17-4 PH SS Manufactured via Selective Laser Melting: High Cycle Fatigue Properties

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Abstract. In the recent years, Additive Manufacturing (AM) is becoming an emerging technology and more and more material powders are available on the market. The knowledge of their specific mechanical behaviour is a fundamental aspect for their large-scale adoption, also considering the lack of reliable data and dedicated standards. In this work the High Cycle Fatigue characterization of a 17-4 PH Stainless Steel (SS) is presented. The cylindrical samples used were manufactured via Selective Laser Melting (SLM) technology using an EOS M280 machine. Two separate series of samples differing in terms of surface finishing were tested. The first series of samples was used in the as-build condition while the second series was machined in order to obtain a better surface finishing. The effect of the surface finishing on the fatigue behaviour of AM materials is fundamental considering that in most of the applications the parts – reticular or lattice structures with complex geometries – are set into operation in the as-build condition because a surface finishing is not feasible. The comparison of the results obtained for the two different series of specimens allows the quantification of the reduction of the mechanical performances due to the actual limits of the SLM technology. The fatigue limit was obtained with the short stair-case approach according to the Dixon statistical method. The maximum number of cycles (run-out) was set equal to 500000. The left part of the Wöhler diagram was also studied by means of additional tests at higher stress levels. Additional quasi-static tests were performed in order to characterise the static behaviour.

1. Introduction
Laser sintered 17-4 PH SS, is a material with a very good corrosion resistance and high strength guaranteed by its martensitic structure [1]. The high strength is due to the precipitation of fine Cu-rich face centred cubic phase. A dendritic structure with body centred cubic martensite and about 50% of reserved austenite is favoured by the SLM process. According to [2], the mechanical properties of additive manufactured materials are comparable with those produced with classic technologies. Additive Manufacturing (AM) is characterized by high solidification speeds, leading to a metastable austenite phase in the matrix. For this reason, this material is generally hardened. Nevertheless, in literature are present several works in which this type of material shows a low fatigue resistance. Internal and surface defects like porosities, inclusions and a high roughness in the as-build condition, can act as crack nucleation sites [3]–[5].

For this reason, in addition to a first series of as-build samples which surface roughness is the one that can be obtained with the SLM process, a second series of samples was produced with the same technology and successively machined.
Tests were performed on both series of samples in order to understand the harmful effect of the low surface quality achievable with SLM. This comparison is particularly significant considering that the AM technologies are suitable for producing complex geometries such as reticular or lattice structures, that cannot be successively surface finished.

2. Chemical composition and microstructure

The chemical composition of 17-4 PH SS is shown in Table 1. The particles of the powder have a mean size of 44.454 µm. Chromium interacts with Carbon, forming chromium carbides along grains [6].

|   | C  | Si | Mn | P  | S  | Cr | Ni | Mo |
|---|----|----|----|----|----|----|----|----|
|   | 0.036 | 0.78 | 0.33 | 0.009 | 0.004 | 16.2 | 4.02 | 0.002 |
| Co | 0.012 | 0.018 | 0.002 | 0.372 | 0.009 | 0.004 | 0.001 | 0.29 |

In order to prevent the creation of Cr$_2$C$_6$ and to increase strength, Niobium is used. It promotes the formation of NbC. Silicon decreases the mechanical properties promoting the formation of ferrite, but it is useful for fluidizing the material during the casting. To compensate this effect, Chromium and Nickel are used. They reduce the formation of ferrite in favour of austenite. Nickel and Manganese are helpful to avoid the formation of Cr$_2$C$_6$ and FeS phases respectively, forming Cr$_2$N and MnS instead. Cuprum helps increasing the total strength of the material forming precipitates.

Despite the chemical analysis, Scanning Electron Microscopy (SEM) measurements have been made to better characterize the size of the defects that was found to be up to 100 µm.

