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Research article

On the effect of loading and printing parameters that influence the fatigue behavior of laser powder-bed fusion additively manufactured steels

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A R T I C L E I N F O

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A B S T R A C T

The aim of this paper is to investigate the factors (build orientation, sample conditions, and R-ratio) that affect the cyclic response of laser powder-bed fusion stainless steel 316L and 17-4 PH parts. Initially, the data set was analyzed to confirm the normality assumption. The significant and insignificant factors that affect the fatigue life were identified using analysis of variance (ANOVA). Main effects for different sample conditions were also analyzed. Process and reproducibility assessment were performed to study the effect of process factors. Combining fatigue data sets was recommended as the best approach to accurately predict the fatigue behavior of LPBF 316L and 17-4 PH parts. Finally, the effect of sample conditions on fatigue life was quantified. The highest fatigue life was achieved with Machined-Polished surfaces.

1. Introduction

Traditional manufacturing processes frequently lead to material wastage due to their subtractive nature [1]. Additive manufacturing (AM), on the other hand, provides a potential solution to these issues, as it enables the production of complex geometries with minimal material waste. In addition, additive manufacturing simplifies the complexity of challenging geometries by building them in layers [2].

Laser powder-bed fusion (LPBF) is widely used metal AM technology for industrial purposes and is capable of producing near-full dense components from a variety of engineering alloys [3]. The LPBF process uses a laser to fuse powder particles in order to create the intended part in a layer-by-layer fashion. The process involves an intricate melting/solidification and thermal cycle within each layer which can influence the final microstructure and part properties [4].

Porosity, lack of fusion of powder particles, etc. are some of the most common defects observed in LPBF parts [5]. These defects can cause deterioration in the properties of the printed parts which can lead to early failure. This is not limited to static failure and can also affect the fatigue properties of LPBF-AM parts [6]. To enhance the efficiency and performance of LPBF components, it is essential to perform a comprehensive review on the available data of frequently used LPBF materials, such as stainless steels [7–10]. In this context, numerous researches have been carried out on the static and cyclic properties of stainless steel LPBF parts due to their superior

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mechanical properties as these components are used in biomedical, aerospace, automotive and nuclear industries [11–15].

When subjected to cyclic loading, AM - LPBF parts can fail due to inherent defects present in printed parts [16]. The defects and porosity in AM parts can act as local stress concentration and fatigue crack initiation sites under cyclic loading [17,18]. Materials differ in their tolerance to defects that initiate fatigue crack growth. For instance, stainless steel 316L exhibits high defect and residual stress tolerance, owing to its high ductility resulting from its single-phase austenitic structure. This reduces its notch sensitivity and makes it ideal for many applications [17,19].

The fatigue performance of AM - LPBF parts can be affected by a variety of factors including build orientation, surface condition, heat treatment, etc. To determine the significance of these factors, conventional brute force approaches do not provide a quantitative and viable solution. However, statistical analysis can be used to quantify the significance and effect of each parameter [20]. Some researchers have utilized probabilistic approaches to predict fatigue behavior of notched samples [21–24]. However, their approaches are mostly focused on capturing the size effects [22,23]. Therefore, this study suggests a statistical approach to analyze and examine the factors that affect the fatigue performance of laser powder-bed fusion stainless steel 316L and 17-4 PH parts. Data for the proposed statistical analysis was gathered on un-notched samples from existing literature. A multiple regression analysis was employed to identify the significant fatigue factors. Further, analysis of variance (ANOVA) was conducted to examine the correlation between independent and dependent variables.

