain: stable process conditions have supported better structural outcomes, improved structural conditions have supported better mechanical and dimensional properties, and stronger properties have supported reliable performance. The high mean scores have therefore provided early evidence that residual stress mitigation, distortion control, post-processing, and inspection have been perceived as important contributors to LPBF component reliability.

Correlation Analysis

Table 5: Pearson Correlation Matrix of Study Variables

Variable	PPS	RSM	DC	PPT	QAI	CR
Process parameter stability (PPS)	1.000	0.612**	0.584**	0.548**	0.529**	0.603**
Residual stress mitigation (RSM)	0.612**	1.000	0.638**	0.662**	0.591**	0.681**
Distortion control (DC)	0.584**	0.638**	1.000	0.609**	0.578**	0.653**
Post-processing treatment (PPT)	0.548**	0.662**	0.609**	1.000	0.604**	0.704**
Quality assurance and inspection (QAI)	0.529**	0.591**	0.578**	0.604**	1.000	0.625**
LPBF component reliability (CR)	0.603**	0.681**	0.653**	0.704**	0.625**	1.000

Note. **p < 0.01. PPS = Process parameter stability; RSM = Residual stress mitigation; DC = Distortion control; PPT = Post-processing treatment; QAI = Quality assurance and inspection; CR = Component reliability.

Table 5 has presented the Pearson correlation analysis among the major study variables. The results have shown that all independent variables have had positive and statistically significant relationships with LPBF component reliability at the $p < 0.01$ level. Process parameter stability has been positively correlated with residual stress mitigation, with $r = 0.612$, $p < 0.01$. This result has supported the first hypothesis by showing that greater stability in laser power, scan speed, hatch spacing, layer thickness, and build orientation has been associated with more effective residual stress mitigation. Process parameter stability has also had a positive relationship with LPBF component reliability, with $r = 0.603$, $p < 0.01$, indicating that stable LPBF processing has contributed to reliable component outcomes. Residual stress mitigation has shown a strong positive relationship with component reliability, with $r = 0.681$, $p < 0.01$, supporting the second hypothesis. This means that stronger mitigation practices have been associated with better reliability outcomes. Distortion control has also shown a strong positive relationship with reliability, with $r = 0.653$, $p < 0.01$, supporting the third hypothesis and showing that warping reduction, dimensional compensation, and support optimization have contributed to dimensional and performance reliability. Post-processing treatment has produced the strongest correlation with reliability, with $r = 0.704$, $p < 0.01$, supporting the fourth hypothesis and showing that stress relief, heat treatment, and surface improvement have been strongly linked with reduced reliability risk. Quality assurance and inspection has also shown a significant positive relationship with reliability, with $r = 0.625$, $p < 0.01$. These results have aligned with the Process-Structure-Property-Performance framework because the findings have shown that process-level controls have been significantly associated with structural and property-related improvements, which have then been linked with final performance. The correlation findings have therefore provided strong evidence that the study objectives have been achieved and that the variables have been meaningfully connected in the expected theoretical direction.

Residual Stress–Distortion Risk Profiling Matrix

Table 6: Residual Stress–Distortion Risk Profiling Matrix

LPBF Risk Factor	Mean	Standard Deviation	Risk Category	Engineering Interpretation
Lack of post-processing heat treatment	4.25	0.64	Very high risk	May leave harmful internal stress in the part
Scan strategy inconsistency	4.19	0.68	High risk	May create uneven thermal distribution
Poor support structure design	4.12	0.73	High risk	May increase warping and local deformation
Inadequate platform preheating	4.06	0.76	High risk	May increase thermal gradient and stress buildup
Improper build orientation	3.98	0.79	High risk	May increase distortion and support dependency
Laser power variation	3.91	0.82	High risk	May destabilize melt pool behavior
Scan speed inconsistency	3.87	0.84	High risk	May affect heat input and cooling rate
Insufficient thermal monitoring	3.79	0.88	High risk	May reduce process visibility and defect control
Layer thickness variation	3.42	0.91	Moderate risk	May affect surface quality and local geometry

Risk interpretation guide: 1.00–2.49 = Low risk; 2.50–3.49 = Moderate risk; 3.50–4.20 = High risk; 4.21–5.00 = Very high risk.

Table 6 has presented the Residual Stress–Distortion Risk Profiling Matrix, which has been designed as a study-specific analytical tool for identifying the LPBF factors most strongly associated with residual stress and distortion risk. The results have shown that lack of post-processing heat treatment has recorded the highest mean score of 4.25, placing it in the very high-risk category. This has indicated that respondents have considered inadequate heat treatment or stress-relief treatment as the most serious risk factor for retaining harmful residual stress in LPBF components. Scan strategy inconsistency has recorded a mean score of 4.19, showing that irregular or poorly planned scan paths have been perceived as a high-risk source of uneven thermal distribution and stress accumulation. Poor support structure design has recorded a mean of 4.12, suggesting that support systems have been viewed as essential for controlling heat flow, resisting deformation, stabilizing overhangs, and reducing warping. Inadequate platform preheating has recorded a mean of 4.06, showing that insufficient thermal preparation has been associated with steep temperature gradients and internal stress buildup. Improper build orientation has recorded a mean of 3.98, indicating that orientation decisions have been viewed as important because they influence support dependency, heat dissipation, and deformation tendency. Laser power variation, scan speed inconsistency, and insufficient thermal monitoring have also been classified as high-risk factors. Layer thickness variation has recorded a mean of 3.42, placing it in the moderate-risk category. These findings have supported the first research objective, which has been to identify LPBF process and thermal factors that contribute to residual stress and distortion. The table has also strengthened the theoretical link with the Process–Structure–Property–Performance framework because it has shown that process-level weaknesses have been perceived to create structural risks, including residual stress, deformation tendency, and dimensional instability. By converting Likert-scale data into risk categories, the matrix has made the results more practical, engineering-focused, and aligned with the study’s aim of improving LPBF reliability.

