

# Heat Treatment Effect on the Fatigue Characteristics of Additive Manufactured Stainless Steel 316L

Ashwin Polishetty and Guy Littlefair

**Abstract**—Stainless steel is an age old and popular alloy known for its high corrosion resistance. This paper is an attempt to explore ways to enhance the fatigue characteristics using heat treatment. The additive manufacturing technique used in this paper is based on Selective Laser Melting (SLM). The material used in this paper is SLM Stainless steel 316L. The specimen printed using SLM technique are subjected to low cycle fatigue tests as per the ASTM standards. Out of the twelve printed specimens, two sets for as-built and heat-treated were separated. A set of six was heat-treated at recrystallisation temperature of 700° C for 2 hours and air cooled. Two specimen each for the as-built and heat-treated category were reserved for tensile testing to evaluate the yield strength, ultimate tensile strength and strain. The remaining eight printed specimen of as-built and heat-treated were allotted for fatigue testing (four each of as-built and heat-treated). After tensile tests, fatigue tests were conducted on the specimens at mean stress equals to 75%, 70%, 65% and 60% of tensile strength, keeping stress ratio,  $r = 0.5$  and at frequency of 5 Hz. Number of cycles to failure were obtained for each specimen for similar loading conditions to plot the S-N curve. The paper concludes by making an analogy in the fatigue characteristic of as-built and heat-treated specimen.

**Index Terms**—Fatigue, stainless steel 316L, additive manufacturing, selective laser melting and heat treatment.

## I. INTRODUCTION

Steel is defined as an Iron-Carbon alloy containing varying amounts of carbon from 0.008 to 2.1 %. The variation of carbon concentrations and addition of alloying elements varies the properties of steels drastically [1]. Steels are present in various phases depending on the eutectoid temperature. The physical properties exhibited by steels depend largely on the phases present after the phase transformation. The phases present in steels after heat treatment can be manipulated by addition of alloying elements. The alloying elements shift the phase diagram depending on their weightage. Depending on the microstructural phase, steels are classified as Austenitic Stainless Steel, Ferritic Stainless Steel, Duplex Stainless Steel and Martensitic Stainless Steel [2]. Austenitic Stainless Steel (316L) is a popular choice in design applications because of its high corrosive resistance. The potential areas of application are petroleum, chemical, biomaterial and

automobile industries. The stainless-steel parts are generally produced by conventional methods like casting, forging, or extrusion. Due to the high chromium content, machining is a drawback but new technology such as additive manufacturing has solved the issue to an extent in certain application involving complex shapes and monolithic structures. There are lot of unknowns especially on the fatigue and creep of additive manufactured components.

Though for production of complex parts, they need to be machined or welded, which may cause inter-granular corrosion affecting the mechanical properties of the part [3]. Hence, various new advanced manufacturing technologies are developed. These processes make production of complex parts easier, without affecting the mechanical properties of the material [4], [5]. Additive Manufacturing (AM) technologies can be processed using various scientific process and methods. Such as different layer-wise production processes like 3-D printing, stereo lithography, Selective Laser Sintering (SLS) or Selective Laser Melting (SLM), electron beam melting (EBM), and many more. All the technique of advanced production focus on expanding the areas of application by developing new materials and improving the quality of part by optimizing the material integrity to improve the density, surface quality and the mechanical properties respectively [6]. Some Advanced processes have already attained a maturity, where the parts manufactured are utilized directly in the end application [7].

Selective Laser Melting (SLM), is a type of AM technique, which involves layer by layer manufacturing using a micrometer sized particle powder and laser beam as source of heat to melt and bind the powder [8], [9]. The specimen manufactured is free from the fabrication of materials. A complete 3D model of the specimen is made using CAD software. The model is then divided in various layers of micrometer thickness with the help of a customized AM software [8]. In SLM, the laser performs an essential operation of scanning of the thin layer of the powder which are deposited on the base of the chamber. The process of material forming goes in the same direction of laser beam scanning. Sequentially, elongated lines of molten powder are filled in every cross-section of the part. The quality of the specimen manufactured by SLM method will depend on the layer thickness, powder size, power of the laser beam, scanning speed, hatching, the orientation and build-direction [9]. Hence, SLM manufacturing process is parameter sensitive process. SLM manufactured specimens of 316 stainless steel show high tensile, compression, hardness, and part density as compared to wrought or cast materials, this is because the parts are subjected to high cooling rates during manufacturing process which results for a short grain microstructure.