2. Methodology

2.1. Factors of interest

The fatigue behaviors of additively manufactured parts are affected by various factors, such as build orientation, surface condition, and post-processing. The surface roughness of the parts is a key factor, and can vary depending on how the final part was built. Parts built to net-shape or machined to final geometry affect the surface roughness and hence the fatigue behavior. Polishing is also employed to reduce the surface roughness of both machined and as-built components [14]. Post-processing such as heat treatment (HT) or hot isostatic pressure (HIP) can also have significant effects on the fatigue performance of LPBF parts [25]. Likewise, the build orientation may also influence the fatigue response as LPBF-AM samples can be built vertically, horizontally, or at any other intermediate angle (Fig. 1) [26,27]. All the factors discussed in this section are included as factors of interest in the statistical analysis performed in this work.

2.2. Statistical analysis

Analysis of Variance (ANOVA) is a statistical technique used to determine the effect of different factors, and their interactions, on the response parameters by using the F-ratio, P-value and Pareto charts. This statistical technique divides the total variability of a data set into random and systematic components to analyze the relationship between independent and dependent variables. The F-ratio is utilized to derive inferences based on the assumptions of random error and variance. The null hypothesis states that if there is no significant difference between the experimental groups and the distribution, the F statistic, which follows the F-distribution, will result in a F-ratio of close to one [28]. Like the F statistic, P-value analysis can also be used for statistical analysis of engineering data. In this approach, a factor is considered to be significant if its P-value is less than the level of significance ($\alpha = 0.05$).

A single factor analysis of variance model is shown below (Equations (1) and (2)) [28]:

$$y_{ij} = \mu + \tau_i + \epsilon_{ij} \begin{cases} i = 1, 2, \ldots, a \\ j = 1, 2, \ldots, n \end{cases} \tag{1}$$

$$\mu_i = \mu + \tau_i \tag{2}$$

where y_{ij} is the ijth observation, μ is the overall mean, τ_i is the ith factor level effect, a is the total level of the treatment, n is the number of observations under the ith treatment, while ϵ_{ij} is the random error. The error component is assumed to be independent and normally distributed. The observations (Equation (3)) also follow a normal distribution and are given as:

$$y_{ij} \sim N(\mu + \tau_i, \sigma^2) \tag{3}$$

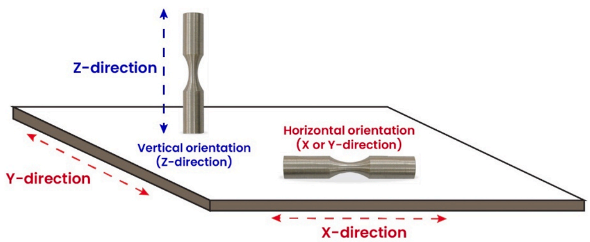


Fig. 1. Build orientations used in the studied literature.

where σ^2 is the variance.

The analysis of variance involves separating the total variability to its component parts to find the F-test. The total corrected sum of squares (Equations (4) and (5)) is given as the sum of squares due to treatments (factor levels) and the sum of squares due to error.

$$\sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij}-\bar{y}_{..})^2 = n\sum_{i=1}^{a}(\bar{y}_{i.}-\bar{y}_{..})^2+\sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij}-\bar{y}_{i.})^2 \tag{4}$$

$$SS_T = SS_{Treatments} + SS_E \tag{5}$$

where the bar denotes the overall mean. Equation (4) can be represented as Equation (5) with each term corresponding respectively. SS_T is the total corrected sum of squares, $SS_{Treatments}$ is the sum of squares due to treatments (factor levels) and SS_E is the sum of squares due to error.

To find the F-ratio, mean square of treatments (Equation (6)) is defined as:

$$MS_{Treatments} = \frac{SS_{Treatments}}{a-1} \tag{6}$$

Where mean square of treatments ($MS_{Treatments}$) is the ratio of $SS_{Treatments}$ to its degree of freedom. The degree of freedom of the $SS_{Treatments}$ is the number of independent values that were used in estimating the $SS_{Treatments}$.