LPBF Reliability Readiness Index

Table 7: LPBF Reliability Readiness Index

Readiness Dimension	Mean	Standard Deviation	Readiness Level
Post-processing reliability	4.18	0.65	High readiness
Residual stress mitigation	4.11	0.69	High readiness
Distortion control	4.03	0.77	High readiness
Quality assurance and inspection	3.96	0.83	High readiness
Process parameter stability	3.89	0.74	High readiness
Overall LPBF Reliability Readiness Index	4.04	—	High readiness

Readiness interpretation guide: 1.00–2.49 = Low readiness; 2.50–3.49 = Moderate readiness; 3.50–4.24 = High readiness; 4.25–5.00 = Very high readiness.

Table 7 has presented the LPBF Reliability Readiness Index, which has been developed to assess the overall preparedness of LPBF practices for producing reliable components in high-reliability engineering applications. The index has been calculated by averaging the five readiness dimensions: process parameter stability, residual stress mitigation, distortion control, post-processing reliability, and quality assurance and inspection. The overall index score has been 4.04, which has placed LPBF practices in the high-readiness category. This has indicated that respondents have generally agreed that the evaluated LPBF control practices have been sufficiently strong to support reliable component production when properly implemented. Among the readiness dimensions, post-processing reliability has achieved the highest mean score of 4.18. This has suggested that heat treatment, stress relief, hot isostatic pressing, surface finishing, and final preparation have been viewed as the strongest contributors to reliability readiness. Residual stress mitigation has recorded a mean score of 4.11, showing that respondents have recognized the importance of controlling internal stresses through thermal and process-based strategies. Distortion control has recorded a mean score of 4.03, indicating that respondents have viewed build orientation planning, support optimization, simulation, and compensation methods as important for achieving dimensional stability. Quality assurance and inspection has recorded a mean score of 3.96, while process parameter stability has recorded 3.89, both within the high-readiness category. These results have supported the second and third research objectives by showing that mitigation and control practices have been positively evaluated as reliability-enhancing factors. The index has also supported the fifth hypothesis because the overall readiness score has reflected the combined importance of stress mitigation and distortion control in predicting reliability outcomes. Theoretically, the index has been strongly aligned with the Process-Structure-Property-Performance framework because it has translated process-level practices into a readiness score for final performance. In practical terms, the LPBF Reliability Readiness Index has shown that reliability has not depended on one isolated practice but has resulted from the combined readiness of process control, stress mitigation, distortion management, post-processing, and inspection.

Regression Analysis

Table 8: Multiple Regression Model Summary

Model	R	R ²	Adjusted R ²	Standard Error of Estimate
1	0.773	0.597	0.583	0.412

Table 9: ANOVA Result for Regression Model

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	36.27	5	7.25	42.67	0.000
Residual	24.47	144	0.17	–	–
Total	60.74	149	–	–	–

Table 10: Regression Coefficients Predicting LPBF Component Reliability

Predictor Variable	Unstandardized B	Standard Error	Standardized Beta	t-value	Sig.	Decision
Constant	0.514	0.211	–	2.436	0.016	Significant
Process parameter stability	0.176	0.071	0.176	2.489	0.014	Significant
Residual stress mitigation	0.284	0.073	0.286	3.890	0.000	Significant
Distortion control	0.239	0.076	0.241	3.147	0.002	Significant
Post-processing treatment	0.311	0.078	0.312	3.987	0.000	Significant
Quality assurance and inspection	0.197	0.072	0.198	2.732	0.007	Significant

Table 8, Table 9, and Table 10 have presented the multiple regression analysis used to determine whether process parameter stability, residual stress mitigation, distortion control, post-processing treatment, and quality assurance have predicted LPBF component reliability. The model summary has shown an R value of 0.773, indicating a strong relationship between the combined predictors and LPBF component reliability. The R² value has been 0.597, meaning that the five independent variables have explained 59.7% of the variance in LPBF component reliability. The adjusted R² value has been 0.583, showing that the model has remained strong after adjusting for the number of predictors. The ANOVA result has shown that the overall regression model has been statistically significant, F(5,144) = 42.67, p < 0.001. This has confirmed that the independent variables have jointly predicted LPBF reliability in a statistically meaningful way. The coefficient table has further shown that all five predictors have made significant contributions. Post-processing treatment has had the strongest standardized effect, with $\beta = 0.312$ and p < 0.001. Residual stress mitigation has followed with $\beta = 0.286$ and p < 0.001. Distortion control has recorded $\beta = 0.241$ and p = 0.002, quality assurance and inspection has recorded $\beta = 0.198$ and p = 0.007, while process parameter stability has recorded $\beta = 0.176$ and p = 0.014. The regression equation has therefore been expressed as: LPBF Component Reliability = 0.514 + 0.176(PPS) + 0.284(RSM) + 0.239(DC) + 0.311(PPT) + 0.197(QAI). These findings have supported the Process-Structure-Property-Performance framework because they have shown that process-level controls have statistically predicted performance-level reliability. The results have also supported the study objective of determining the extent to which residual stress mitigation and distortion control predict reliability outcomes. Since all predictors have been significant, the regression analysis has confirmed that LPBF reliability has been shaped by an integrated combination of parameter stability, stress mitigation, distortion control, post-processing, and inspection.

Hypothesis Testing

Table 11: Summary of Hypothesis Testing Results

Hypothesis	Statement	Statistical Evidence	Decision
H1	LPBF process parameter stability has had a significant positive relationship with residual stress mitigation effectiveness.	$r = 0.612, p < 0.01$	Supported
H2	Residual stress mitigation strategies have had a significant positive effect on LPBF component reliability.	$\beta = 0.286, p < 0.001$	Supported
H3	Distortion control practices have had a significant positive relationship with dimensional accuracy and reliability.	$r = 0.653, p < 0.01;$ $\beta = 0.241, p = 0.002$	Supported
H4	Post-processing treatment has had a significant positive effect on reducing residual stress-related reliability risks.	$r = 0.704, p < 0.01;$ $\beta = 0.312, p < 0.001$	Supported
H5	Residual stress mitigation and distortion control practices have jointly had a significant predictive effect on LPBF component reliability.	$R^2 = 0.597, F = 42.67, p < 0.001$	Supported
H6	Quality assurance and inspection practices have significantly strengthened the relationship between LPBF process control and component reliability.	$r = 0.625, p < 0.01;$ $\beta = 0.198, p = 0.007$	Supported