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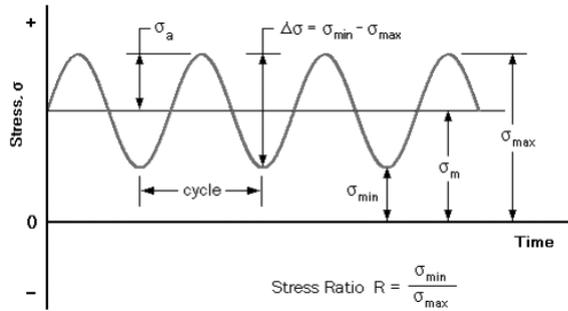


Fig. 1. Fatigue cycle.

Though, they are reported with low fatigue strengths, caused by the defects during production like porosity, inclusions and anisotropy [10]. Fatigue is a limited, dynamic and permanent deformation in a structure which occurs to the materials being subjected to fluctuating or repeated stress and strain cycles. This results in development of crack in the material after a specific number of cycles [11].

Fatigue occurs by the simultaneous actions of repeated, tensile stresses and plastic strain. If any of the above stresses and strain is absent, then initiation and propagation of fatigue crack will not occur. Fatigue crack initiates because of cyclic stress, and tensile stress results in crack propagation [11]. A typical fatigue cycle is shown in fig.1. Unlike other materials, the mechanical properties of the stainless steel can be changed by heat treatment [12]. There are many heat treatment processes like annealing, normalizing, hardening and tempering. It is a combination of simultaneously heating and then cooling the specimen to obtain better mechanical properties such as hardness, toughness, yield strength, tensile strength, etc. (most of the static and dynamic mechanical properties) and a fine grain microstructure of the specimen [13].

#### A. Literature Review

There are various research works carried out on the SLM process especially titanium alloys, mostly on alloy Ti-6Al-4V [14]. The results show that the SLM processed specimens of Ti-6Al-4V alloy can achieve high specific strengths, even in case of repeated loading and crack growth [15], [16]. However, for optimizing properties like ductility, hardness, etc. specific treatments were necessary after the SLM production process. This was due to the defects such as porosity caused during the production process [16]. Similarly, there are research studies conducted on aluminum alloys, steels and nickel alloys focusing on static and dynamic properties, the process of production and microstructure [17]. Even, there are various reports on the properties of alloys produced by SLM and other conventionally manufacturing process [15], [16]. However, the number of papers on processing, surface finish, and the defects occurred during production in SLM 316L stainless steel are very less.

There are results of fatigue strength of SLM 17-4PH stainless steel subjected to repeated bending by Sehrt and Witt in 2010. For better results the specimens were produced in horizontal orientation. However, tensile fatigue tests are more severe than bending fatigue tests [18]. The results of investigation on fatigue performance of SLM 316L and SLM 17-4H stainless steel was published by Spierings and Starr in 2013. The specimens were produced in vertical orientation with Checker board type laser scanning strategy. It stated that

surface quality have a comparable effect in fatigue life [19]. Strain-controlled testing of notched specimens was not studied. The investigation conducted on SLM 304 stainless steel by Guan and Wang in 2013 stated that the mechanical properties increases with increasing interval of layers.