Similarly, mean square of error (Equation (7) - MS_E) is defined as:

$$MS_E = \frac{SS_E}{N-a} \tag{7}$$

The F-test statistic (Equation (8) - F_0) is for the hypothesis when there are no differences in the mean of treatments and is given as:

$$F_0 = \frac{MS_{Treatments}}{MS_E} \tag{8}$$

The null hypothesis is rejected if F_0 is greater than 1. This means that there are significant differences in the factor levels (treatments).

The standard residual (Equation (9) - d_{ij}) plots used in statistical analysis should follow a typical normal distribution. This can be used to check the equality of variance, where d_{ij} is the residual and e_{ij} is the error term.

$$d_{ij} = \frac{e_{ij}}{\sqrt{MS_E}} \tag{9}$$

In this work, data was extracted from five different publications with different factors that affect the fatigue strength of LPBF parts. Number of cycles (to failure), R-ratios, Orientations (vertical (Z) and horizontal (XY)) and Conditions (as-built (AB), machined (M), polished (P), heat treated (HT), high-frequency mechanical impact (HFMI)) and the combinations of these conditions were reserved as the independent factors. The extracted data was then sorted into independent groups and analyzed using Minitab®. This work studies the mechanical response from LPBF stainless steel 316L and 17-4 PH parts under cyclic loading. The statistical approach used in this work identifies the most significant parameters. In addition, the analysis highlights the most effective post-processing condition along with a study on the repeatability of LPBF AM parts.

Table 1
Summary of Authors, Conditions, Orientations, and R-ratios for 316L stainless steel analysis.

Authors	Conditions	Orientation	R-ratio
Shrestha et al. [13]	As-built (AB)-Heat treated (HT)	Z	−1
	Machined (M)-Polished (P)-Heat Treated (HT)		
Elangeswaran et al. [14]	Machined (M)		
	As-built (AB)		
	Machined (M)-Heat Treated (HT)		
	As-built (AB)- Heat treated (HT)		
Lai et al. [29]	As-built (AB)-Polished (P)		
	Machined (M)-Polished (P)		
	As-built (AB)-Polished(P)- Heat treated (HT)		
	Machined (M)-Polished (P)- Heat treated (HT)		
Afkhami et al. [12]	Machined (M)		
	As-built (AB)		
	High Frequency Mechanical Impact (HFMI)		
	Machined (M)	XY	
Zhang et al. [17]	Machined (M)-Polished (P)	Z	0.1

3. Results and discussion

The data collected (Tables 1 and 2) for this study was based on stainless steel 316L and 17-4 PH LPBF parts. All the fatigue data was examined (α = 0.05) using the statistical methods outlined in the preceding section. Factors that influence the fatigue strength were analyzed as inputs (Number of cycles (to failure), Condition, Orientation, R-ratio, Authors)) with the maximum stress (σ_{max}) as the corresponding response.

3.1. Normality test

Before commencing the statistical analysis, it is important to check if the data set follows a normal distribution. This is important, as normality is a requirement for conducting analysis of variance (ANOVA). If the data is found to be normally distributed, then statistical analysis with ANOVA can be performed directly on the data set. On the other hand, if the data does not show normality, other approaches such as Welch ANOVA or Brown-Forsythe test can be used [32].

Normal probability distribution is a visual plot of the spread for a specific data set and indicates the probability of whether the data set follows a normal distribution. Fig. 2a illustrates that the normal probability plot for 316L samples exhibit a near normal distribution. It is worth noting that fatigue strength predictions near high residuals (0.2 and −0.2) show slight discrepancies. This could be attributed to experimental inaccuracies or anisotropic response observed in these alloys. Similarly, Fig. 2b shows the normal probability plots for 17-4 PH samples are also normally distributed with minor deviation near −0.15 and 0.15.

