

Research Article

Infill Structure Analysis of 17-4 PH Materials Extrusion Additive Manufacturing based on Finite Element Method

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ABSTRACT

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This study evaluates the mechanical performance of 17-4 precipitation-hardened (PH) stainless steel components fabricated via material extrusion additive manufacturing (MEAM), with a focus on the role of the infill structure. Finite element method (FEM) simulations and tensile testing were used to analyze how different infill patterns and densities affect structural integrity. The results show that increasing infill density improves mechanical strength and load distribution, reducing stress concentrations that lead to failure. A 30% infill density was identified as an effective balance between strength and material efficiency, making it suitable for high-pressure applications. However, this choice may limit weight reduction and material savings compared to lower infill densities. These findings highlight the importance of infill optimization in enhancing the reliability and cost-effectiveness of MEAM-produced 17-4 PH components for engineering use.

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1. Introduction

The growth of additive manufacturing (AM) technologies in recent years has been a major driver in the reshaping of modern manufacturing, enabling them to produce parts with complex geometries and tailor-made properties. This technology has become a global sensation in the automotive industry because it can be used for many applications. AM can offer automated manufacturing processes, novel designs, as well as intricate shapes which are considered as part and parcel of Industry 4.0 (Wegner *et al.*, 2018; Thompson *et al.*, 2015). Material extrusion additive manufacturing (MEAM) is one of many forms of AM techniques that have been investigated extensively due to their flexibility and low-cost requirements.

The mechanical characteristics of 17-4 PH stainless steel are well known for their excellent qualities such as high strength, toughness, and high resistance to corrosion, achieved through the martensitic precipitation hardening process. Some studies have been carried out on 17-4 PH in AM pointing to the issue of thermal and mechanical behaviors during layer-by-layer fabrication. For instance, Buchanan and Gardner (2019) showed that the presence of Al₂O₃ ceramic in the metal matrix increased its wear resistance but caused a significant decrease in hardness. They also observed that porosities existed in processed metals than those expected from corresponding PM preforms, resulting into lower densities. MEAM part mechanical performance is defined by infill structures. Their impact can be felt on strength, mass, and material utilization. Wu *et al.* (2015)

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examined different densities and patterns of infilling and found that optimized infill could significantly enhance the mechanical properties of printed components. Besides, Han *et al.* (2020) used FEM to analyze stress distribution in various types of infilling, thereby providing knowledge on how these patterns affect the overall performance of the part.

The Finite Element Method (FEM) is a robust technique used to evaluate mechanical characteristics of Additive Manufacturing (AM) parts. In 2014, Zhang *et al.* (2017) carried out FEM research to predict the AM stress distribution, deformation, and failure mechanisms. Crucially, FEM has been utilized in optimizing infill structures, as shown by Smith and Ritchie (2021), who used FEA to find the best infills for efficient, lightweight, high-strength components.

Connecting rods are essential components in internal combustion engines, with extremely high cyclic loads and stress. Common production methods such as forging and casting have been employed to fabricate these parts. Despite this, the recent development of AM technology has shown its promise in manufacturing connecting rods with complex geometries and improved properties. According to Kumar and Kumar (2022), research was conducted on AM used for the manufacture of a rod, in which they observed that weight reduction could be achieved by optimizing design features and materials. Knowing how a connecting rod behaves under tensile stress is significant since failure in this mode can result into severe engine destruction. Researchers indicate that tensile stress concentration areas around the small end and big end bores of the rod are critical zones for fatigue failure. Using FEM, Lee *et al.* (2019) simulated tension loading on connecting rods to determine stress concentration factors and possible points of breakage. However, limited research has addressed how infill pattern and density specifically affect the mechanical behavior of 17-4 PH stainless steel connecting rods produced using MEAM technology. This represents a key research gap that this study aims to address.

Therefore, the main goal of this research is to analyze the infill structures of 17-4 PH stainless steel MEAM parts, especially connecting rods using FEM. The objective of this study is to assess the mechanical behaviors of various patterns of infill, find out what influence is exerted by filling density on structural integrity and identify the best infill shapes that improve performance and lifespan under tensile stress conditions for connecting rods. When it comes to the results, it is expected that they will contribute to AM technologies development and adoption of 17-4 PH stainless steel in important engineering applications in general.