The specimens were produced in vertical orientation [20]. Riemer and Leuders (2014) in their work on SLM 316L stainless steel stated that there is no significant effect of heat treatment on monotonic properties of the specimen [21]. The specimen used were standard compact tension fatigue testing specimen. Increase in ductility were reported in both the specimens. The tests were conducted on Universal Testing Machine. However, SLM 316L stainless steel showed similar fatigue properties to conventionally manufactured material in their as-built conditions. Even, Fatigue behavior of SLM 17-4PH and conventionally manufactured 17-4 PH were studied and compared. Rotating bending tests were performed on the specimens by Akita and Uemastu in 2016. It was noted that due to lower hardness, SLM 17-4PH exhibited lower fatigue strengths [22]. However, SLM specimens were more resistant to fatigue crack propagation than conventional manufactured sample. In 2016, Deev and Kuznetcov investigated the mechanical properties and impact strength of 316L stainless steel under room temperature. The specimens were built in vertical orientation with different building directions. the research suggested that the impact strength of the specimen is dependent on the power of the laser beam[23]. Although no effects were found on the hardness values of the specimen. According to the work of Suryawanshi and Prashanth (2016), tensile and toughness property of 316L stainless steel produced by SLM with both single melt and checker board type scanning strategy remain anisotropic in nature [24]. Moreover, reduction in stress intensity factor for fatigue crack initiation and propagation was also found during investigation. Furthermore, Liu and Cheng also investigated formation of microstructures during deposition process and the phase transformation under different heat conditions. The specimen used for investigation were SLM AISI 431 stainless steel. It was reported that stainless steel had optimal mechanical properties after heat treatment at 1050°C [25]. From the above review, it is eminent that SLM 316L stainless steel have comparable properties to that of conventionally built materials.

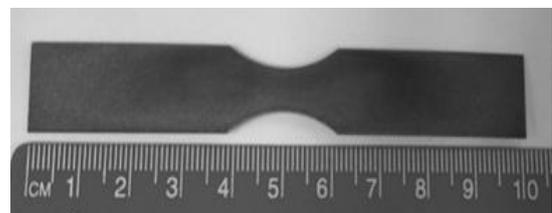


Fig. 2. Fatigue testing specimen.

TABLE I: FATIGUE TESTING SPECIMEN DIMENSIONS

Parameters	(mm)
Length	110
Width	14
Thickness	3.5
Radius of Notch	7
Width at notch	7

However, there is very little knowledge regarding the behavior of fatigue crack growth and initiation of 316L stainless steel flat sheet specimen produced by SLM, and stress relieved by heat treatment. This paper is an attempt to fill the research gap.

## II. EXPERIMENTAL DESIGN

This paper investigates and compares the fatigue behavior of SLM 316L stainless steel, as-built and heat-treated respectively using low cycle reverse fatigue theory. The experimental design for this paper is divided in to three parts.

### A. Specimen Preparation

The specimens required for fatigue testing are designed as per the ASTM standards.

TABLE II: SLM PRINT CONDITIONS

Scan Speed (mm/s)	560
Power output (W)	175
Offset (mm)	2
Exposure time (μs)	1
Layer thickness (mm)	0.03

Fatigue Specimen with rectangular cross-section were built on SLM 125 machine in horizontal orientation as shown in Fig. 2. All dimensions are in millimeters and defined in table I. Horizontal orientation was considered while printing for optimum results. The specimens were printed in a block of size 110x80x14mm. Using a wire cut EDM machine, the specimen was sliced to the thickness of 3.5mm. Twelve specimens were generated after cutting process. The cut specimens were checked for porosity and defects. The defect free specimens were further polished to a micrometer finish and checked for stress concentration zones and cracks. Out of the twelve printed specimens, two sets of six each for as-built and heat-treated were separated.

### B. Heat treatment Process

A set of six specimens were heat-treated at recrystallisation temperature. The selected specimen was heat-treated in a furnace supplied with argon gas to ensure vacuum environment and prevent oxidation. The defined heat treatment parameters are 700°C and 2 hours at the rate of 10° C/min. The specimens were air cooled.

### C. Fatigue Testing

In this stage, all the eight specimens as-built and heat-treated were subjected to low cycle fatigue testing. Two specimen each for the as-built and heat-treated category were reserved for tensile testing to evaluate the yield strength, Ultimate Tensile Strength (UTS) and strain. These properties play a significant role in deciding the parameters and loading conditions for fatigue testing. Tensile testing was done on an Instron tensile testing machine of 100 KN capacity, as shown in Fig. 3. The fatigue testing was conducted on the a specially designed fatigue rig. Fatigue testing is a complex process requiring simultaneous monitoring of the support systems involved till the specimen fails. This may require hours to a day of monitoring time in regular intervals.