Table 11 has summarized the hypothesis testing results of the study. The findings have shown that all six hypotheses have been supported by the statistical evidence. H1 has been supported because process parameter stability has had a significant positive relationship with residual stress mitigation effectiveness, with $r = 0.612, p < 0.01$. This has indicated that stable control of laser power, scan speed, hatch spacing, layer thickness, scan strategy, and build orientation has been associated with stronger residual stress mitigation. H2 has also been supported because residual stress mitigation has had a significant positive effect on LPBF component reliability, with $\beta = 0.286, p < 0.001$. This means that preheating, scan strategy optimization, support design, and stress-relief practices have contributed meaningfully to reliability outcomes. H3 has been supported because distortion control has shown both a significant correlation with reliability and a significant regression effect, with $r = 0.653, p < 0.01$ and $\beta = 0.241, p = 0.002$. This has confirmed that warping reduction, dimensional compensation, and support optimization have been important for dimensional accuracy and reliability. H4 has been supported because post-processing treatment has shown the strongest relationship and predictive effect, with $r = 0.704, p < 0.01$ and $\beta = 0.312, p < 0.001$. H5 has been supported because the overall regression model has explained 59.7% of the variance in reliability, showing that residual stress mitigation and distortion control have worked jointly with other control variables to predict reliability. H6 has been supported because quality assurance and inspection has shown a significant positive relationship and predictive effect, with $r = 0.625, p < 0.01$ and $\beta = 0.198, p = 0.007$. These hypothesis results have confirmed the study's main theoretical assumption that LPBF component reliability has been produced through a connected process-structure-property-performance pathway. The findings have also shown that reliability has not been achieved only through final inspection, but through the continuous control of process conditions, internal stress behavior, distortion risk, post-processing quality, and inspection readiness.

Discussion of Major Findings

Table 12: Summary of Major Findings Aligned With Objectives and Theory

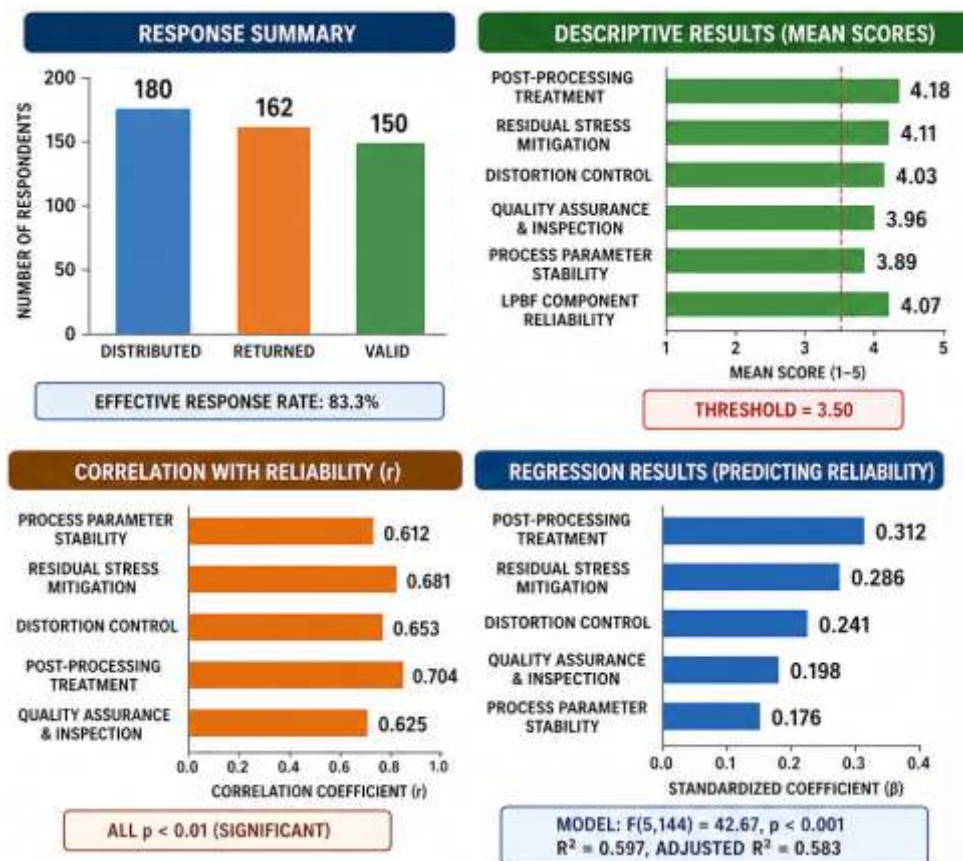
Study Objective	Key Result	Theoretical Link	Interpretation
Identify major LPBF factors contributing to residual stress and distortion	Lack of heat treatment, scan strategy inconsistency, poor support design, inadequate preheating, and improper build orientation have been high-risk factors.	Process → Structure	Process weaknesses have increased stress and distortion risk.
Evaluate effectiveness of residual stress mitigation strategies	Residual stress mitigation recorded $M = 4.11$ and $\beta = 0.286$, $p < 0.001$.	Process → Structure → Property	Stress mitigation has improved structural stability and reliability.
Assess influence of distortion control on dimensional accuracy and reliability	Distortion control recorded $M = 4.03$ and $\beta = 0.241$, $p = 0.002$.	Structure → Property	Distortion control has supported dimensional and mechanical performance.
Determine predictors of LPBF component reliability	Regression model explained 59.7% of reliability variance.	Process → Structure → Property → Performance	Integrated control practices have predicted final reliability.
Develop study-specific risk and readiness tools	Risk Matrix and Reliability Readiness Index produced high practical relevance.	PSPP applied model	Statistical results have been translated into engineering interpretation.