2. Materials and Methods

The material used for this test is 17-4PH stainless steel, which has tiny grain size and a thermoplastic organic binder. Composite materials like this one were made and used during

the printing process to ensure maximum performance and precision. The chemical composition of the 17-4PH stainless steel specimens is given in Table 1 below.

Table 1 Chemical compositions of AM feedstock 17-4 PH.

Chemical compositions (%wt)				
Fe	Cr	Ni	Cu	C
70.98-77.28	15.5-17.75	3.00-5.00	3.00-5.00	0.007 (max)

2.1 Metal 3D printing process

To create the AM 17-4PH stainless steel specimens, Desktop Metal's studio system is used. This sophisticated material extrusion additive manufacturing (MEAM) process contains three main parts that are essential to the production procedure: a 3D printer, a debinding machine and, a sintering furnace. The green part is first obtained from the 3D printer and is referred to as the as-printed object. Thus, this green part was passed through debinding followed by sintering to enhance its mechanical strength and structural integrity.

The printing parameters for this study were set specifically with utmost care, including a nozzle diameter of 0.4 mm, a nozzle temperature of 165 °C, a chamber temperature of 50 °C, a stage temperature of 65 °C, a printing rate of 8 cc/hr and a layer thickness of approximately 4.5 millimeters. The construction of these green parts in a horizontal orientation ensured that uniformity and precision were maintained during the fabrication process alone.

2.2 Heat treatment process for 17-4PH stainless steel

In the heat treatment of experimental samples, two different methods were employed: solution treatment and aging treatment. Solution heat treatment was performed at 1038 °C for a time range of 15 to 30 minutes followed by quick air cooling to retain desired microstructure. The solution-treated specimens were subsequently aged for one hour at 482 °C and then, air-cooled. The purpose of this aging stage was to improve mechanical properties and stabilize the structure of the sample. The solution and aging protocols used in this study were modified from studies by Sun *et al.* (2018) and Yoo *et al.* (2006). Figure 1 shows the complete heat-treating diagram indicating temperature and duration of each stage.

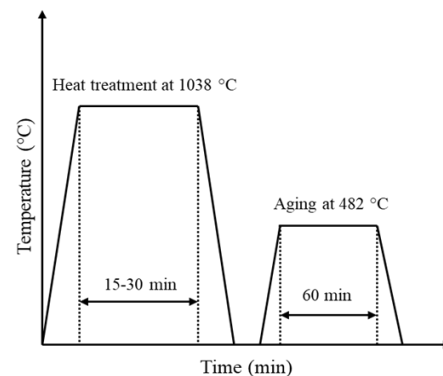


Figure 1 Heat treatment pattern of 17-4PH specimens.

2.3 Tensile testing

The tensile tests were conducted using a SHIMADZU AGS X 100 kN universal testing machine at room temperature with a strain rate of 0.00025 mm/(mm·sec) to avoid the effect of dynamic loading during the test, as recommended in the ASTM E8 standard. The specimen dimensions followed the ASTM E8 standard methods for tension testing of metallic materials, as shown in Figure 2(a).

2.4 Computer simulation setup and mesh convergence analysis

Using ANSYS Workbench, the numerical simulation was done with a license from King Mongkut's University of Technology North Bangkok (KMUTNB). In the simulation process, the material properties utilized were obtained from experimentally determined mechanical properties and stress-strain curves. Figure 2(a) displays the tensile specimen dimensions according to the ASTM E8 standard. In Figure 2 (b), region A is under displacement while region B is a fixed support with zero displacement in the simulation setup. During the entire simulation, a strain rate of 0.00025 mm/(mm·sec) developed by displacing 0.5 mm over approximately 80 seconds. To ensure an accurate and meaningful analysis, the CAD model meshing is shown in Figure 2 (c).

A mesh sensitivity study was performed to determine appropriate mesh size for this model and ensure reliable results when simulating it. Three-dimensional 10-node tetrahedral structural solid elements (SOLID187) were employed in this study using a nonlinear static analysis approach. The convergence of maximum equivalent stress in the gauge length area as a function of the number of mesh elements was analyzed. Simulation results began stabilizing after using approximately 356,420 tetrahedral elements (mesh size: 0.75 mm), as seen in Figure 3, which we adopted as our mesh configuration for this research. It should be borne in mind that if one compares the highest similar stresses between both meshes, where their sizes are respectively 0.25 mm and 0.75 mm there will be less than a one percent difference observed between them.