The authors have ensured the confidence in the results by

early detection and avoiding pre-mature failures due to slipping and other mechanical conditions. To ensure repeatability in the outcome, each category as-built and heat-treated was tested at least twice especially on tensile testing. Considering the economics and financial viability of printing a SLM specimen. The authors have attempted to publish a quality and reliable results using the number of defect free specimens in hand. Fatigue tests were conducted on the eight specimens of as-built and heat-treated respectively. The test was stress-controlled. The mean stresses for the four specimens consisting of as-built and heat-treated category were 75%, 70%, 65% and 60% of UTS. Stress ratio,  $r = 0.5$  and the frequency,  $f = 5\text{Hz}$  were constant for each specimen. During the fatigue testing experiment, the stress amplitude and the number of cycles to failure of each specimens were recorded. The fatigue testing process consists of applying stress of 0.1% lower of the ultimate tensile strength on the specimen till the failure, to record the number of cycles (N) before failure. Similarly, fatigue tests with 0.1% lower stress of the previous stress will be applied on remaining specimens to produce a four-point S-N curve. The selected cycle loading parameters are shown in Table III.

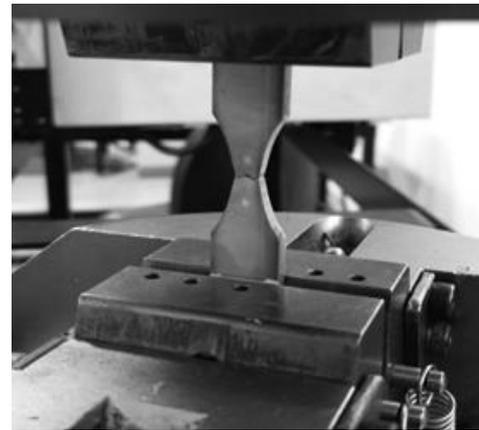


Fig. 3. Tensile testing on Instron machine.

TABLE III: CYCLIC LOADING PARAMETERS

Specimen	As-built		Heat-treated	
	Stress amplitude (MPa)	Mean stress (MPa)	Stress amplitude (MPa)	Mean stress (MPa)
1	143	10	87	12
2	147	11	141	11
3	151	10	156	10
4	182	12	163	10

## III. RESULTS AND DISCUSSION

The results obtained from the experiments are divided in to two parts: tensile and fatigue test results. Table IV shows the tensile test results for as-built and heat-treated specimen. From the data, we can observe that the UTS of heat-treated specimens are higher than as-built specimens. Moreover, yield stress of heat-treated specimen is lower than as-built specimens.

This means the elastic region of heat-treated specimens is lower than as-built. The plastic region is higher which indicate heat-treated specimens are more ductile than the as-built specimens. The stress-strain curve for the as-built

and heat-treated specimen is given in Fig. 4 and Fig. 5 respectively. From the graphs, it can be observed that heat-treated specimen has higher strain values than as-built specimen. This may be attributed to the slightly elongated grain microstructure developed during heat-treatment. This results in increase in ductility and relieves stresses which were induced during the manufacturing process. The UTS for the heat-treated specimens are higher than as built specimen. Moreover, yield stress of heat-treated specimen is lower which means the elastic region is lower than as-built ones and the plastic region is more, making them more ductile. A general prediction can be done based on the tensile test results with respect to the expected fatigue test results. To ensure repeatability, the average value of the tensile test results on the two specimens is taken into consideration.

TABLE IV: TENSILE TEST RESULTS

Stress (MPa)	As-built	Heat-treated
Ultimate tensile stress	630	652
Yield stress	471	390
Young's Modulus	2.4	2.2

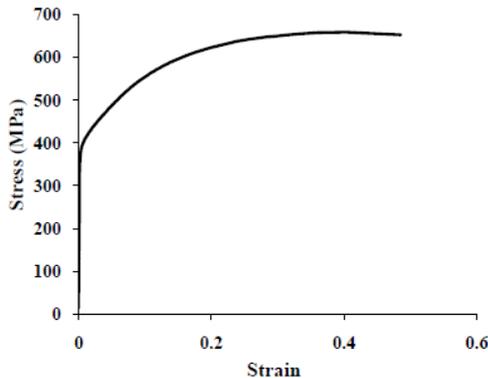


Fig. 4. Stress-Strain curve for as-built specimen.

