Statistical analysis of fatigue behavior in additively manufactured steels

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Abstract. The effect of building orientations, sample conditions, and loading ratio (R-value) are important factors in terms of fatigue behavior. The aim of this paper is to investigate the factors that affect the fatigue behavior in additively manufactured laser powder-bed fusion (LPBF) 316L stainless steel. A statistical analysis was performed to point the significant and insignificant factors with different building orientations, samples conditions, and R-value. This statistical analysis provides the most significant factors to be considered for fatigue behavior of 316L stainless steel additive manufacturing.

1. Introduction

Conventional manufacturing processes have been extensively used for producing everyday industrial parts. Over the years, scientists and engineers have identified limitations in fabricating complex geometries using these techniques. In addition, conventional manufacturing processes result in wastage of material due to their subtractive nature [1]. Additive manufacturing (AM) provides a solution that can print complex geometries with little to no waste of material. Unlike the conventional manufacturing, AM simplifies the complexity of challenging geometries by manufacturing in a layer-by-layer fashion [2].

There are various commercially available AM technologies. However, laser powder-bed fusion (LPBF) is one of the most used AM process for industrial applications [2]. In this process, a laser is used as a source of thermal energy that fuses powder particles together to get the final shape in a layer-by-layer. Each layer is bonded to the next and previous layers to achieve the final part [2]. The process of LPBF involves a complex solidification and thermal cycle that can affect the development of microstructure. Since metal powders are the raw material used in LPBF, its performance can vary depending on the properties of the powder [3].

Besides cracks and surface deformation, other factors such as porosity, lack of fusion in powder particles, and stress risers can cause deterioration in the properties of LPBF. This can lead to an early catastrophic failure. In order to improve the performance of LPBF parts produced with various LPBF machines using similar process parameters, a comprehensive review of the available data is necessary. This process involves comparing the various studies that were conducted on the different test parameters, material sources and their sample conditions.

Several materials have been studied for analysis of mechanical properties for LPBF parts. Stainless steels have also been extensively studied due to their strength and applicability in producing functional components [4]. Stainless steel 316L is used in biocompatibility studies. These include internal fixation implants for hip joint surgeries [5], [6]. Besides biomedical applications, 316L is also widely used in various other industries such as aerospace, automotive, and the nuclear industry [4], [7]–[9]. Although 316L is widely used by various techniques, such as cutting, drawing, and stampeding, it is not easy to make final shape components due to its high work hardness, ductility, and low thermal conductivity. Due to these factors, it is often difficult to perform machining on 316L components. Using AM technology, which eliminates the need for a tool, it can be used to produce near-net-shape 316L components [8].

The objective of this study was to analyze the various factors that influence the fatigue performance of each factor. Through a multiple regression analysis, fatigue factors termed as significant factors were identified. Next, variance analysis (ANOVA) was performed to analyze the relationship of independent variables with the dependent variable. In this work, LPBF Stainless steel 316L fatigue data of un-notched samples was collected from literature and then used as input to the analysis software (Minitab ®). Results from the statistical analysis highlight the commonly used relationships already established in the statistical analysis along with an in-depth analysis of other factors.

2. Methodology

2.1 Factors of interest

There are many factors that affect the fatigue behaviors for different orientations and conditions as well as post-processing. The surface and part conditions are related to the surface roughness whether the samples are built to the net-shape or as a cylindrical or square rods and then machined. Also, polishing is an important factor can be applied to both machined and as-built samples [8]. Post-processing such as heat treatment (HT) such as annealing or hot isostatic pressure (HIP) applied to specimens can also be applied to samples which may affect their fatigue performance [10]. Different building orientations have also shown a pronounced effect on the fatigue behaviors of LPBF 316L parts [5]. Whether the samples were built vertically, horizontally or at any other intermediate angle can greatly affect the fatigue behavior.

Process parameters during fabrication of the samples is an important parameter as different authors use different machines and powder suppliers. In addition, different authors follow a slight variation of from the specific process parameters. Also, the material itself could cause a variation on the fatigue behaviors. This is due to the powder manufacturing process as each production company has different production system whether it's gas, water, plasma, atomization [11].