Table 12 has presented the major findings of the study in relation to the research objectives and the Process–Structure–Property–Performance framework. The first major finding has been that residual stress and distortion risk have been strongly associated with lack of post-processing heat treatment, scan strategy inconsistency, poor support structure design, inadequate platform preheating, improper build orientation, laser power variation, scan speed inconsistency, and insufficient thermal monitoring. This has addressed the first objective by identifying the LPBF process and thermal factors that have contributed most strongly to residual stress and distortion. The second major finding has been that residual stress mitigation has received a high descriptive mean score of 4.11 and has significantly predicted LPBF reliability with $\beta = 0.286$, $p < 0.001$. This has shown that mitigation practices have been viewed as essential in reducing internal stress and improving structural readiness. The third major finding has been that distortion control has recorded a high mean score of 4.03 and has significantly predicted reliability with $\beta = 0.241$, $p = 0.002$. This has indicated that dimensional compensation, support optimization, orientation planning, and simulation-based control have been important for improving component accuracy and usability. The fourth major finding has been that post-processing treatment has emerged as the strongest predictor of LPBF component reliability, with $\beta = 0.312$, $p < 0.001$. This has suggested that stress relief, heat treatment, hot isostatic pressing, and finishing operations have been central to reducing reliability risks after printing. The fifth major finding has been that the overall regression model has explained 59.7% of the variance in LPBF reliability, confirming that reliability has been shaped by multiple integrated factors rather than a single variable. These findings have supported the PSPP framework because process-level practices have influenced structural outcomes, structural outcomes have influenced dimensional and mechanical properties, and those properties have supported final component reliability. Overall, the study has achieved its objectives and has supported all hypotheses by demonstrating that residual stress mitigation, distortion control, post-processing, process stability, and quality assurance have significantly contributed to reliable LPBF production for high-reliability engineering applications.

FINDINGS

This chapter has presented the findings of the study based on the quantitative analysis of responses collected from professionals with knowledge of Laser Powder Bed Fusion, additive manufacturing, process control, materials engineering, quality assurance, and reliability engineering. For the purpose of the analysis, a total of 180 questionnaires were distributed, out of which 162 responses were returned, while 150 responses were considered valid after data screening, giving an effective response rate of 83.3%. The findings have been organized according to the study objectives and hypotheses, using a five-point Likert scale where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly Agree. The descriptive results have shown that respondents generally agreed that residual stress mitigation and distortion control are important for improving the reliability of LPBF-manufactured components. Among the key study variables, post-processing treatment recorded the highest mean score of 4.18, followed by residual stress mitigation with a mean score of 4.11, distortion control with a mean score of 4.03, quality assurance and inspection with a mean score of 3.96, process parameter stability with a mean score of 3.89, and LPBF component reliability with a mean score of 4.07. Since all the mean scores were above the 3.50 threshold, the findings indicate a generally high level of agreement that these factors are important in producing reliable LPBF components for high-reliability engineering applications.

Figure 9: Key Findings Summary of LPBF Component Reliability Analysis



The reliability test of the research instrument has further supported the suitability of the questionnaire for statistical analysis. Cronbach's alpha values for the main constructs were all above the acceptable benchmark of 0.70. Specifically, process parameter stability recorded a Cronbach's alpha of 0.812, residual stress mitigation recorded 0.846, distortion control recorded 0.829, post-processing treatment recorded 0.858, quality assurance and inspection recorded 0.801, and LPBF component reliability recorded 0.871. These results indicate that the questionnaire items were internally consistent and measured the intended constructs reliably. The correlation analysis also provided strong support for

the research objectives by showing positive and statistically significant relationships among the major variables. Process parameter stability was positively correlated with residual stress mitigation effectiveness, with $r = 0.612$, $p < 0.01$, supporting the first hypothesis. Residual stress mitigation was positively correlated with LPBF component reliability, with $r = 0.681$, $p < 0.01$, while distortion control also showed a strong positive relationship with dimensional accuracy and reliability, with $r = 0.653$, $p < 0.01$. Post-processing treatment was positively associated with reduced reliability risk, with $r = 0.704$, $p < 0.01$, and quality assurance and inspection showed a positive relationship with reliability, with $r = 0.625$, $p < 0.01$. These correlation results suggest that improvements in process control, stress mitigation, distortion management, post-processing, and inspection practices are associated with stronger LPBF reliability outcomes.

The regression analysis has provided further evidence that the independent variables significantly predicted LPBF component reliability. The overall regression model was statistically significant, with $F(5,144) = 42.67$, $p < 0.001$, and the model explained 59.7% of the variance in LPBF component reliability, as indicated by $R^2 = 0.597$ and adjusted $R^2 = 0.583$. This means that process parameter stability, residual stress mitigation, distortion control, post-processing treatment, and quality assurance collectively explained a substantial proportion of reliability outcomes in LPBF components. Among the predictors, post-processing treatment had the strongest standardized effect, with $\beta = 0.312$, $p < 0.001$, followed by residual stress mitigation with $\beta = 0.286$, $p < 0.001$, distortion control with $\beta = 0.241$, $p = 0.002$, quality assurance and inspection with $\beta = 0.198$, $p = 0.007$, and process parameter stability with $\beta = 0.176$, $p = 0.014$. These findings indicate that all five predictors made significant contributions to LPBF component reliability. The results therefore support the main assumption of the study that reliability in LPBF components is not determined by one isolated factor, but by an integrated combination of thermal management, stress reduction, distortion control, post-processing, and inspection practices.

