The Influence of Process Parameters on the Low-Cycle Fatigue Properties of 316L Steel Parts Produced by Powder Bed Fusion

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In this paper, the influence of the additive manufacturing (AM), powder bed fusion (PBF) process parameters on the low-cycle fatigue (LCF) properties of 316L steel samples is shown. Based on the previous research, five parameter groups were selected. To make this analysis broader, research results of AM parts have been compared to the conventionally made counterparts. Such an approach allowed analyzing the manner different parameters affect the tensile and LCF behavior. The preliminary tests indicated that AM specimens are characterized by 65 pct of the total LCF strength in comparison to the conventionally made material. Further LCF tests indicated differences in the dissipated energy of some samples, which was visible in the hysteresis loops generated during testing in the total strain amplitude range from 0.30 to 0.45 pct. Based on the Morrow approach, it was possible to register an increased share of the plastic component during the fracture process in the Additive Manufacturing (AM) parts in the LCF tests with the total strain amplitude above 0.45 pct. The final microscopical investigation of parts’ fractures surfaces indicated the influence of the layered structure, and internal imperfections (such as unmelted powder particles and lack of fusion) of the as-built AM parts on the cracking process, which caused an increased number of multiplanar cracks and generation of the complex fracture morphology characterized by the layered structure of AM parts and share of imperfections—mostly porosity caused by unmelted powder particles which potentially was a base of secondary stage cracks.

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1. INTRODUCTION

A still increasing amount of the research results related to the AM metallic parts often indicates better mechanical properties of parts obtained by AM in comparison to the conventionally manufactured counterparts.[1–3] Nowadays, it is well known that despite such good research results on the mechanical properties of the AM parts, anisotropy plays an important role in the performance properties, which is especially important in some industrial applications.[4,5] From the point of view of fatigue properties, it is very important to take into account some technologically based issues, such as porosity,[6,7] the increased surface roughness of the as-build parts,[8,9] residual stresses,[10,11] or the influence of build orientation during the process.[12,13] The phenomenon related to the occurrence of lower fatigue strength of AM parts could be compensated by adjusting the geometry of the parts to the so-called “Design for Additive Manufacturing.”[14,15] Additionally, it is possible to affect (within a certain range) the process parameters which could significantly improve the fatigue performance of the AM parts.

Products obtained through PBF technologies are characterized by the specific microstructure and may also contain defects mentioned above. This is especially significant in the case of a part’s operation in a range of LCF conditions. The presence of such defects especially in the “near the external surface” area is very deleterious, due to the notch effect.[16,17] Such fracture mechanisms are especially important in the LCF of materials characterized by increased strain (316L steel). Andreau et al.[18] indicated in their research that surface pores...
with threshold root areas (around 20 μm below the surface) are far more deleterious in comparison to the pores placed in some deeper volume (200 μm below the surface).

In the case of the research conducted by Sausto et al.,\textsuperscript{[19]} crack propagation speed reduction was visible because of the occurrence of the vertical ramifications, which led to the increasing of fatigue strength. Such a statement could be treated as valid only in the case of single defects. If there is some porous agglomeration or share of unmelted grains—there is a need to use the Murakami approach—that statement has been justified in the work by Liang et al.\textsuperscript{[20]} The authors found that multiple clustering defects act synergistically as one large defect, which easily initiates fatigue cracking. Another very important issue has been taken into account by Merot et al.,\textsuperscript{[21]} where the authors indicated that corrosion pits affect the fatigue strength of the material, and there is no specific influence of defect morphology (regardless of its type) on the crack initiation phenomenon. It is also very crucial to take into account geometrical features which certainly affect the notch sharpness, and degree of multiaxiality—such an approach has been tested by Wang et al.\textsuperscript{[22]} Based on a literature review related to the fatigue of AM materials, there are several visible factors that significantly affect the fatigue properties. Of course, there are some research studies related to heat treatment\textsuperscript{[16,23,24]} or surface treatment.\textsuperscript{[25–27]} Also, the authors of this paper performed research related to the influence of heat treatment on LCF properties.\textsuperscript{[28]} It has to be taken into account that heat treatment significantly changes the microstructure of the AM parts which changes the fracture mechanisms. That is why it is very important to characterize the as-built AM samples in different fatigue conditions—especially under LCF conditions, because of the existence of the significant research gap in such a field.

