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Original article

# Influence of aging and surface treatments on the fatigue response of L-PBF manufactured steel parts

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## ABSTRACT

*The processes of metal additive manufacturing (AM) offer advantages over traditional technologies, especially when it comes to producing parts with complex designs. Thanks to the flexibility in manufacturing processes and the relatively high speed of part production, AM technologies can now be found across various industries. A better understanding of the mechanical properties and fatigue behavior of metal parts is crucial for their successful integration in different sectors. Numerous factors play a key role in influencing the fatigue properties of metal parts produced through AM. This study investigates the impact of heat treatment and surface treatment on the fatigue behavior of components made from marginal steel (MS1) and stainless steel (PH1). After subjecting MS1 and PH1 steel to heat treatment, it is expected that the fatigue limits will increase compared to their original state. Additionally, experimental findings show that not only do surface treatments significantly affect fatigue strength when used alone, but also that changing the order of subsequent treatments can either enhance or diminish fatigue strength.*

**Key words**: *fatigue strength, additive manufacturing, maraging steel, stainless steel*

## 1. INTRODUCTION

Additive manufacturing (AM) is a relatively new technology that differs fundamentally from conventional methods by building parts through the addition of material. AM processes add material only where required, constructing parts layer by layer. This approach enables the production of components with highly complex geometric shapes that are difficult or impossible to achieve using traditional methods. The ability to produce such intricate designs makes it possible to optimize the mass and load capacity of parts through methods like lattice structures, topological optimization [1], and bionic optimization [2], which can be easily achieved using AM.

AM encompasses a wide range of technologies and materials, categorized into seven distinct groups. However, due to the diversity of production processes, material types, and the relatively recent emergence of AM, there is insufficient data to comprehensively evaluate the fatigue life of AM-produced parts. Fatigue life refers to the number of stress cycles a material can endure before failure under repeated loading, a crucial consideration in industries where safety and reliability are paramount.

Studies have shown that additive manufacturing (AM) parts often display different fatigue properties compared to those made using traditional methods [3]. The layer-by-layer deposition process in AM can create microstructural defects and anisotropy, which may negatively impact the

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material's fatigue performance [4]. Such factors can result in early fatigue failure, posing risks to part reliability.

It is essential for engineers and designers to understand the fatigue behavior of AM parts. Without this critical insight, components could fail prematurely, leading to safety concerns, significant repair costs, and liability issues.

This paper investigates metal parts produced using Direct Metal Laser Sintering (DMLS) and evaluates the role of post-processing techniques like shot-peening, heat treatment, and machining in modifying the fatigue behavior of steel components. DMLS, also known as Selective Laser Melting (SLM), is a powder bed fusion (PBF) technology, where the metal parts are produced in layers. Each layer of the part is created by melting of the metal powder by laser beam, which is guided by digital CAD file. After printing a layer, new layer of powder is spread over previous layer and the process is repeated.

This paper is part of the research conducted under the Horizon 2020 project "Advanced Design Rules for Optimal Dynamic Properties of Additive Manufacturing Products - A_MADAM." The project systematically examines the fatigue behavior of steel components fabricated using Laser Powder Bed Fusion (LPBF) technology. Its primary objective is to establish design guidelines that maximize the fatigue performance of LPBF-manufactured parts.

## 2. MATERIAL AND SPECIMEN

The testing was conducted in accordance with the ISO 1143 standard [5], which specifies the geometry of test specimens and the procedures for conducting rotational bending fatigue tests. According to the standard, the test specimens are designed as cylindrical test tubes, with a gauge diameter of 6 mm and an end diameter of 10 mm. A detailed drawing of the specimen, including all specified dimensions and tolerances, is provided in Fig. 1.

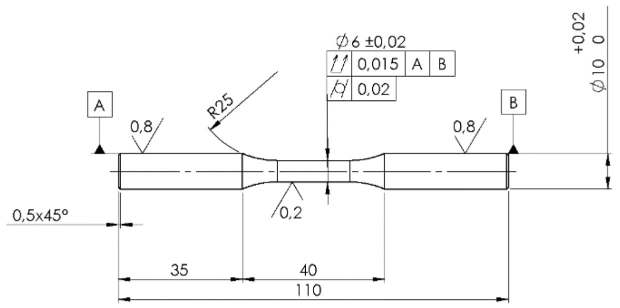


**Fig. 1.** *Specimen with 6 mm diameter at gage in agreement with ISO 1143 standard [5]*

The specimens were manufactured by LPBF machine EOSINT M280 equipped with Ytterbium fibre laser with 200 W power and emitting 0.1 mm thickness and 1064 mm wavelength infrared light beam. The process takes place in an inert environment, without Oxygen, and the scanning speed may range up to 7000 mm/s. The production chamber machine has a horizontal baseplate with dimensions 250×250 mm, and is capable to produce part up to 325 mm of height.

It should be noted that the specimens in this study were tested in their "as-built" state, deviating from the ISO standard specifically in terms of surface roughness. This approach was taken to explore the effects of various parameters on fatigue performance.