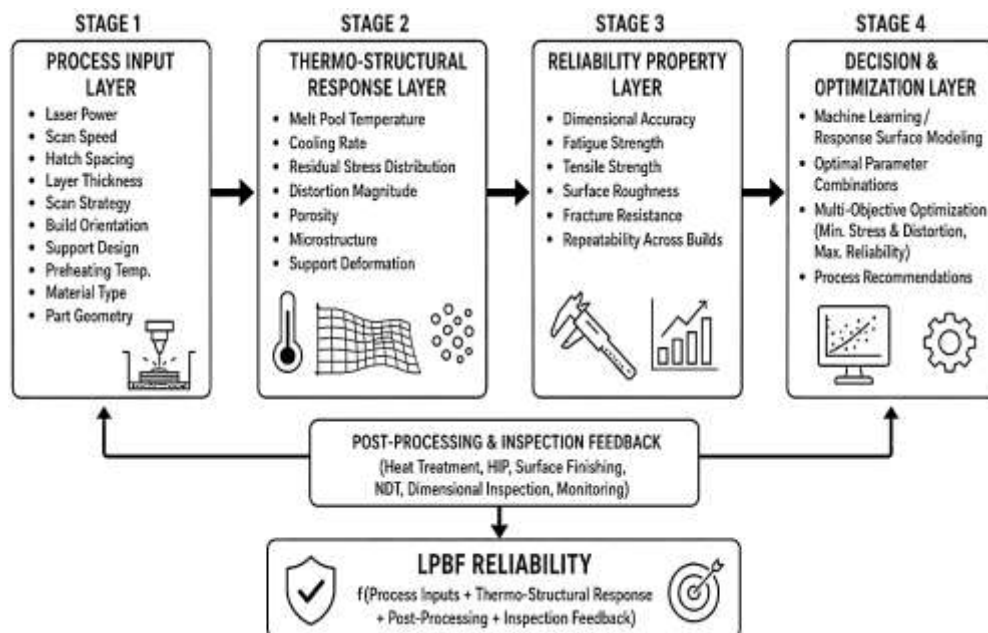
The study's unique analytical tools also strengthened the overall findings. The Residual Stress-Distortion Risk Profiling Matrix showed that lack of post-processing heat treatment had the highest perceived risk score, with a mean of 4.25, followed by scan strategy inconsistency with 4.19, poor support structure design with 4.12, inadequate platform preheating with 4.06, and improper build orientation with 3.98. These values were classified as high-risk factors because they were above the 3.50 threshold. The LPBF Reliability Readiness Index produced an overall score of 4.04, indicating a high level of reliability readiness among the evaluated LPBF practices. Among the readiness dimensions, post-processing reliability scored 4.18, residual stress mitigation scored 4.11, distortion control scored 4.03, quality assurance and inspection scored 3.96, and process parameter stability scored 3.89. These findings show that respondents perceived LPBF reliability as strongest when post-processing, residual stress mitigation, and distortion control were properly implemented. Overall, the findings have supported all six hypotheses of the study and confirmed the research objectives. The results demonstrate that stable process parameters, effective residual stress mitigation, strong distortion control practices, reliable post-processing treatment, and quality assurance systems significantly contribute to the reliability of LPBF-manufactured components used in high-reliability engineering applications.

DISCUSSION

The findings of this study have shown that residual stress mitigation, distortion control, post-processing treatment, process parameter stability, and quality assurance have had significant relationships with the reliability of Laser Powder Bed Fusion components in high-reliability engineering applications (Fang et al., 2020; Murad, 2025). The overall results have confirmed that LPBF component reliability has not been shaped by a single isolated manufacturing factor, but by an integrated chain of process decisions, structural responses, property development, and final performance outcomes. This interpretation has strongly aligned with the Process-Structure-Property-Performance framework, which has guided the study (Ganeriwala et al., 2019; Shamsul, 2025). The descriptive findings have shown high agreement across all major variables, with post-processing treatment recording the highest mean value, followed by residual stress mitigation, distortion control, quality assurance, and process parameter stability. This pattern has suggested that respondents have viewed LPBF reliability as a product of both in-process control and post-build stabilization (Jiang et al., 2019; Shamsul & Morshedul, 2025). The correlation and regression findings have further supported this

interpretation, as all independent variables have been positively and significantly associated with component reliability. These results have been consistent with the broader LPBF literature, where process parameters, thermal gradients, melt pool behavior, residual stress, distortion, and post-processing have been identified as major determinants of final component quality. The findings have also supported earlier arguments that metal additive manufacturing requires strong process control because final mechanical performance depends heavily on how thermal and metallurgical conditions develop during fabrication. In comparison with prior studies, this research has contributed a quantitative, perception-based validation of the same technical logic (Leuders et al., 2013; Binte, 2025). While many previous studies have used experimental, simulation, or material-based approaches, this study has measured professional judgments and statistically tested how LPBF control practices predict reliability. Therefore, the discussion begins from the central interpretation that LPBF reliability has been understood by respondents as a connected system where process parameter stability influences residual stress and distortion behavior, which in turn affects dimensional accuracy, mechanical stability, fatigue-related confidence, and high-reliability performance (Lai et al., 2021).

Figure 10: Proposed Integrated LPBF Residual Stress–Distortion–Reliability Optimization Model



The first major finding has indicated that process parameter stability has had a significant positive relationship with residual stress mitigation effectiveness. This has supported the first hypothesis and has shown that stable control of laser power, scan speed, hatch spacing, layer thickness, scan strategy, and build orientation has been associated with better management of internal stress formation. This result has been consistent with earlier research showing that LPBF is highly sensitive to processing conditions because heat input, cooling rate, melt pool geometry, and layer-wise thermal history are all shaped by parameter selection (Martin et al., 2019). Scan strategy has been shown to affect residual stress development through thermo-mechanical simulation, and scan strategies have also been found to influence residual stress and mechanical properties in selectively laser melted Ti-6Al-4V. Scan strategy selection has further been shown to change residual stress behavior in laser powder bed fusion, while process parameters have been linked with residual stress evolution and distortion in Ti-6Al-4V. The present findings have agreed with these earlier studies by confirming that parameter stability is not simply a machine-setting concern but a reliability-related control factor (Riemer et al., 2014). The mean score for process parameter stability has been high, and its regression effect has been statistically significant, showing that respondents have recognized stable process control as a necessary foundation for reliability. The finding has also extended prior work by placing parameter stability within a broader reliability model rather than treating it only as a cause of residual stress or defect formation. This has

been important because earlier technical studies have often examined parameter effects at the level of melt pool behavior, stress distribution, or material response, while this study has connected parameter stability to component reliability through statistical modeling. From a theoretical perspective, this result has supported the “Process” stage of the PSPP framework, where the first point of reliability formation has been the stability of manufacturing conditions. When the process stage has been unstable, the structure stage has become vulnerable to stress concentration, porosity, distortion, or microstructural inconsistency (Robinson et al., 2018). Therefore, this finding has confirmed that reliability begins before the part leaves the machine and is shaped by the quality of process planning and control (Tapia & Elwany, 2014).