In connection with the possibility of modifying the process parameters of the Selective Laser Melting (SLM) process, it is reasonable to test different factors that influence the LCF properties of 316L steel samples. To better understand the fracture mechanisms, such analysis should be extended with fractographic description. Such an approach has been suggested in this paper—five different process parameter groups are considered to detect some differences in the LCF behavior of the SLMed 316L stainless steel.

II. EXPERIMENTAL

A. Material

The powder used for all manufactured samples was bought commercially, as a material dedicated for Laser Powder Bed Fusion (L-PBF)—atomized in argon atmosphere, with grain diameter in a range of 20 to 63 μm, density equal to 7.92 g/cm\(^3\), and flowability on the level of 14.6 s/50 g. Scanning electron microscope (SEM) analysis of the material is depicted in Figure 1, and its chemical composition is shown in Table I.

![Fig. 1—SEM image of 316L powder grains captured in 100 μm scale.](image)

| Table I. 316L Steel Chemical Composition |
|------------------------------------------|
| Element (Wt Pct) | 316L Stainless Steel |
|------------------|---------------------|
| Fe               | balanced            |
| C                | 0.027               |
| Cr               | 17.8                |
| Cu               | 0.02                |
| Mn               | 0.98                |
| Mo               | 2.31                |
| Ni               | 0.09                |
| Cr               | 12.8                |
| O                | 0.02                |
| P                | 0.011               |
| S                | 0.004               |
| Si               | 0.72                |

The powder grains are characterized by mostly spherical shapes, but there are also some satellites visible. Such deformations and a small number of satellites are related to reusing the same powder after the process, which is allowed in such manufacturing processes as SLM.

B. Manufacturing Process Description

The geometry of samples dedicated to the fatigue analysis (shown in Figure 2) was designed in the SolidWorks 2021 software, based on ASTM E466-21 standard. The dimensions of samples were selected in a way to fit their total length to the SLM 125HL device.

Process parameters were selected based on our own previous research.\textsuperscript{[29]} Those analyses were based on the process parameters modification in a small range equal
to 10 pct above, and below the default value, with some exceptions taken from the literature. The mentioned modifications included the following factors: laser power, laser exposure velocity, and hatching distance. Based on a broad group from the preliminarily determined parameters, the five most significant groups were chosen. The parameters’ values are specified as follows: (1) “S_15”—parameters group with increased hatching distance but surprisingly low porosity (the lowest in all samples with increased hatching distance factor), (2) “S_17”—parameters group with registered highest porosity reached during the manufacturing process with the lowest energy density from all tested parameters groups. It was also discovered that the lowest microhardness in samples was made using that group of parameters, (3) “S_27”—process parameters composition which allowed obtaining the highest microhardness values, (4) “S_30”—parameters group characterized by the highest value of energy density, based on the research.

The list of process parameters was kept with the same samples’ descriptions as it was in our own preliminary research to clarify the research results interpretation. All samples from the specified parameters set were manufactured during a single process (S_01 samples are shown in Figure 3) to assure repeatability of the material properties in each samples group. For each parameter set, five samples were tested during tensile testing. All manufacturing processes were performed in an argon atmosphere with an oxygen content lower than 0.1 pct. All samples were oriented horizontally. That orientation assured the highest possible strength and elongation of the additively manufactured elements. After SLM processing, the samples were cut out of the substrate plate using a Wire Electric Discharge Machining (WEDM). Additionally, a sidewall of each sample was milled. The Sidewalls’ sharp edges were roll-burnished to minimize the possibility of stress raisers in that area during LCF testing.