2.2 Statistical Analysis

ANOVA is a statistical technique that splits the aggregate variability in a data set into different parts, namely, the random and systematic factors. Although the former has a statistical influence, the latter does not. This allows the analysis of the relationship between independent and dependent variables and can be measured using the F-ratio. The F-ratio is also used to draw conclusions based on the assumptions of the random errors and variance. The null hypothesis in this analysis states that the results of the ANOVA's F-ratio test will be close to one if no real difference exists between the tested groups where the distribution of the F statistic follows the F-distribution [12]. The extracted data used in this work was sorted accordingly into a set of different independent groups which lead to a set of dependent fatigue performance responses. Then, statistical analysis was conducted via Minitab® statistical software. The corresponding results are presented below.

3. Results

The data collected for this study is based on 316L LPBF Stainless steel.

Table *1* shows the corresponding references with the conditions, orientations and R-values extracted from each paper. All data was analyzed ($\alpha = 0.05$) using statistical approaches as discussed in the previous section. Factors that affect the fatigue strength were analyzed as inputs with the maximum stress (σ_{max}) as the corresponding response.

*Table 1: Authors, conditions, orientations, and **R**-values for 316L analysis.*

Authors	Conditions	Orientation	R-Value
Shrestha et al. [7]	As built-HT Machined-Polish-HT	Z	-1
Elangeswaran et al [8]	M As built Machined-HT As-built-HT		
Lai et al. [13]	As built-Polished Machined-Polished As built-Polished-HT Machined-Polished-HT		
Afkhami et al. [9]	Machined As built HFMI		
	Machined	XY	
Zhang et al. [14]	Machined-Polish	Z	0.1

P-value analysis is one of the most used tools in statistical analysis of engineering analysis [12]. In addition to *P*-value analysis, Pareto charts can also be used to show the significance level of various factors. Table 1 shows the level of significantly for each factor.

Figure 1 shows the results of F-value where the dotted black horizontal line (at 1.97) highlights the significant factors. The results show that the number of cycles has the highest significance, then the conditions. Lastly, the *R*-value. Part orientation is not deemed as a significant factor in our analysis. However, there are various reports in literature where LPBF parts printed with different orientations show unequal responses [5].

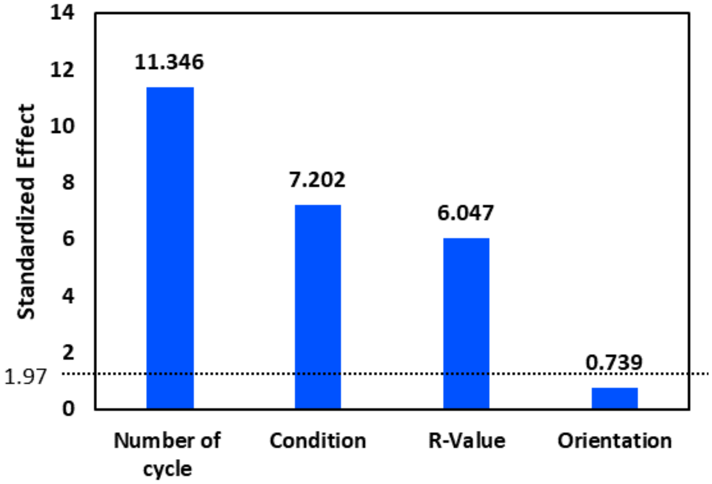

Figure 1: ANOVA table and Pareto Chart to identify the significant factors for 316L

Table 2: Analysis of variance results

Source	Seq SS	Cont.	Adj SS	Adj MS	F-Val	P-Val
Regression	6.1870	84.1%	6.18702	0.5624	79.57	0.00
Log Number of cycles	2.7062	36.8%	0.90999	0.9099	128.73	0.00
R-value	1.4221	19.3%	0.25847	0.2584	36.56	0.00
Orientation	0.0005	0.00%	0.00386	0.0038	0.55	0.46
Condition	2.0585	27.9%	2.05853	0.2573	36.40	0.00

Error	1.1663	15.8%	1.16637	0.0070		
Lack-of-Fit	1.1632	15.8%	1.16324	0.0070	2.26	0.49
Pure Error	0.0031	0.04%	0.00313	0.0031		

Figure 2 shows the investigation of why part orientation was not identified as a significant factor. Figure 2 shows the builds orientations from all publications with the same R-value [5], [8], [9], [13]. The results show that the statistical variance observed within the vertical samples contained all the results from the horizontal samples which deemed the orientation as insignificant. This is due to a lack of data for horizontal samples (only 1 study [9]).