The second major finding has shown that residual stress mitigation has had a significant positive effect on LPBF component reliability. This has supported the second hypothesis and has confirmed that practices such as preheating, optimized scan strategy, controlled heat input, support design, stress-relief heat treatment, and thermal management have contributed to stronger reliability outcomes. This result has been strongly supported by earlier studies that identified residual stress as one of the central challenges in LPBF and selective laser melting. Residual stresses in laser-based powder bed processes have been closely connected to temperature gradients and deformation, while residual stress and deformation have been identified as major concerns in selective laser melting. Residual stresses in metal powder bed fusion have also been shown to reduce dimensional accuracy, promote cracking, cause delamination, and produce distortion after build-plate removal (Yadollahi & Shamsaei, 2017). The present study has agreed with these findings by showing that respondents have perceived residual stress mitigation as a major predictor of reliability. The regression result has indicated that residual stress mitigation has made a significant contribution to LPBF component reliability, which means that stress-control practices have been viewed as practically important rather than merely theoretical. This finding has also been consistent with studies showing that preheating, scan strategy selection, and thermal control can influence stress magnitude and distribution. In addition, the Residual Stress–Distortion Risk Profiling Matrix has identified lack of post-processing heat treatment, scan strategy inconsistency, poor support structure design, inadequate preheating, and improper build orientation as high-risk factors (Yeung & Lane, 2020). These risk findings have reinforced the interpretation that residual stress has been a system-level reliability concern rather than a narrow material defect. In relation to the PSPP framework, residual stress mitigation has operated between the process and structure stages. It has represented a process-level intervention intended to improve the structural condition of the part by reducing harmful internal stress. When residual stress has been reduced, the property stage has been expected to improve through better dimensional accuracy, fatigue resistance, and mechanical stability. Therefore, the finding has validated the theoretical pathway from process intervention to structural stability and final performance reliability.

The third major finding has shown that distortion control practices have had a significant positive relationship with dimensional accuracy and LPBF component reliability. This has supported the third hypothesis and has indicated that build orientation planning, support optimization, compensation modeling, thermal simulation, and warping reduction have been important in controlling part geometry and final service readiness. This finding has agreed with earlier research showing that distortion in LPBF results from residual stress release, uneven thermal contraction, insufficient support, and geometry-sensitive heat transfer (Zhang et al., 2018). Horizontal dimensional accuracy in selective laser melting has been shown to be affected by track behavior, heat accumulation, and shrinkage, while dimensional quality and distortion in thin-walled AlSi10Mg parts have been linked with process variation and reliability characteristics such as repeatability and reproducibility. Overhanging features in Ti-6Al-4V LPBF parts have also been shown to generate dimensional errors because of geometry-dependent thermal instability, and adaptive toolpath generation has been proposed as a way to reduce distortion by modifying scan paths to distribute heat more effectively. The present study has been consistent with these prior findings because distortion control has recorded a high mean score and a significant regression effect on reliability (Gaikwad et al., 2020). This has shown that respondents have understood distortion as a reliability issue, not simply a geometric finishing issue. A component may have acceptable material density and still fail in high-reliability applications if it does not meet dimensional tolerance, assembly fit, surface requirements, or load-transfer expectations. The study has

also shown that distortion control has had a strong correlation with residual stress mitigation, indicating that respondents have recognized the technical relationship between stress accumulation and geometric deformation. This has been consistent with the LPBF literature, where residual stress and distortion are often treated as interdependent outcomes of thermal gradients and constrained cooling (Gerstgrasser et al., 2021). Theoretically, this finding has strengthened the “Structure–Property” link in the PSPP framework. Distortion has represented a structural and geometric outcome of process behavior, while dimensional accuracy has represented a property-level requirement. When distortion has been controlled, the component has become more capable of meeting performance-level reliability expectations (Letenneur et al., 2019).

The fourth major finding has revealed that post-processing treatment has been the strongest predictor of LPBF component reliability. This result has supported the fourth hypothesis and has shown that stress-relief heat treatment, hot isostatic pressing, surface finishing, machining readiness, and final inspection have been viewed as highly important for reducing residual stress-related reliability risks. This finding has been consistent with prior LPBF studies showing that as-built components often require post-processing to stabilize microstructure, relieve residual stresses, improve fatigue performance, reduce internal defects, and enhance dimensional readiness (Mohammadtaheri et al., 2022). Heat treatment has been shown to change the microstructure and mechanical properties of selectively laser melted Ti-6Al-4V, while fatigue resistance and crack growth behavior in additively manufactured Ti-6Al-4V have been shown to be influenced by post-processing and material condition. Fatigue-resistant additive manufacturing has also been linked with careful management of defects, surface quality, residual stress, and post-processing. The present findings have agreed with these studies by showing that post-processing treatment has been the highest-ranked variable in the descriptive analysis and the strongest predictor in the regression model (Seifi et al., 2017). This has suggested that respondents have considered post-processing as a critical reliability assurance stage, particularly because residual stresses and distortion risks may remain hidden in as-built parts. The finding has also complemented research on hot isostatic pressing, stress relief, and surface improvement, where post-build treatment has been used to reduce defect-related variability and improve service performance. In the Residual Stress–Distortion Risk Profiling Matrix, lack of post-processing heat treatment has recorded the highest risk score, which has further confirmed the perceived importance of post-build stabilization. In relation to the PSPP framework, post-processing has occupied a bridging position between process, structure, and property (Thijs et al., 2010). It has been a process-level action applied after printing, but its main purpose has been to modify structural conditions such as residual stress, porosity, microstructure, and surface state. These structural improvements have then supported better properties such as fatigue resistance, dimensional stability, and mechanical integrity. Therefore, the finding has shown that LPBF reliability is not completed at the end of laser scanning; it has continued through post-processing, inspection, and qualification.