C. Tensile Testing

To allow determination of the basic values for LCF testing, the previously prepared static tension diagram from own research was used (Figure 4). P_1 course is a test result for samples made of conventionally manufactured 316L steel (made of commercially bought cold-rolled metal sheets). To be consistent with the AM process—P_1 samples were cut out from the metal sheet in such a way that is was possible to keep the rolling direction similar to the layers deposition in the AM parts. Tensile test results (Figure 5) indicated a 40 pct decrease in total strain and a 16 pct decrease in ultimate tensile strength in the case of S_17 specimens. Such phenomenon was caused by a 20 pct reduction of energy density, in comparison to S_01 parts, produced with the use of default settings for 316L steel. The highest strain (47.1 pct) was registered for S_15 specimens, which is 75 pct of total strain value registered for conventionally made (P_1) material.
Fig. 4—Stress–strain curves for S_01, S_15, S_17, S_27, and S_30 AM samples and a conventionally produced specimen (P_1). Reprinted from Ref. [6], under the terms of the Creative Commons CC BY license.

Fig. 5—Comparison of tensile test results of AM S_01, S_15, S_17, S_27, and S_30 samples compared to conventionally produced parts (P_1).

Table II. Process Parameters Groups Used for Sample Manufacturing

| Parameters Set | Laser Power $L_P$ (W) | Exposure Velocity $e_v$ (mm/s) | Hatching Distance $h_d$ (mm) | Energy Density $q_E$ (J/mm$^3$) |
|----------------|------------------------|--------------------------------|-------------------------------|---------------------------------|
| S_01           | 190                    | 900                            | 0.12                          | 58.6                            |
| S_15           | 200                    | 810                            | 0.13                          | 63.3                            |
| S_17           | 180                    | 990                            | 0.13                          | 46.6                            |
| S_27           | 180                    | 810                            | 0.11                          | 67.3                            |
| S_30           | 120                    | 300                            | 0.08                          | 167                             |
Fig. 6—The variations of the stress amplitude $\sigma_a$, and plastic strain amplitude $\varepsilon_a$ charts with a load loop number.
D. LCF Testing Description

The LCF tests were performed with the use of an Instron 8802 servohydraulic testing system, equipped with Instron 2620 to 603 dynamic extensometer with a 25-mm-long gauge. During LCF testing, five levels of total strain amplitude: $\varepsilon_{\text{ac}} = 0.30; 0.35; 0.40; 0.45; \text{and } 0.50\%$ were used; for each strain, level three samples were tested. As it was in the case of tensile testing,[6] also conventionally made samples (described as P1 samples) were considered during LCF analysis to allow extended discussion of the obtained results. The LCF analysis was handled for all AM samples groups shown in Table II—S_01, S_15, S_17, S_27, and S_30. The primary LCF properties were determined with the use of the characteristic parameters of the hysteresis loops obtained at the following conditions (1):

$$\frac{N}{N_f} = 0.5, \quad [1]$$
Fig. 7—Mid-life hysteresis loop of AM and conventionally made samples registered for total strain amplitudes $\varepsilon_{ac} = 0.30$, 0.35, 0.40, 0.45, and 0.50 pct.
Fig. 8—Stabilized hysteresis loops of AM and conventionally made samples registered for representative total strain amplitudes $\varepsilon_{ac} = 0.30$ and 0.50 pct for all tested AM and conventionally made specimens (rows a to f).
where $N$—current number of cycles, $N_f$—number of cycles to failure.

An occurrence of the crack was adopted as a fracture criterion; detection of the crack was selected as a “cut-off signal” for the testing machine. To properly describe the LCF fracture mechanisms, the fracture surfaces were analyzed using a JEOL JSM-6610 SEM.

### III. RESULTS AND DISCUSSION

#### A. LCF Properties Analysis

The characteristics of the material’s behavior under conditions of variable loading during LCF are significantly important because such phenomena are responsible for local defect generation as microcracks or

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Fig. 8—continued.

(d) $S_27$

(e) $S_30$

(f) $P_1$
structural notches. That kind of issue in the material volume causes fatigue cracking initiation, and further fracture of the whole part or construction. In the case of the SLM-ed parts, the LCF analysis is significantly important because of specific internal defects caused by different factors, such as powder imperfections, lack of powder particles fusion, unreliable gas flow in the machine chamber, etc. Such phenomena could directly affect the LCF properties of manufactured parts. At the same time, generation of those phenomena could be limited by process parameter corrections. That is why at the first step of the conducted research, the stress amplitude $\sigma$ and plastic strain amplitude $\epsilon$ charts with a load loop number were made (Figure 6). All AM samples (S_01, S_15, S_17, S_27, and S_30) were compared with parts (P_1) made in a conventional manner.