To analyze the significant factors observed with the statistical analysis, R-value results from various authors were plotted as shown in Figure 3 [13], [14]. Experimental observations from various R-values (0.1, -1) show that the $R = 0.1$ partially overlaps with the deviation range of $R = -1$. This difference in the results between the two reported R-values results in a significant factor as shown in Figure 1.

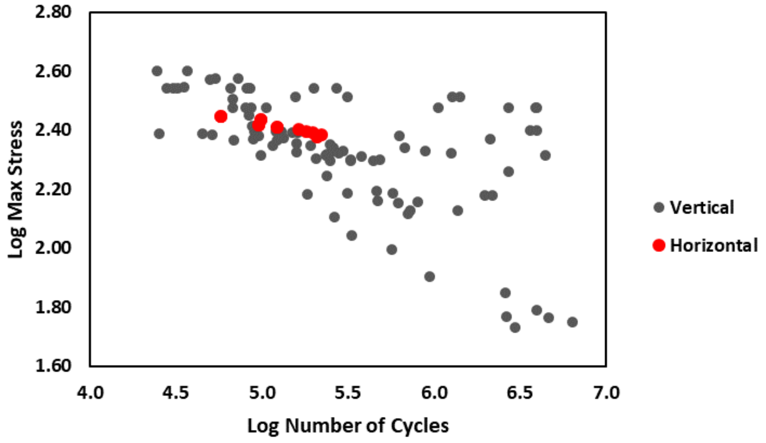

Figure 2: Fatigue data for different orientations 316L samples.

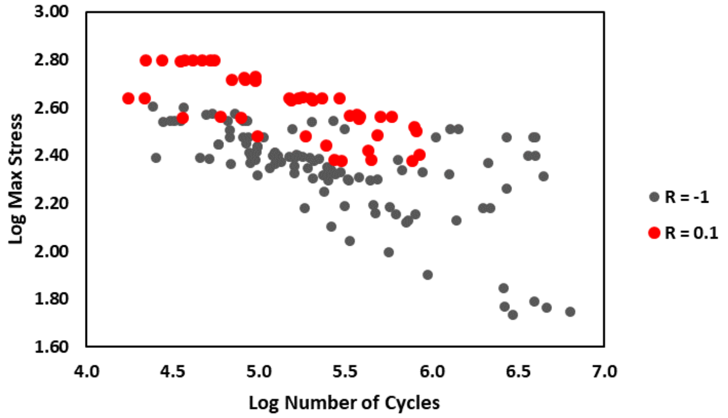

Figure 3: Fatigue data for different R-Values 316L samples.

It is important to analyze the statistical data to perform ANOVA. In this regard, several tools are used by researchers to identify if a certain set can be analyzed using statistical analysis. Normal probability plot is a graphical representation of the distribution of a given data set. It shows the likelihood that if or not the data set is distributed normally. Figure 4 shows that the fatigue data for 316L samples used in this study and shows a near normal distribution. It should be noted that a few points near 0.2 and -0.2 show minor deviations. This could be due to experimental error or anisotropic material behavior.

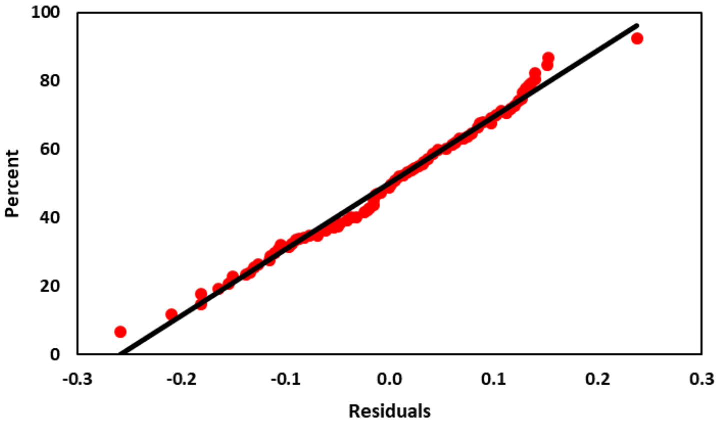

Figure 4: Normal probability plot for 316L samples.

A commonly used technique for performing a successful ANOVA is to create a scatter plot of the residuals and the fitted values. This type of plot is useful in detecting outliers, non-linearity, and unequal error variances. Figure 5 shows that the majority of the data correspond to a normal, equal error variance with few outliers.