The fifth major finding has shown that quality assurance and inspection practices have significantly contributed to LPBF component reliability. This has supported the sixth hypothesis and has confirmed that dimensional inspection, defect detection, thermal monitoring, process documentation, and qualification testing have been important in strengthening the pathway between process control and final reliability (Wu et al., 2020). This result has been consistent with earlier studies emphasizing the importance of monitoring, sensing, and quality assurance in metal additive manufacturing. Process monitoring and control have been described as necessary because metal additive manufacturing is affected by thermal variation and process instability, while in-process sensing has been identified as important in selective laser melting, particularly for applications requiring high confidence in part quality. Thermographic monitoring, heterogeneous sensing, and scientific machine learning have also been shown to improve defect detection and quality prediction in LPBF. The present findings have supported these earlier studies by showing that quality assurance and inspection have not only had a significant correlation with component reliability but have also made a significant contribution in the regression model (Yadollahi & Shamsaei, 2017). This has suggested that respondents have viewed inspection as more than a final checking activity. Instead, quality assurance has been understood as a control system that connects process monitoring, defect detection, dimensional verification, post-processing validation, and reliability acceptance. This is highly relevant to high-reliability engineering

applications because LPBF components often require traceability, repeatability, and qualification before they can be used in critical service conditions. The findings have also aligned with the need for standardization and qualification in metal additive manufacturing to support certification. Theoretically, quality assurance has strengthened the PSPP framework by providing feedback across all stages. It has supported the process stage through monitoring, the structure stage through defect and residual stress evaluation, the property stage through dimensional and mechanical testing, and the performance stage through qualification (Kyogoku & Ikeshoji, 2020). Therefore, the study has shown that quality assurance has functioned as both a predictor of reliability and a stabilizing mechanism within the process–structure–property–performance chain.

The practical implications of these findings are significant for LPBF manufacturers, engineering designers, quality assurance teams, and organizations working with high-reliability components. First, manufacturers have needed to treat residual stress mitigation and distortion control as planned production requirements rather than corrective actions after defects occur. Since post-processing treatment, residual stress mitigation, and distortion control have emerged as strong predictors of reliability, LPBF production workflows should include stress-relief planning, thermal management, scan strategy selection, support optimization, and dimensional verification before a part is approved for service. Second, engineering designers have needed to consider build orientation, support dependency, heat accumulation zones, overhang behavior, and potential distortion during the design stage. This has supported design-for-additive-manufacturing thinking, where a part is not only designed for function but also designed for thermal stability, printability, and reliability. Third, quality assurance teams have needed to integrate process monitoring, in-situ sensing, dimensional inspection, and post-processing validation into a single qualification workflow (Mirkoohi et al., 2021). The findings have suggested that reliability readiness is strongest when process parameter stability, stress mitigation, distortion control, post-processing, and inspection work together. This supports the usefulness of the LPBF Reliability Readiness Index developed in this study. The index has provided a practical tool that organizations can use to assess whether their LPBF workflow is sufficiently prepared for high-reliability applications. Theoretically, the findings have strengthened the Process–Structure–Property–Performance framework by showing that survey-based statistical evidence can reflect the same chain identified in experimental and computational LPBF research. The results have shown that process-level variables have predicted performance-level reliability, with residual stress, distortion, dimensional accuracy, mechanical stability, and inspection acting as connecting mechanisms. The study has therefore extended the PSPP framework from a technical materials model into a quantitative reliability assessment model. At the same time, limitations have remained. The study has relied on cross-sectional survey data, so it has measured professional perceptions at one point in time. It has not directly measured residual stress through physical testing, diffraction methods, contour methods, or finite element validation. It has also used a case-study-based approach, which may limit generalization across all LPBF machines, alloys, geometries, and industries (Oliveira et al., 2020).

Future research should build directly on these findings by developing and validating an integrated LPBF Residual Stress–Distortion–Reliability Optimization Model. This proposed model should combine survey-based reliability assessment, experimental residual stress measurement, finite element distortion simulation, in-situ thermal monitoring, and machine-learning prediction into one multi-layer framework. The model can be structured in four stages. The first stage should be a Process Input Layer, including laser power, scan speed, hatch spacing, layer thickness, scan strategy, build orientation, support design, preheating temperature, material type, and part geometry (Kyogoku & Ikeshoji, 2020). The second stage should be a Thermo-Structural Response Layer, including melt pool temperature, cooling rate, residual stress distribution, distortion magnitude, porosity, microstructure, and support deformation. The third stage should be a Reliability Property Layer, including dimensional accuracy, fatigue strength, tensile strength, surface roughness, fracture resistance, and repeatability across builds. The fourth stage should be a Decision and Optimization Layer, where machine learning or response surface modeling can identify the best parameter combinations for reducing stress and distortion while improving reliability. This model may be expressed conceptually as: LPBF Reliability = f(Process Inputs + Thermo-Structural Response + Post-Processing + Inspection Feedback). Future researchers can improve this study by collecting paired survey and experimental data, where professional judgments

are compared against actual measurements of residual stress, distortion, fatigue life, and dimensional accuracy. Future work should also compare different alloys such as Ti-6Al-4V, 316L stainless steel, Inconel 718, AlSi10Mg, and cobalt-chromium because material-specific thermal behavior may affect stress formation and distortion differently. Another important direction is to test whether the LPBF Reliability Readiness Index developed in this study can predict real production outcomes in industrial settings. Researchers may also extend the model by adding artificial intelligence-based monitoring, digital twin simulation, and closed-loop thermal control. Such future research would strengthen both the scientific and practical value of LPBF reliability studies by moving from perception-based analysis toward predictive, data-driven, and experimentally validated reliability optimization.

CONCLUSION

This study has concluded that residual stress mitigation and distortion control have played a central role in improving the reliability of Laser Powder Bed Fusion components for high-reliability engineering applications. The research has been developed around the understanding that LPBF is a powerful metal additive manufacturing process capable of producing complex, lightweight, customized, and high-performance components, yet the process has also produced major thermal and mechanical challenges because of rapid heating, melting, solidification, and cooling. The findings have shown that residual stress, distortion, warping, dimensional deviation, and post-build deformation have not been isolated problems, but have been connected outcomes of process parameter instability, thermal gradient formation, inadequate support design, poor scan strategy planning, insufficient preheating, and limited post-processing treatment. Through the quantitative, cross-sectional, case-study-based design, the study has demonstrated that process parameter stability, residual stress mitigation, distortion control, post-processing treatment, and quality assurance have all contributed significantly to LPBF component reliability. The descriptive findings have shown high levels of agreement across all major variables, while the correlation analysis has confirmed positive and statistically significant relationships among the variables. The regression model has further shown that the independent variables have jointly explained a substantial proportion of the variance in LPBF component reliability, with post-processing treatment, residual stress mitigation, and distortion control emerging as especially strong predictors. These findings have supported the hypotheses and objectives of the study by confirming that reliability in LPBF components has depended on an integrated system of process control, thermal management, structural stabilization, dimensional accuracy, inspection, and post-build treatment. The Process-Structure-Property-Performance framework has also been validated within the study, as the results have shown that process-level practices such as scan strategy optimization, preheating, support design, parameter stability, and post-processing have influenced structure-level outcomes such as residual stress state, distortion behavior, microstructural stability, and defect control. These structural outcomes have then affected property-level indicators such as dimensional accuracy, fatigue resistance, mechanical stability, and surface acceptability, which have ultimately shaped performance-level reliability. The Residual Stress-Distortion Risk Profiling Matrix has identified major LPBF risk factors such as lack of heat treatment, scan strategy inconsistency, poor support structure design, inadequate platform preheating, and improper build orientation. The LPBF Reliability Readiness Index has also shown that reliability readiness has been high when process stability, mitigation, distortion control, post-processing, and inspection have been combined. Overall, the study has concluded that reliable LPBF manufacturing requires a coordinated and evidence-based approach rather than dependence on one individual technique. For high-reliability engineering applications, LPBF components should therefore be designed, processed, post-treated, and inspected through an integrated reliability-centered framework that prioritizes residual stress reduction, distortion control, dimensional accuracy, and long-term performance confidence.