Furthermore, a scatter plot of the residuals was also used to determine if the errors had a constant variance, determine outliers, and the presence of any non-linearity in the data. As depicted in Fig. 3a and b, the bulk of the data corresponds to a normal, constant error variance with few outliers. Comparison between the 316L and 17-4 PH shows that although 316L had higher number of data points than 17-4 PH, both materials show no trends of increasing or decreasing variance within the whole data set. It should be noted that experimental data with uneven variance would show a skewed trend with unequal distributions about the zero residuals mark.

Similarly, an order plot was used to detect the presence of non-linearity and error dependence. This is of utmost importance as observed non-linearity or data dependence would render the analysis void. The residual versus order plot analysis for 316L and 17-4 PH are shown in Fig. 4a and b, respectively. A normal data should exhibit a random data plot along the zero residuals line. In addition, the data should not follow any definitive patterns. This guarantees independence and normality. It can be observed from Fig. 4a and b that most of the experimental data is independent as the residuals are random and do not show any recognizable pattern.

Finally, histograms are plotted to identify the statistical distribution or anomalies in the recorded data. They are employed to analyze the distribution of a given data across various bins or intervals. In theory, a normal distribution should show a zero mean with reducing frequencies on either side, i. e a histogram with typical bell shape. This translates to a peak that is symmetric around the zero mean. Fig. 5a and b exhibit the highest frequency of zero residuals, accompanied by a standard normal distribution. However, 316L data (Fig. 5a) shows slight skewness towards the negative residuals. However, this skewness is within the acceptable range of normality. Therefore, it can be concluded that the data for both stainless steel 316L and 17-4 PH adhere to a near normal distribution. It is important to mention that if the data used in this work did not follow a normal distribution, the analysis presented in this work would not be valid. In addition, if the data followed any other distribution, the histograms would exhibit high residuals and would not follow the same trends shown in Fig. 5.

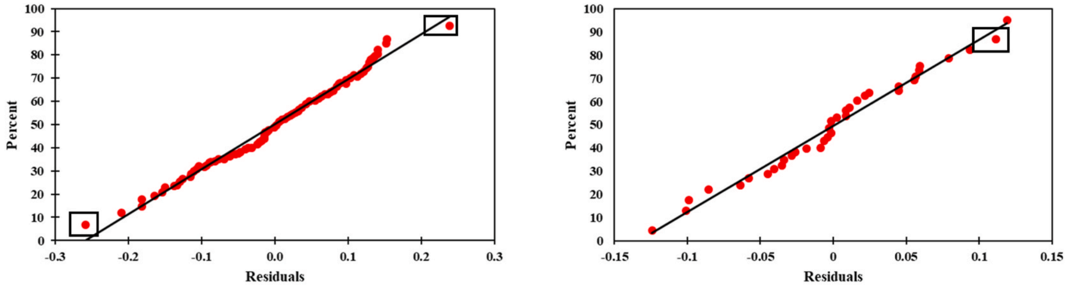
In this section, normal probability plot, residual plots and histograms of residuals were discussed for stainless steel 316L and 17-4 PH parts. Results from these figures (Figs. 2–5) affirm that the data aligns with a normal population and is suitable for further analysis. In addition, results show that even though 316L had more data points, the overall trend for 17-4 PH shows a higher normality and therefore would produce better statistical results.

3.2. Analysis of variance (ANOVA) results

Results from the previous section guarantee the normality of the fatigue data extracted from literature. Therefore, analysis of variance (ANOVA) can be performed to analyze the results using statistical approaches. The corresponding results from the statistical analysis of 17-4 PH and 316L stainless steels are shown in Table 3. ANOVA table for 316L stainless steel (Table 3a) show that only the Orientation had a P-value greater than 0.05, which indicates that it is insignificant. However, other factors (Number of cycles, R-ratio, and Condition) all have P-value which is less than 0.05, indicating they are all significant factors that affect the fatigue performance of 316L stainless steel parts. Similarly, Table 3b shows the ANOVA table for 17-4 PH stainless steel. A few factors (Number of cycles and Orientation) were found to be significant, while Condition was found to be insignificant. The lack of a few factors (Orientation and Condition) as significant factors does not seem in-line with the literature and therefore requires additional analysis (Fig. 7). In addition