Based on the obtained results, depicted in Figure 6, significant strain amplitude changes in the whole range of load loops number are visible. Such fluctuations prove AM 316L steel’s tendency to cyclically soften at the whole load loops range. In the case of conventionally made samples, the cyclic softening stage is transient and is strictly dependent on the total strain amplitude (from 8 pct for lower $\epsilon_{ac}$ values to 90 pct for $\epsilon_{ac} = 0.50$ pct).

Further course of the stress amplitude $\sigma$ and plastic strain amplitude $\epsilon$ curves testifies to the cyclical stabilization of both material types (AM, and conventionally made). The highest LCF properties in the case of AM were registered for S_01 and S_30 samples (about 6000 cycles), and the lowest for S_17 samples (about 1200 cycles). This gives 65 pct of the total LCF strength of P_1 samples in the case of S_01 and S_17 samples and 15 pct in the case of the S_17 samples.

The mid-life hysteresis loop analysis was the second step in the LCF analysis (Figure 7), which allows registering increased stress levels for S_01 samples in the total strain amplitude range from 0.30 to 0.45 pct. In the case of almost all AM samples, very similar hysteresis loop courses could be observed for the total strain amplitude equal to 0.50 pct.

Comparing AM and conventionally made samples, lower strain values for exact total strain amplitude are visible. Some differences are also visible in the hysteresis
be described with the following Eq. [2]:

\[ \log \sigma_a = \log K' + n' \log \varepsilon_{ap}, \]

where, \( \sigma_a \)—fatigue strength coefficient (MPa), \( \varepsilon_{ap} \)—fatigue ductility coefficient, \( K' \)—cyclic strength coefficient, \( n' \)—cyclic strain hardening exponent. The obtained results in a form of the chart with the double-logarithmic scale are shown in Figure 9.

For each tested samples, group Eq. [2] has the following form:

\[ \log \sigma_{aS_0} = \log 754.4 + 0.101 \log (\varepsilon_{ap}) \]
\[ \log \sigma_{aS_1} = \log 543.3 + 0.07 \log (\varepsilon_{ap}); \]
\[ \log \sigma_{aS_2} = \log 631.7 + 0.09 \log (\varepsilon_{ap}); \]
\[ \log \sigma_{aS_0} = \log 554.3 + 0.07 \log (\varepsilon_{ap}); \]
\[ \log \sigma_{aS_0} = \log 562.1 + 0.07 \log (\varepsilon_{ap}); \]
\[ \log \sigma_{aP_1} = \log 656.5 + 0.14 \log (\varepsilon_{ap}); \]

Further analyses were made based on the Morrow Eq. [3]:

\[ \varepsilon_{ac} = \varepsilon_{ae} + \varepsilon_{ap} = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon_f (2N_f)^c, \]

where \( \varepsilon_{ac} \) is total strain amplitude, \( \varepsilon_{ae} \) is elastic strain amplitude, \( \varepsilon_{ap} \) is plastic strain amplitude, \( E \) is Young’s modulus, \( \sigma_f \) is fatigue strength coefficient, \( \varepsilon_f \) is fatigue ductility coefficient, \( b \) is fatigue strength exponent, and \( c \) is fatigue ductility exponent.

Equation [3] allows for the preparation of LCF charts in the strain terms for all tested samples (S_01, S_15, S_17, S_27, and S_30) and made in a conventional manner (P_1) (Figure 9). Depicted curve courses indicate domination of the share of the plastic component during the samples’ fracture process below \( \varepsilon_{ac} = 0.45 \) pct. The highest values of \( \sigma_f \) and \( \varepsilon_f \) factors were registered for the S_17 samples. In this case, the line’s inclination angle, which is dedicated for the \( \varepsilon_{ap} \) plastic component in comparison to the \( \varepsilon_{ae} \) elastic component line is the biggest. Such a phenomenon indicates the highest expected share of the plastic component in the total strain amplitude, which is visible in Figure 10(c).