The specimens were made from two types of material: maraging steel (MS1) – equivalent to DIN 1.2709 shown in Fig.2.a, and stainless steel (PH1) – equivalent to DIN 1.4540 shown in Fig.2.b [6].

To ensure the results of this research are applicable to all users of LPBF technology, the process parameters were chosen based on the recommendations provided by the material manufacturer. Specifically, the layer thickness was set to 20 µm for stainless steel (PH1) using the EOS "Surface" parameter set and 40 µm for maraging steel (MS1) using the EOS "Performance" parameter set. A parallel scan strategy with alternating scan direction was employed. To minimize or mitigate in-plane property variations, the scanning direction was rotated by approximately 70° between successive layers [7].

a) MS1

b) PH1

**Fig. 2.** *Orientation of the samples in the EOS M270*

Five set of specimens from maraging steel MS1 were produced. Four sets of stainless steel PH1 specimens were made. Each set, MS1 and PH1 had 10 specimens.

**Table 1.** *Specimens postprocessing methods for fatigue testing*

| Material | Specimens postprocessing methods | | | | |
|---|---|---|---|---|---|
| MS1 | P | PH | PM | PHM | MP |
| PH1 | P | PH | | PHM | HMP |

In order to evaluate the effects of shot peening, heat treatment, and machining, each set was subjected to a specific treatment. In cases where multiple post-processing treatments were applied, their sequence is denoted by letters in the set name, as shown in Table 1. "P" refers to shot peening, "H" to heat treatment, and "M" to machining. All samples were treated by micro shot-peening by steel spheres with diameter of 0.7mm, under the 5-bar pressure. The heat treatment of maraging steel specimens was carried out using an age-hardening process at 490°C for 6 hours, resulting in a hardness of approximately 50 HRC. Similarly, stainless steel parts manufactured from PH1 underwent heat treatment at 482°C for 4 hours, achieving a typical hardness of 43 HRC. After cooling in fresh air, the specimens were carefully detached from the building plate using a wire electrical discharge machine to avoid damage. Subsequently, the specimens were machined and refined by grinding to achieve the required surface roughness and dimensional specifications, as well as to enhance fatigue performance.
It is noteworthy that aging not only increased hardness but also enhanced the tensile and yield strength of the specimens. For MS1, the tensile strength improved significantly, from 1100 MPa to 2050 MPa. Similarly, PH1 specimens experienced a rise in tensile strength from 1200 MPa to 1350 MPa [6]. These mechanical property enhancements demonstrate the effectiveness of the heat treatment and post-processing steps in preparing the materials for advanced engineering applications.

## 3. Test procedure

To ensure the reliability and durability of the produced samples, comprehensive fatigue testing and analysis were conducted. This process involved subjecting the parts to cyclic loading conditions that replicate real-world operating scenarios and evaluating their performance over time.
The fatigue campaign enabled the determination of S-N curves and fatigue limits. A staircase method was employed to estimate fatigue life, using a series of failure and non-failure events analyzed via the Dixon method [8]. For this purpose, a life duration of $10^7$ 1 cycles was defined as the run-out limit. The Dixon method, a simplified version of the staircase approach, allows for the estimation of fatigue life based on a limited number of trials (four to ten in this study).The results in the finite life domain were analysed according to the Standard ISO 12107 standard [9]. The staircase method was then used to determine the fatigue limit of the specimens.

The specimens were tested under rotating bending fatigue using a rotary bending testing machine. The machine applied a four-point bending configuration, ensuring a constant bending moment along the entire length of the specimen, particularly at its gauge section. The sample was pinched at its ends by a pressure of approximately 70 MPa [11]. All the tests were conducted under fully reversed bending load (stress ratio R =-1) at the frequency f of 60 Hz.

## 4. Results and discussion

During the testing campaign, some samples exceeded the run-out limit of $10^7$ cycles. These specimens were excluded from the analysis used to develop the S-N curves. Furthermore, samples that fractured at the head section during testing were not considered in the determination of the S-N curves. Based on the archived results of testing a S-N curves for MS1, shown in the Fig 3, and SN curves for specimens from PH1, shown in Fig4, were created.