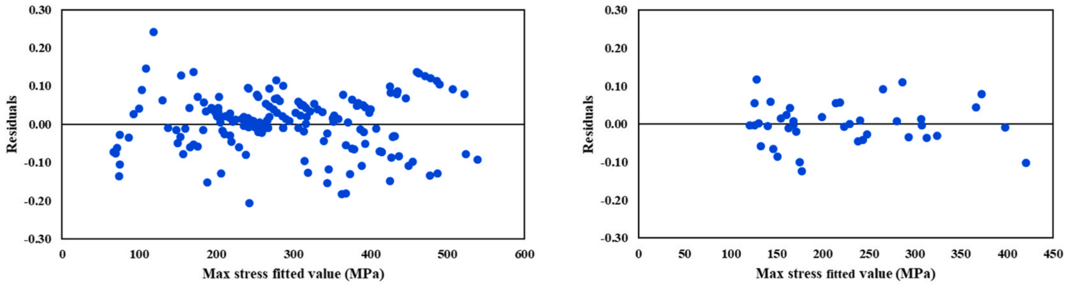
Table 2
Summary of Authors, Conditions, Orientations, and R-ratios for 17-4 PH stainless steel analysis.

Authors	Conditions	Orientations
Yadollahi et al. [30]	Machined (M)- Polished(P)-Heat Treated (HT)	XY
	Machined (M)- Polished(P)	Z
Yadollahi et al. [31]	Machined (M)- Polished(P)- Heat treated (HT)	Z
	Machined (M)- Polished (P)	



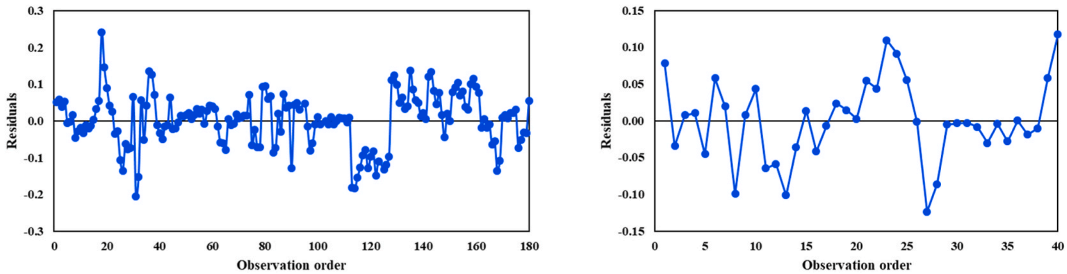
(a) (b)

Fig. 2. Normal probability plot for (a) 316L and (b) 17-4 PH stainless steel.



(a) (b)

Fig. 3. Residual versus Fitted value for (a) 316L and (b) 17-4 PH stainless steel.



(a) (b)

Fig. 4. Residual versus observation order for (a) 316L and (b) 17-4 PH stainless steel samples.

to the explanations provided in Fig. 7, these differences could also be due to material variation, process variation, surface quality and other material and manufacturing factors [17].

Furthermore, these results can also be illustrated in a graphical format using the pareto chart as shown in Fig. 6. ANOVA table provides the P-values can be utilized conclude the significance of certain factors whereas pareto charts can be employed to ascertain the relative significance between different factors. Fig. 6a shows the standardized effect of each factor for LPBF 316L parts, where the black horizontal line highlights the significance level above which the factors are considered significant. The findings reveal that the Number of cycles had the highest significance, followed by Condition, and lastly, the R-ratio. Contrary to results published in literature, Orientation was not deemed as a significant factor [17].