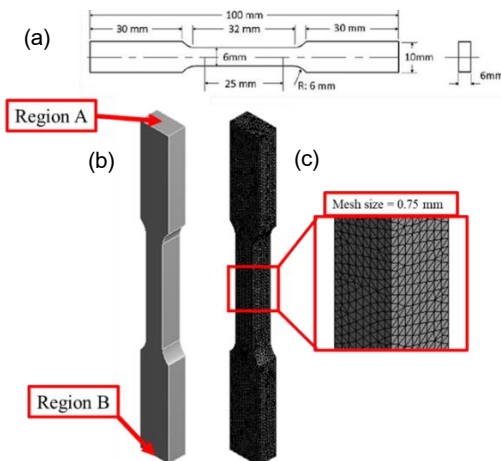


Figure 2 a) tensile specimen dimensions due to ASTM E8 standard, b) boundary condition finite element specimen and c) specimen mesh size.

2.5 Numerical model and design of connecting rod

The connecting rod design used in this research follows the standard size employed in commercial applications. The illustration of this particular connecting rod is included in Figure 4. This is equipment that has been designed to be operated under a pressure of 140 bar, as explained in the work by Witek and Zelek (2019). Cylinder support is used over region A to confine radial, rotational, and tangential movement of model. To find out how much maximum applied pressure the infill structure can withstand under working conditions, 14, 20, 25, 30, 35, 40, 45, and 50 MPa are applied on region B in $-x$ direction. It means that there was an application of triangular-shaped infill structures with weight reductions at region C equalling about 15%, 20%, 25% and 30%, respectively.

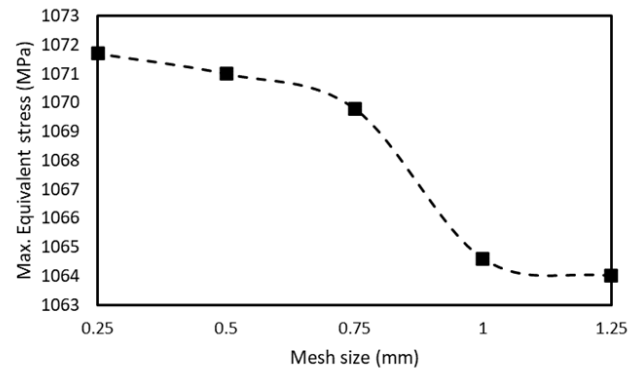


Figure 3 Mesh sensitivity analysis used in this model.

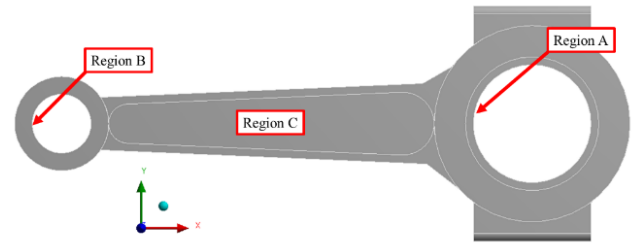


Figure 4 Boundary conditions defined in numerical model.

Figure 5 shows the infill structures having percentages equal to (a) 15%, (b) 20% (c) 25%, and (d) 30%, respectively. Nonlinear static analysis was utilized when calculating models because there were large deformations taking place at high applied loads. Considering numerical calculations, the maximum principal (σ_1) stress distributions for the connecting rod were obtained at operational loads. Namely, tensile σ_1 stress influences both fatigue crack initiation and crack propagation in fracture analysis.