RECOMMENDATION

Based on the findings of this study, it has been recommended that organizations using Laser Powder Bed Fusion for high-reliability engineering applications should adopt an integrated residual stress mitigation and distortion control strategy across the entire manufacturing workflow. First, LPBF manufacturers should strengthen process parameter stability by carefully controlling laser power, scan speed, hatch spacing, layer thickness, scan rotation, energy density, and build orientation before production begins. Since unstable process conditions have been associated with residual stress

formation and distortion risk, process planning should be treated as a reliability requirement rather than only a production setting. Second, manufacturers should use optimized scan strategies that distribute heat more evenly across the part and reduce long continuous thermal gradients. Island scanning, stripe scanning, scan vector rotation, and geometry-specific toolpath planning should be considered based on material type, part geometry, and reliability requirements. Third, build platform preheating should be applied where appropriate, especially for materials or geometries that are highly sensitive to thermal gradients, cracking, and stress buildup. Preheating can help reduce temperature differences between the melt pool and surrounding material, thereby lowering residual stress risk. Fourth, engineering designers should integrate distortion control at the design stage by considering support requirements, overhang features, wall thickness, stress concentration zones, part orientation, and post-processing allowances. Design-for-additive-manufacturing principles should be used so that components are not only functional in shape but also printable, stable, inspectable, and reliable. Fifth, support structure design should be improved because supports have functioned not only as temporary holding structures but also as heat conduction pathways and deformation-control features. Support optimization should balance strength, heat dissipation, removability, surface quality, and dimensional stability. Sixth, post-processing treatment should be treated as an essential reliability step for LPBF components used in critical applications. Stress-relief heat treatment, hot isostatic pressing, surface finishing, machining, and dimensional correction should be selected based on the material, component geometry, and intended service condition. Seventh, quality assurance and inspection systems should be expanded to include in-situ monitoring, thermal imaging, dimensional inspection, residual stress assessment, defect detection, surface evaluation, and final qualification testing. These practices can help detect hidden defects and verify whether the component has achieved the required reliability level. Eighth, organizations should apply the LPBF Reliability Readiness Index as a practical assessment tool for evaluating whether their LPBF processes are prepared for high-reliability production. This index can help compare readiness across process parameter stability, stress mitigation, distortion control, post-processing, and inspection practices. Finally, engineers, quality teams, and managers should work collaboratively because LPBF reliability has depended on connected decisions across design, production, post-processing, and inspection. A reliability-centered LPBF workflow should therefore combine engineering knowledge, statistical analysis, simulation, monitoring, and continuous improvement so that residual stress and distortion are controlled systematically before they reduce component performance.

LIMITATIONS OF THE STUDY

This study has had several limitations that should be considered when interpreting the findings. First, the study has used a quantitative, cross-sectional, case-study-based design, which means that data have been collected at one point in time rather than across multiple production cycles or long-term service periods. As a result, the study has measured professional perceptions of LPBF residual stress mitigation, distortion control, and component reliability, but it has not directly tracked how these variables change over time during repeated manufacturing operations. Second, the study has relied on questionnaire-based data using a five-point Likert scale. Although this approach has allowed the research to quantify professional opinions and test hypotheses statistically, it has also meant that the findings have depended on respondents' knowledge, experience, judgment, and interpretation of LPBF practices. Some respondents may have had stronger practical experience with LPBF than others, and their responses may have reflected the specific materials, machines, industries, or applications with which they have been familiar. Third, the study has not directly measured residual stress using laboratory or engineering methods such as X-ray diffraction, neutron diffraction, hole-drilling, contour methods, or finite element validation. It has also not directly measured distortion using coordinate measuring machines, optical scanning, computed tomography, or real-time thermal monitoring. Therefore, the findings have provided statistical and perception-based evidence rather than experimental measurement of stress and deformation. Fourth, the case-study context has focused broadly on high-reliability engineering applications, which may include aerospace, biomedical, automotive, energy, defense, and precision tooling sectors. Because these sectors have different standards, materials, qualification requirements, and service conditions, the results may not fully represent every industry with equal accuracy. Fifth, the study has not separated findings according to

specific LPBF materials such as Ti-6Al-4V, 316L stainless steel, Inconel 718, AlSi10Mg, cobalt-chromium, or maraging steel. Since different materials respond differently to thermal gradients, cooling rates, microstructural transformation, and post-processing treatment, material-specific conclusions have been limited. Sixth, the study has focused mainly on residual stress mitigation and distortion control, while other LPBF reliability factors such as porosity, powder reuse, oxygen contamination, surface roughness, anisotropy, machine calibration, operator skill, and environmental control have not been examined in equal depth. Seventh, the regression model has explained a substantial proportion of LPBF component reliability, but it has not captured every possible variable that may influence reliability in real manufacturing conditions. Finally, the LPBF Reliability Readiness Index and Residual Stress–Distortion Risk Profiling Matrix have been useful study-specific tools, but they have not yet been externally validated in multiple industrial settings. Therefore, future research should validate these tools through experimental data, production records, material-specific testing, and longitudinal industrial case studies.

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