Fig. 6b presents the standardized effect of each factor for LPBF 17-4 PH parts. The findings reveal that the Number of Cycles and Orientation were identified as significant parameters while Condition was deemed insignificant. The R-ratio was excluded from the analysis as it was identical for all samples. It should be noted that Number of Cycles was the most significant factor for both materials. Therefore the statistical analysis identifies the same parameters as present in many commercially available fatigue models [33].

Results from Fig. 6a and b highlight Orientation and Condition as being insignificant factors. These conclusions require extensive analysis as Orientation of a LPBF sample can account for a major difference in fatigue response [17]. Fig. 7a shows fatigue results from 316L samples in vertical and horizontal orientations from all studies ([12,14,26,29]). The findings indicate that the statistical variance

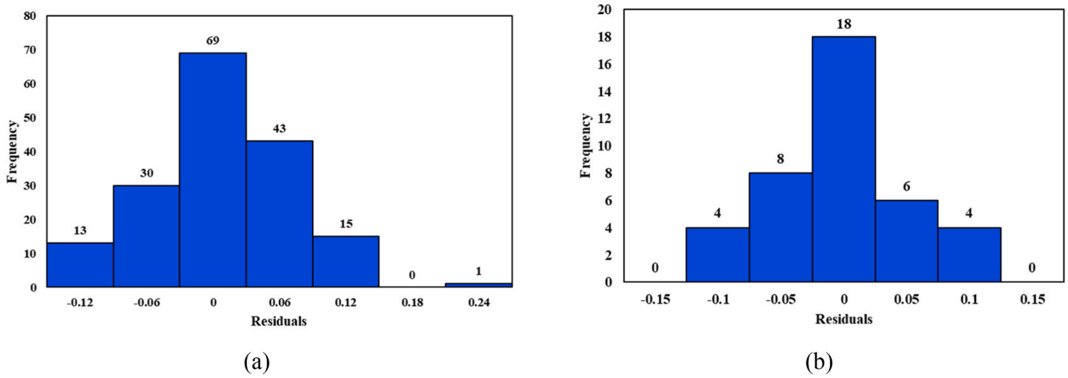


Fig. 5. Histogram plot for (a) 316L and (b) 17-4 PH stainless steel samples.

Table 3
Analysis of Variance (ANOVA) results (a) 316L and (b) 17-4 PH stainless steel.

Source	Adj SS	Adj MS	F-Value	P-Value
(a)				
Regression	6.4210	0.5837	102.48	0.000
Log Number of cycles	0.8384	0.8385	147.21	0.000
Orientation	0.0003	0.0003	0.05	0.827
R-ratio	0.3092	0.3092	54.29	0.000
Condition	2.2974	0.2872	50.42	0.000
Error	0.9398	0.0057		
Total	7.3604			
(b)				
Regression	0.97467	0.324888	99.71	0.000
Log Number of cycles	0.95420	0.954204	292.84	0.000
Orientation	0.04713	0.047133	14.46	0.001
Condition	0.00398	0.003982	1.22	0.276
Error	0.11730	0.003258		
Total	1.09197			

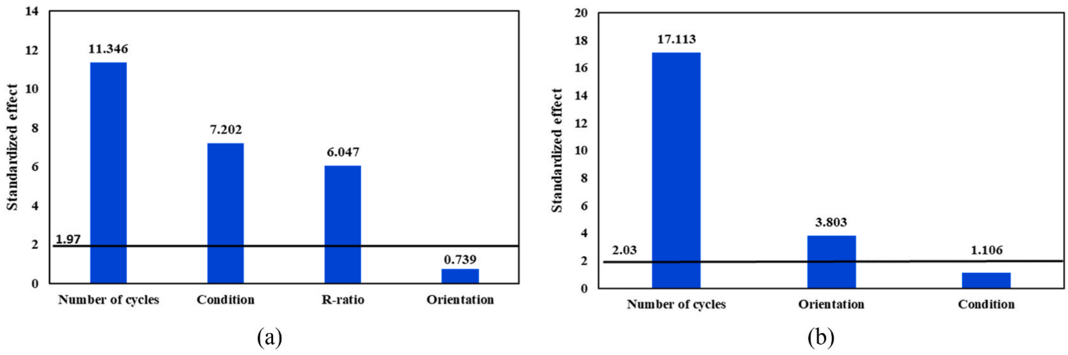


Fig. 6. Pareto chart to identify the significant factors for (a) 316L and (b) 17-4 PH stainless steel samples.