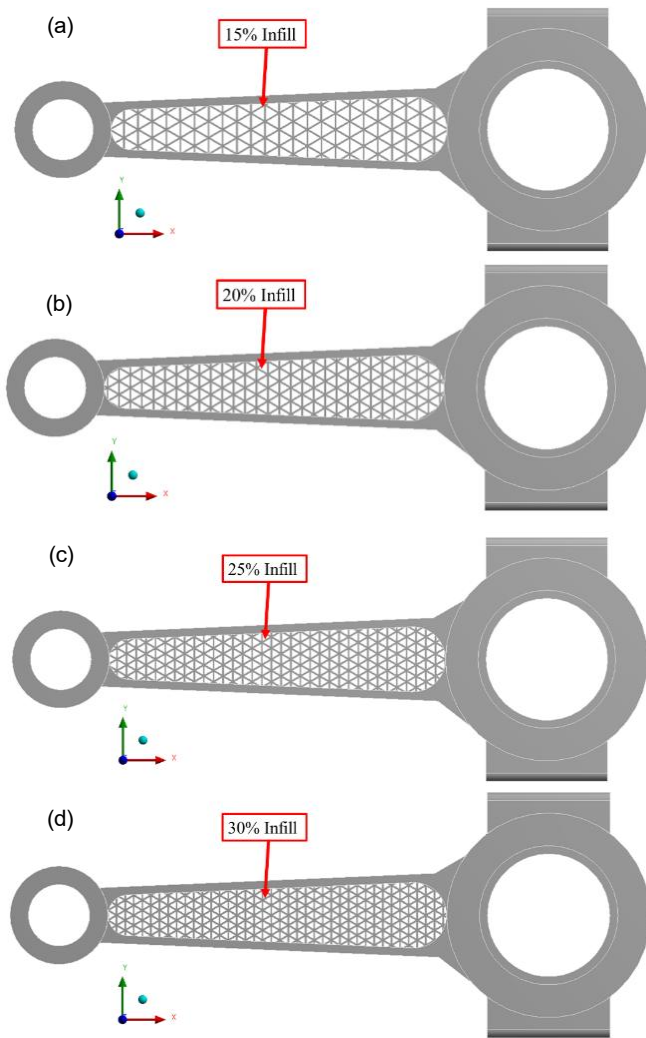


Figure 5 Infill structure design of connecting rod including a) 15%, b) 20%, c) 25% and d) 30% infill.

3. Results and Discussion

3.1 Tensile test

The engineering stress-strain curve of the AM 17-4PH stainless steel specimens is illustrated in Figure 6 and the tensile properties are shown in Table 2. Thus, when compared to the sintered specimen, it is observed that the samples revealed a higher strength in the elongation combination. A striking observation in this case was that this study sample had exceptional mechanical features, unlike MEAM 17-4PH steels mentioned in literature (Jones *et al.*, 2023; Andreacola *et al.*, 2021; Carneiro *et al.*, 2019).

Table 2 Tensile properties of 17-4PH stainless steel.

Yield stress (MPa)	Young's modulus (GPa)	Ultimate tensile strength (MPa)	Elongation (%)
675	191	1014	4.1

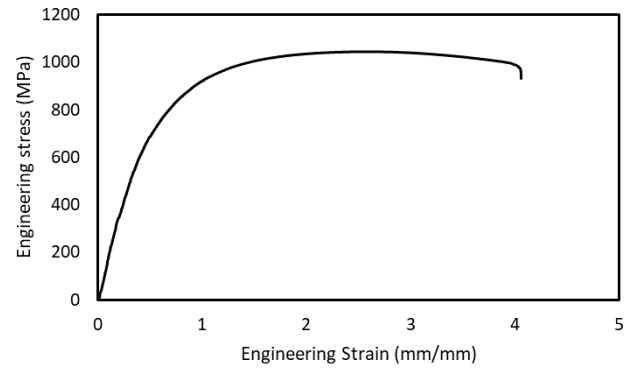


Figure 6 The engineering stress-strain curve of the AM 17-4PH stainless steel specimens.

3.2 Simulation results and experiment validation

The correlation between the simulation and direct measurements of the true stress-strain curve and true strain for the additive manufactured (AM) 17-4PH stainless steel specimen is shown in Figure 7. The figure provides an extensive comparison of the simulated data against the actual experimental results, displaying their link at different deformation stages. These validation outcomes prove that the simulation adheres to the experimentation, thereby showing how this technique is reliable and accurate.

The deviation between the experimental and numerical results remains under 5%, which proves a high accuracy of simulation procedure used. This minimal discrepancy emphasizes how well this method simulates true mechanical behaviour of AM 17-4PH stainless steel under given conditions. In addition, similarity level suggests that simulation is highly robust while also suggesting its applicability for predicting performance of AM materials within practical settings. A strong coincidence between the two shows that these simulations can be safely relied upon when undertaking further analysis on filling structure designs to optimize them as per requirements, due to their resemblance to the real process as indicated by the stress-strain curve.