At the same time, the smallest share of the plastic component in the total strain amplitude was registered for the S_27 samples (Figure 10(d)).

Different LCF behavior of the AM parts produced with five process parameters groups could be related to different residual stresses level. That kind of phenomenon is typical for AM processes.\[9,10,32\] In the case of the S_01, S_17, and S_30 samples, residual stresses have been measured as a part of other research works.\[6,33\] Measured residual stresses for AM samples are shown in Figure 11.

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Fig. 10—continued.

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It can be observed that low values of energy density (i.e., S_17 samples) increase the share of compressive stresses. From the fatigue properties point of view, such phenomenon has a positive influence on the LCF behavior, but only in the case of uniform distribution of the residual stresses level in the whole part. In the case of AM parts, the residual stresses level is strictly related to the manufactured part geometry.\cite{34,35}

Characteristic features of LCF behavior were determined with the microfractographical analysis of the fracture surfaces images. Microscopic images observations were made for the samples’ surfaces subjected to test with total strain amplitudes equal to 0.30 and 0.50 pct. Detailed images of fracture surfaces taken from all AM samples and also from the conventionally made sample are shown in Figure 12. Column “a” in Figure 12 shows the whole fracture surface. White arrows indicate the direction of fracture propagation, from the crack initiation spot. Selected areas with higher magnification are illustrated in column “b” in Figure 12.

All fractures of both groups—AM and conventionally made are characterized by plastic fracture behavior with clearly visible fatigue striations. It is worth highlighting that conventionally made P_1 sample’s fracture surfaces have a significantly less complex morphology. A layered structure of the AM samples significantly affected the occurrence of shattered structure and multiplanar cracking behavior. When comparing only AM samples fractures, a less complex fracture surface is visible in the case of the S_30 sample. It is a result of the high energy used during the manufacturing of those samples, which caused a kind of homogenization annealing. On the fracture images of the S_17 samples, a significant number of unmelted powder particles and numerous pores are visible. Such a big amount of defects in the volume of the S_17 sample caused local stress damping.

That kind of phenomenon allowed the occurrence of small microcrack initiation which pass through the unmelted powder particles boundaries, which potentially was a base of secondary stage cracks. That kind of phenomenon is shown in Figure 13.

Additionally, in the case of S_17 samples, local crack sources were observed not only in the external surface, but also in the internal volume. Such a phenomenon is compliant with the issue described by Liang et al.\cite{18} where authors found that multiple clustering defects act synergistically as one large defect, which easily initiates fatigue cracking; such behavior is called a Murakami approach.

**IV. SUMMARY AND CONCLUSIONS**

The technological meaning of AM has a significant potential because of the ability to change performance properties of the obtained parts (i.e., mechanical and fatigue properties). It allows producing parts characterized by unique properties, which could be shaped in some exact range. Results obtained in this research provide new knowledge about the influence of process parameters on LCF properties. Using higher values of energy density (167 J/mm\(^2\)—S_30 samples) than the default values for 316L steel (58.6 J/mm\(^2\)—S_01 samples) allows making the fracture process of AM parts similar to the conventionally made counterparts. Based on conducted research, the following conclusions could be drawn:

1. Modification of the SLM process parameters affects the porosity of the manufactured parts, which strictly influences the LCF of those parts.
2. Values of different process parameters affect the amount of dissipated energy of the samples subjected to LCF tests. The main differences are visible in the hysteresis loops generated during testing in the total strain amplitude range from 0.30 to 0.45 pct.
3. Based on the Morrow approach, an increased share of the plastic component during the fracture process in AM parts during LCF tests with total strain amplitude above 0.45 pct was registered.
4. The microfractographical analyses indicated a more complex morphology of the AM parts fractures in comparison to the conventionally made counterparts. A visible layered structure of the as-built AM parts affected the LCF cracking process, which caused an increased number of multiplanar cracks.
Fig. 12—Fracture images of the LCF tested samples.
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CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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