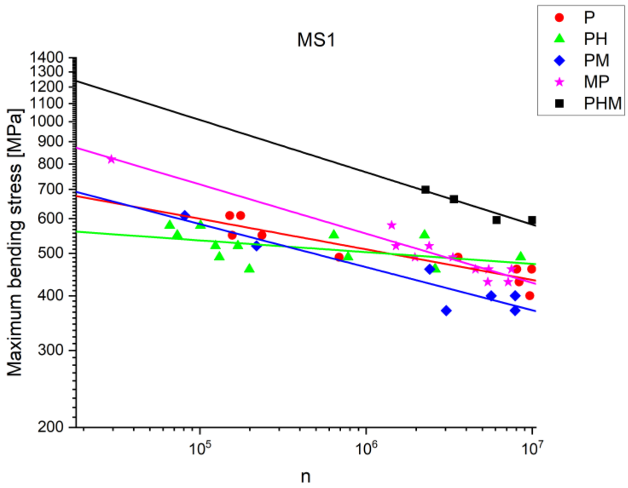


***Fig. 3.*** *S-N curves in the finite life domain for specimens made from MS1*

Analyzing the samples produced from MS1 material, it can be observed that the lowest position on the S-N curve corresponds to specimens subjected first to shot peening and then to machining, as indicated by the blue squares in Fig. 3. This behavior can be attributed to the introduction of additional surface irregularities during machining, which act as initiation points for cracks.
The S-N curve for specimens where machining was applied first, followed by shot peening, is slightly higher than the previous set, as shown by the violet stars and line in Fig. 3. Specimens treated only with shot peening exhibit an S-N curve at the same level as the previous set, but with a lower slope, indicating reduced fatigue performance at higher stress levels.
The highest position on the S-N curve corresponds to the sample set treated with three procedures in the following order: shot peening, aging (heat treatment), and finally machining. This sequence of treatments also yielded the highest fatigue limit among the tested samples.

The P, MP, PM and PH sets have fatigue limit ranging from 400 MPa to 550 MPa. The PHM set has fatigue limit of about 650 MPa.

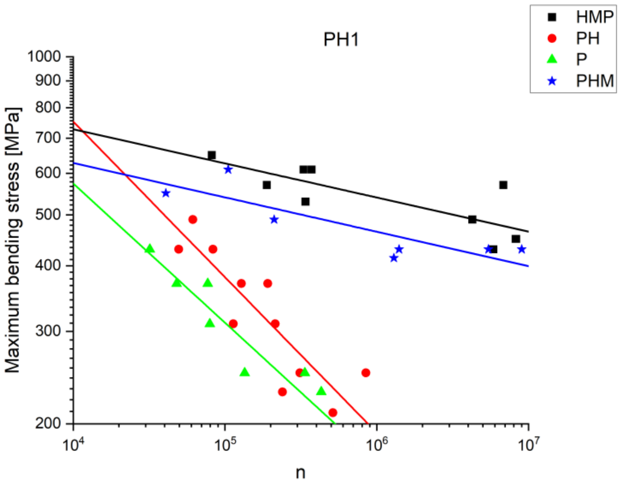


***Fig. 4.*** *S-N curves in the finite life domain for specimens made from PH1*

From Fig. 4, it can be seen that PH1 sets without machining exhibit a steep slope and relatively low fatigue limits. The lowest S-N curve corresponds to the set where only shot peening was applied, denoted by green triangles. When heat treatment was applied to these samples, as shown by the red dots in Fig. 4, the slope of the S-N curve remained unchanged, but the curve shifted to higher fatigue values compared to the shot-peened-only samples. However, when heat treatment was applied after shot peening, the S-N curve not only shifted to higher values but also exhibited a change in slope, indicating improved fatigue performance at higher stress levels. For the set subjected to heat treatment, Fig. 4 shows that the order of postprocessing operations significantly influences the S-N curves and fatigue limits.

The highest S-N curve describes the set where the samples were first subjected to heat-treatment, after that machining and at the end to shot-peening, denoted with black squares in the Fig 4. This can be explained that shot-peening closes the irregularities which are brought to the surface after machining. The shot-peening applied at the end of the post-processing treatment can decrease the surface quality, bat this is very small change compared to the benefit on the fatigue limit of the samples.

## 5. Conclusions

The fatigue life of AM parts is critical for ensuring the reliability and safety of components used in various industries. By understanding the factors influencing fatigue life, implementing methods to improve durability, and utilizing experimental approaches to assess performance, manufacturers can optimize AM part design and production for enhanced longevity and performance.

Improving the fatigue life of additive manufacturing (AM) parts can be achieved through various strategies, including enhancing surface quality via post-processing techniques or additional surface treatments, applying heat treatment, selecting appropriate materials, optimizing manufacturing parameters, and designing parts specifically for AM processes.

Post-processing techniques such as Isotropic Super-Finishing (ISF) can significantly improve the fatigue life of metal AM parts by reducing surface roughness, which in turn enhances their fatigue resistance. Other methods, including heat treatment, hot isotropic pressing, laser shock peening, ultrasonic nanocrystal surface modification, and advanced finishing and machining, also contribute to better fatigue performance.

Surface treatments like abrasive polishing, laser re-melting, and nickel plating improve surface finish and reduce porosity, which are key factors in enhancing fatigue performance. Additionally, optimizing build orientation, layer thickness, and scanning strategies during the AM process can help minimize defects and residual stresses, ultimately improving fatigue properties.

Choosing the right material for the application and ensuring high-quality feedstock powder are also crucial in enhancing fatigue life. Incorporating design features that reduce stress concentrations, such as fillets and rounded corners, helps distribute loads more evenly, further improving fatigue resistance.

This paper presents an experimental investigation into the influence of post-processing techniques on the dynamic behavior of parts produced from maraging steel (MS1) and stainless steel (PH1) through additive manufacturing. The results indicate that heat treatment and machining significantly impact fatigue life and fatigue limit. Moreover, the order in which post-processing techniques are applied can affect the fatigue limit.

Continued research and development are essential to further advancing the capabilities and applications of additive manufacturing technology.

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## NOTE

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