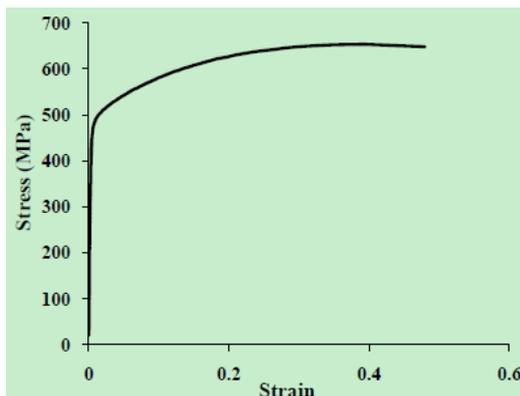


Fig. 5. Stress-Strain curve for heat-treated specimen.

The S-N curve plotted in log scale for as-built and heat-treated specimen is shown in Fig. 6 and Fig. 7 respectively. It can be observed from table V that on an average, the heat-treated specimens have higher number of cycles to failure than the as-built samples at same stress levels. This is because of the lower internal stress present in the heat-treated specimens. This can also be due to the refinement of microstructure leading to increase in ductility in the specimen. A few aberrations can be observed regards to the fatigue test results where there was a pre-mature failures or slippage occurring can be noticed, as in as-built,

specimen 4. Overall, the authors have conveyed their observations regards to improvement in fatigue characteristics upon heat treatment. The results obtained are true to the some of the interesting observation done by previous researchers regards to microstructure grain refinement due to heat treatment and its effect on fatigue life.

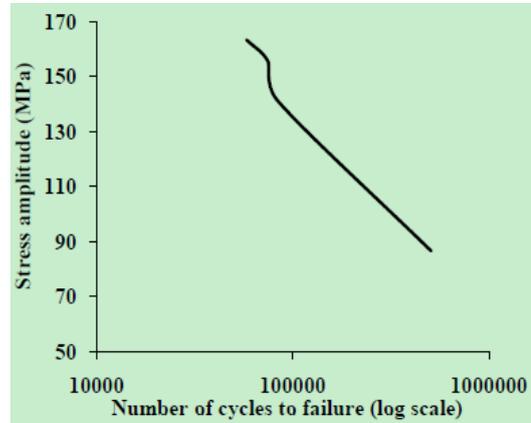


Fig. 6. S-N curve for as-built specimen.

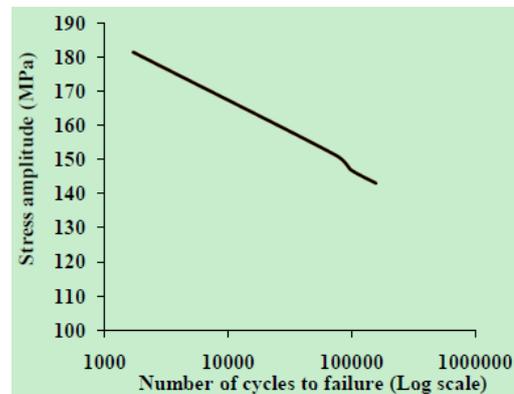


Fig. 7. S-N curve for heat treated specimen.

TABLE V: NUMBER OF CYCLES TO FAILURE

	As-built	Heat-treated
Specimens	No. of cycles to failure	No. of cycles to failure
1	15790	50817
2	98450	83914
3	75000	74800
4	1700	58324

#### IV. CONCLUSION

The fatigue characteristics for as built and heat-treated specimen had varying characteristics. The recrystallisation of the microstructure due to heat treatment influenced fatigue characteristics. Heat-treated specimens have increased workability and ductility whereas as-built specimens are brittle.

#### V. FUTURE WORK

The tests performed in this paper were stress controlled fatigue tests. It would be advantageous in terms of fatigue life, to evaluate the fatigue characteristics using a combination strain controlled and bending moment tests. Investigation on fatigue crack propagation can also be carried out to understand the fatigue behaviour of additive manufactured materials.

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