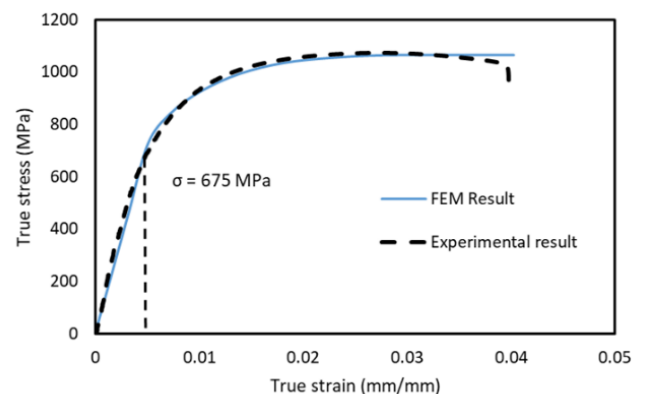


Figure 7 The validation between numerical simulation and experimental results of the true stress strain curve and the true strain for AM 17-4PH stainless steel specimen.

3.3 Influence of infill structure on stress distribution on connecting rod structures

Figure 8 presents the results of a nonlinear finite element simulation with respect to the maximum principal stress (σ_1) distribution on the connecting rod model at 14MPa. Figure 8(a) depicts the σ_1 stress distribution on the solid part. It is evident that, within the connection zone between the said body and rod head, a maximum of 335 MPa value is recorded for σ_1 stress. This concentration of σ_1 stress can cause crevices in this component. Infill development reduces the σ_1 stress concentration within the joint area. However, there may still be some presence of σ_1 stress concentration in the infill fin area of the 15% infill structure, as shown in Figure 8(b). The small proportion of infill structure appears to enhance significantly the concentration of σ_1 stress. In figure 8 (c)-(e), starting from twenty up to thirty percent infill structures, tensile strength decreases gradually but steadily while all other parameters are constant. A large proportion of infill structure can reduce load

concentrations by spreading loads more evenly over the materials under test so that weight bearing capacities are improved and localized stiffness peaks are avoided, thus contributing to global structural integrity (Thompson *et al.*, 2015). Moreover, deformation modes caused by mechanical fracture mechanisms were observed predominantly along bonding interfaces between columns and horizontal layers rather than directly through any struts or nodes themselves as anticipated per their orientation within voids (Lee *et al.*, 2019). Other researchers have reported similar findings; for example, Chou and Hong (2013) showed that increasing the density of fillers in three-dimensional printed objects leads to a more even spread pattern of stresses throughout them, resulting into reduced incidences of fatigue stresses and higher resistance levels among other things. Additionally, Zhang *et al.* (2022) have shown that increasing percentages used for filling materials improves load bearing ability, reducing risks associated with mechanical failure in additively fabricated products.