![SEM analysis of the fracture surface](image)

3. Experimental tests

High-cycle-fatigue (HCF) tests were performed on cylindrical samples (Figure 1) having a geometry according to the ASTM E466 standard [7]. The apparatus used for testing is a STEPLab-UD04 fatigue testing machine capable to apply up to 5 kN at maximum frequency of 35 Hz already used for the Low-Cycle-Fatigue characterization of the same material [8].
In addition to the HCF tests, a quasi-static tensile characterization was performed. The geometry of the adopted samples is shown in Figure 2. Tensile tests were performed at room temperature with a crosshead speed set to 0.1 mm/min.

The tested samples present the typical cone-cup shaped fracture surface (ductile failure). Plastic deformation was also confirmed by the presence of a fibrous and irregular surface (necking region). The Quasi-Static (QS) stress-strain curve is shown in figure 3.

According to the test results, the yielding point was found to be $\sigma_Y = 570 \text{MPa} \ (\varepsilon = 0.2\%)$. This data has been used for defining the left part of the Wöhler ($S-n$) diagram.

HFC tests were performed according to the ASTM E466 standard [7].

The fatigue limit $\sigma_f$ was calculated with the short stair-case approach [9]–[12] on samples having the geometry shown in figure 2 (right).
Several tests at different load levels were performed. The stair-case method prescribes to define a force increment $\Delta F$ (that is directly related to the accuracy of the results that can be achieved). The actual $\Delta F$ was equal to 50 N corresponding to a stress interval $\Delta \sigma$ equal to 10 MPa.

If the initial test, performed at a force level $F_i$, reaches the run-out condition (5000000 cycles without breaking), the next test has to be performed on a force level increased by $\Delta F$ i.e. $F_{i+1} = F_i + \Delta F$.

Otherwise, if the specimen broke, the next force level must be decreased by $\Delta F$ i.e. $F_{i+1} = F_i - \Delta F$.

Figures 4 and 5 show the short stair-case sequences (6 tests) for the two series of samples, as-build and machined.

**Figure 4.** Short stair-case sequences for the as-build and for the machined samples
The number of tested specimens was, for both series of samples, below 15 as suggested by the standards. Therefore the Dixon statistical approach was used [13]. This approach allows the calculation of the fatigue limit taking into consideration a number of tests between 2 and 7. Statistical significance of the results is ensured by the correction coefficients.

![As-build vs Machined](image)

**Figure 5.** S-N curve and comparison of as-build and machined fatigue properties

According to the Dixon approach, the sequence order of runouts (O) – failures (X) is also considered. The fatigue limit can be calculated by means of the following relation

\[ \sigma_F = x_f + k \cdot \Delta \sigma \]  \hspace{1cm} (1)

in which \( \sigma_F \) is the fatigue limit at a 50% probability, \( x_f \) is the stress level of the last test (ID=6 with reference to figure 4) and \( k \) a coefficient depending on the sequence order.

For the as-build testing campaign, the tests order results in O-X-O-X-X-X (\( x_f = 265 \text{ MPa} \)). Having a \( k \) factor equal to 0.661, the fatigue limit results \( \sigma_F = 271 \text{ MPa} \).

For the machined samples, the test order was O-X-O-X-O (\( x_f = 336 \text{ MPa} \)). The Dixon coefficient \( k \) was 0.372 resulting in a fatigue limit equal to \( \sigma_F = 340 \text{ MPa} \).

Additional tests were performed for both the sample groups at higher levels of stress in order to obtain also the left part of the Wöhler diagram.

Figure 4 shows the S-N curve, Run-outs are identified by (○ or □) while failures with (× or ∗). Continuous line refers to the as-build condition, the dashed line to the machined one.
Figure 6. Comparison between the actual S-N curves and the data from literature [14][3][15].

Figure 6 compares the actual results with those obtained by other authors on as-build samples.

4. Conclusions
A 17-4 PH SS was characterized with quasi-static tensile and fatigue tests. The yielding point was found to be 571 MPa and the ultimate strength limit (UTS) at 1027 MPa that is coherent with literature data.

Fatigue tests were performed on as-build as well as machined samples differing in the surface finishing only. The fatigue limit was obtained exploiting the short star-case method and the Dixon’s statistical approach. Fatigue limit results equal to 271 MPa for the as-build samples and 340 MPa for the machined ones. Surface defects act as crack initiation sites reducing the fatigue strength of the material.

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