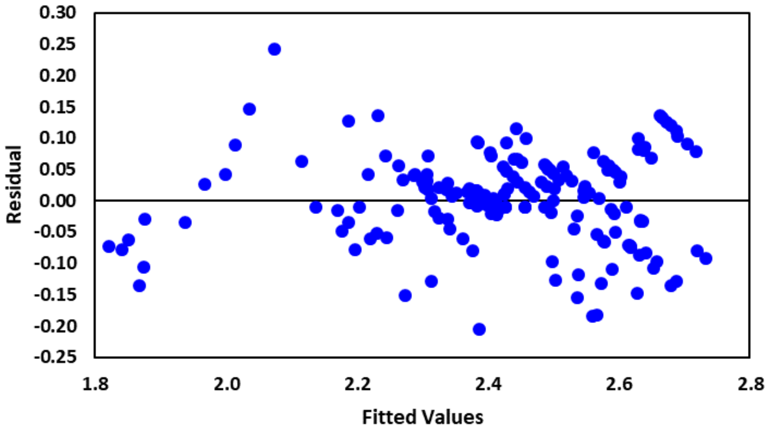

Figure 5: Residuals versus fitted values for 316L samples.

The use of an order plot (Figure 5) versus residual analysis is also useful in detecting the presence of non-independent error terms. It is used to identify the relationship between the various error terms in the sequence. Figure 6 shows that the fatigue data set has violated the independent error terms. Therefore, most experimental observations are independent from each other.

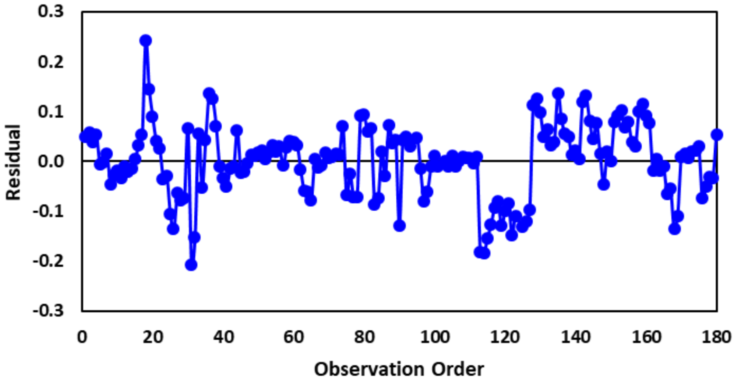

Figure 6: Residual versus observation order for 316L samples.

Finally, histograms are used to observe the dataset to identify anomalies in the recorded data. Histograms show the various data points grouped together into a logical range or bin. It can be used to compare the distribution of the given numerical data in intervals. It can also help an audience visualize and understand the various patterns and meanings of a data set. In addition, it can also be used to help the decision-making process of organizations. Figure 7 shows the maximum frequency for zero residuals along with a typical normal distribution of data as expected. The results from Figures 4-7 confirm that the data corresponds to a normal population and can be analyzed using a normal distribution. In addition, the results concluded from this analysis correspond to the common understanding in fatigue failure

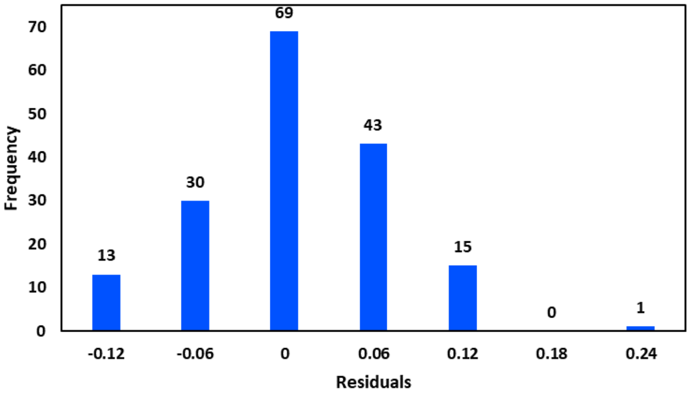

Figure 7: Histogram plot for 316L samples.

4. Conclusions

Fatigue failure data for Laser powder-bed fusion Stainless steel 316L from literature was collected and used in this work to conduct a statistical analysis on fatigue parameters. A few conclusions from this study are given below:

- Number of cycles, conditions, and R-values are identified as significant factors and therefore affect the fatigue strength significantly.
- Building orientation was not identified as a significant factor as the fatigue data of the horizontal build samples was limited and did not show major variation.
- Different R-values show partial significance when comparing $R = -1$ to $R = 0.1$.

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