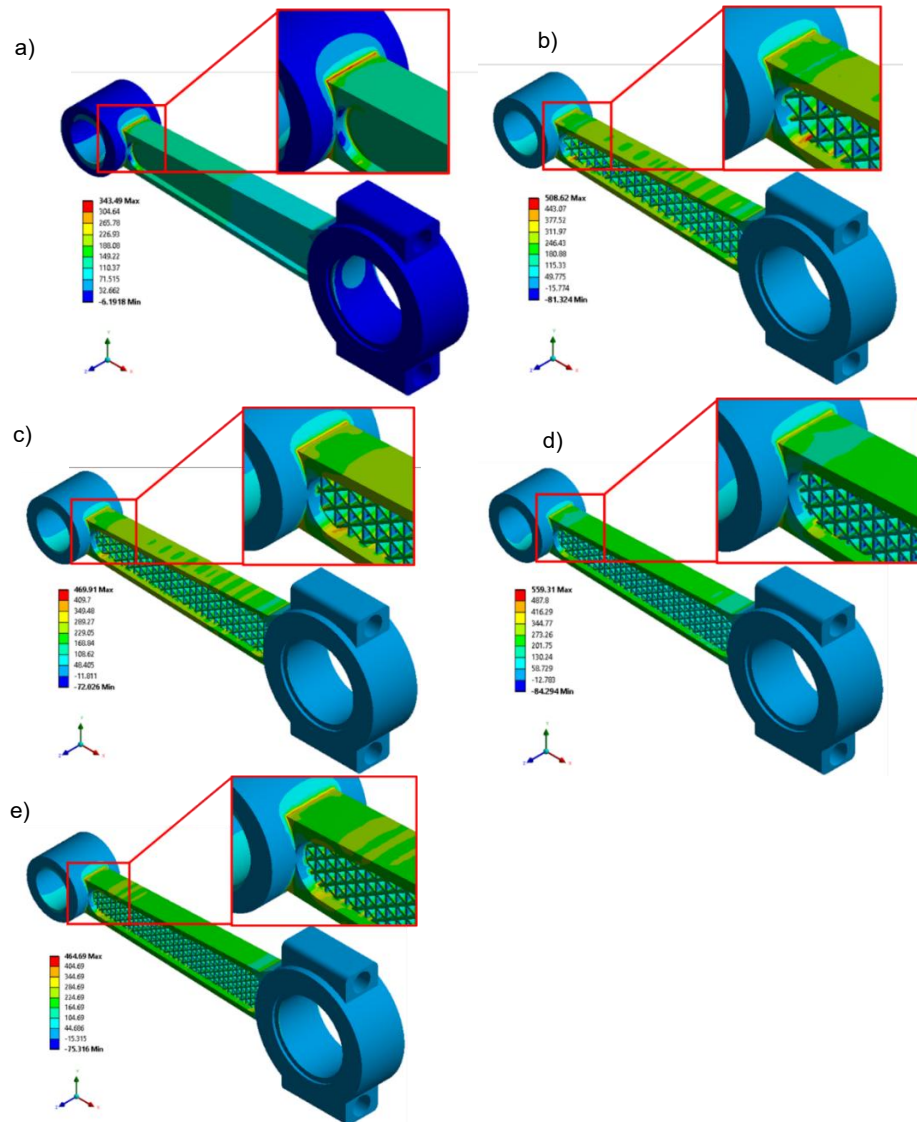


Figure 8 The maximum principal stress distribution of connecting rod under 14 MPa load in different designs including: a) solid, b) 15% infill, c) 20% infill, d) 25% infill and e) 30% infill.

Various infill percentages and solid material are clearly related to applied pressure in Figure 9. Consequently, this leads to an increase in maximum principal stress with increasing applied pressure for all types of materials involved. It is the solid material that indicates consistently higher stress values. On the other hand, infill structures demonstrate a reduction in such stress levels with larger percentages, resulting into lower maximum principal stresses. The 30% infill structure shows the highest reduction in stress followed by the 25%, 20%, and 15% infills, amongst others. Hence it is clear that optimal distribution of applied loads by high density fillers helps to minimize local areas subjected to high levels of stress. Thus, infill percentage optimization is paramount for improving component mechanical performance and serviceability, especially at elevated pressures. Therefore, a better use of materials together with strength can be found on the thirty percent infill structure only. This discovery has a significant bearing on additive manufacturing as it concerns efficient application of materials for best performance results. Stress concentration may be minimized, and lifespan elongated by raising the amount of filling inside components.

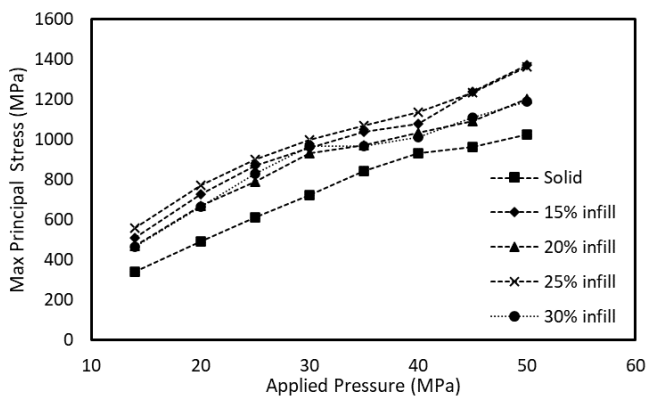


Figure 9 The relationship between applied pressure and maximum principal stress for different infill percentages and a solid material.

Figure 10 shows that the safety factor reduces as applied pressure increases among all materials. The solid sample indicates high safety factors at low pressures, but there is a remarkable decrease with an increase in pressure. Safety factors generally rise with the degree of infill; the higher the percentage of infill, the safer it is. In contrast, the 15% infill structure shows the opposite trend compared to the 30% infill structure as indicated by the lowest and highest safety factors, respectively. The difference between different filler fractions becomes prominent at lower applied pressures. However, at higher applied pressures, these differences diminish as they maintain their hierarchical order. The data suggest that an increasing percentage of infilling improves safety factor, hence offering more margin before failure. Similarly, the 30% infill provides a much greater level of protection than those with smaller proportions, thereby making it attractive for high-pressure applications. Although larger amounts of filling material result in

improved protection levels, one needs to balance this requirement with manufacturing cost and time employed for production. Generally, it is important to optimize the percentage infill when making sure that these components can withstand extremely tough conditions like high pressure, thus enhancing their durability and safety features.

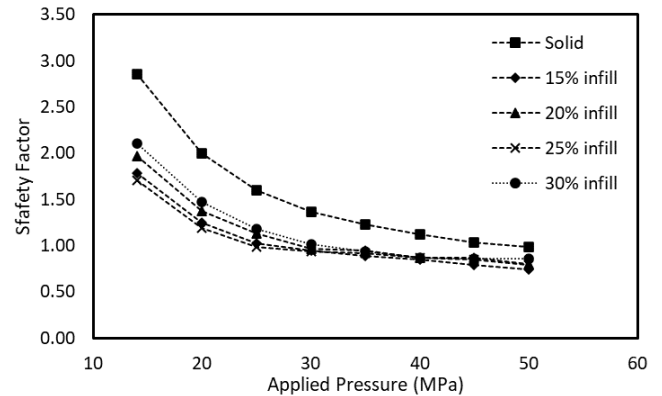


Figure 10 Relationship between safety factor and applied pressure of connecting rod in various designed conditions.

The identification of a 30% infill density as the optimal balance between mechanical strength and material efficiency has important implications for the real-world application of 17-4 PH stainless steel components produced by MEAM. In industries such as automotive, aerospace, and energy, where parts are frequently subjected to cyclic loading, it is essential to consider not only static strength but also performance under dynamic or fatigue conditions. Although this study focused primarily on tensile behaviour under quasi-static conditions, the improved stress distribution and reduced stress concentrations observed in the 30% infill structure suggest enhanced fatigue resistance. A more uniform load path reduces the risk of crack initiation, which is typically driven by local stress peaks in cyclic loading. Therefore, it is expected that the 30% infill configuration would provide superior fatigue life compared to lower-density infill structures, while still offering weight savings and reduced material use compared to solid parts. However, for applications involving high-frequency or long-duration loading cycles, further investigation is required. Real-world fatigue performance depends on factors such as build orientation, interlayer adhesion, and thermal history during processing. Future studies should evaluate the fatigue life of MEAM parts through experimental fatigue testing and life prediction modelling to fully validate their suitability for dynamic applications.

The findings of this study align closely with the objectives of Industry 4.0, particularly in promoting intelligent, resource-efficient, and digitally integrated manufacturing. By optimizing infill structures, such as the 30% density configuration in 17-4 PH stainless steel components, manufacturers can achieve a critical balance between mechanical performance and material efficiency, key principles of sustainable production. In the context of automotive applications, where weight reduction, structural

reliability, and cost control are pivotal, this research supports the adoption of material extrusion additive manufacturing (MEAM) for non-critical and semi-critical components like connecting rods, brackets, and housings. The ability to tailor internal geometries without compromising structural integrity enables design-driven performance enhancement, a hallmark of Industry 4.0's customization potential. Moreover, the validated use of finite element analysis (FEA) integrated with experimental data represents a data-driven design approach that enhances predictive maintenance and digital twin modelling. These capabilities contribute to shorter development cycles, reduced prototyping costs, and smarter production workflows, ultimately fostering more agile and adaptive manufacturing ecosystems.

4. Conclusion

This study shows that the infill pattern significantly influences the mechanical performance of 17-4 PH stainless steel components manufactured using the material extrusion additive manufacturing (MEAM) process. From the configurations tested, an infill density of 30% yielded the best combination of strength, efficiency, and durability, making it suitable for moderate to high mechanical loads. With a validated finite element method (FEM) model performing within 5% of experimental outcomes, simulation-driven design for internal structure optimization in additively manufactured parts can be trusted. These results bolster the case for utilizing MEAM to manufacture functionally critical components, particularly in automotive and aerospace industries where weight and performance are delicately balanced. From a practical standpoint, the 30% infill setting provides a static or quasi-static load enduring structure while remaining economical and maintaining sufficient strength. Further testing is needed to validate these assumptions in realistic use scenarios.

Future work should focus on evaluating the fatigue behaviour of MEAM fabricated 17-4 PH stainless steel components to understand their long-term durability under cyclic loading conditions. In addition, further investigations into performance under various environmental conditions, such as elevated temperatures, humidity, or corrosive environments, would provide valuable insights into their suitability for real-world engineering applications. These directions will help validate the robustness of optimized infill structures and extend the applicability of this manufacturing approach to more demanding and safety-critical industries.

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