in the vertical samples encapsulated the outcomes from the horizontal parts, rendering the Orientation as an insignificant parameter. This can be attributed to the lack of data for horizontal samples (only one study) [12]. The insignificance of Condition for 17-4 PH stainless steel is also due to the result overlap and lack of data.

The same approach was also used to identify one of the significant factors. R-ratio results (0.1, −1) from several researchers were graphed (Fig. 7b) [17,29]. Experimental observations indicate that the data from $R = 0.1$ partially overlays with the variance observations from $R = 1$. This discrepancy in the findings and lack of overlap between the reported results assigns the R-ratio as being a significant factor (Fig. 7b).

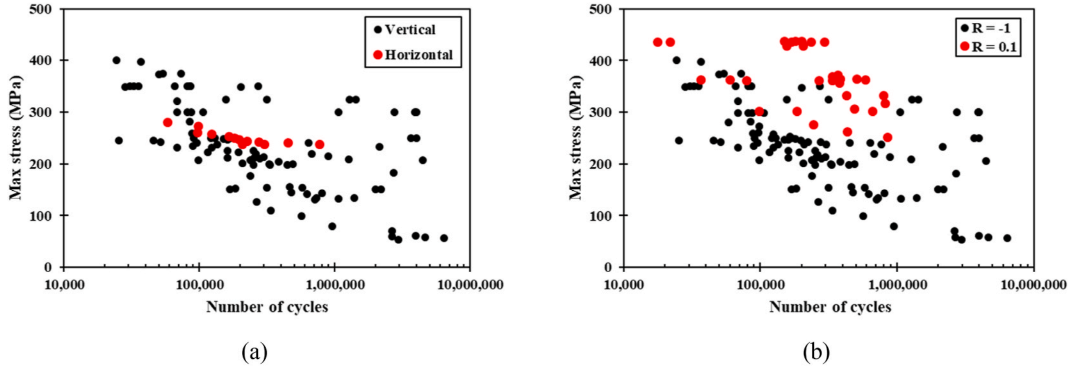


Fig. 7. Fatigue data for 316L samples for (a) Different orientations and (b) Different R-ratios.

3.3. Process and material assessment

Repeatability is a major concern for additively manufactured parts as manufacturing non-repeatable parts reduces confidence of industrial large-scale manufacturers [34]. To determine the repeatability of the LPBF processes and part properties under cyclic loading, process assessment was performed and are presented in Fig. 8. The repeatability analysis presented in this section contains the results from same or different authors, under similar conditions. Confidence intervals with an upper and lower bound were also found for each data set. Finally, all the data was combined to get an overall response and confidence interval. The results are also given in tabular form (Tables 4–7) to quantitatively assess the low cycle fatigue (LCF) and high cycle fatigue (HCF) behavior.

Fig. 8a shows the fatigue data from stainless steel 316L from the same author with different machines [13]. The results show that specimens produced by two different machines result in different confidence intervals due to the scatter in the data. Data A (red) shows a more conservative response (Table 4). However, the confidence intervals from the combined data set (black) captured all the data points from Data A and B. This highlights the importance of extensive testing even within distinctive machines to capture the overall trend of fatigue life for these materials. Comparison between the two data sets showed a 2.75% difference under LCF and a 3.13% under HCF as shown in Table 4. It should be noted that the LCF showed a higher error in the confidence bounds. These differences can be attributed to the different process parameters used in the manufacturing process such as laser power, layer thickness, hatching

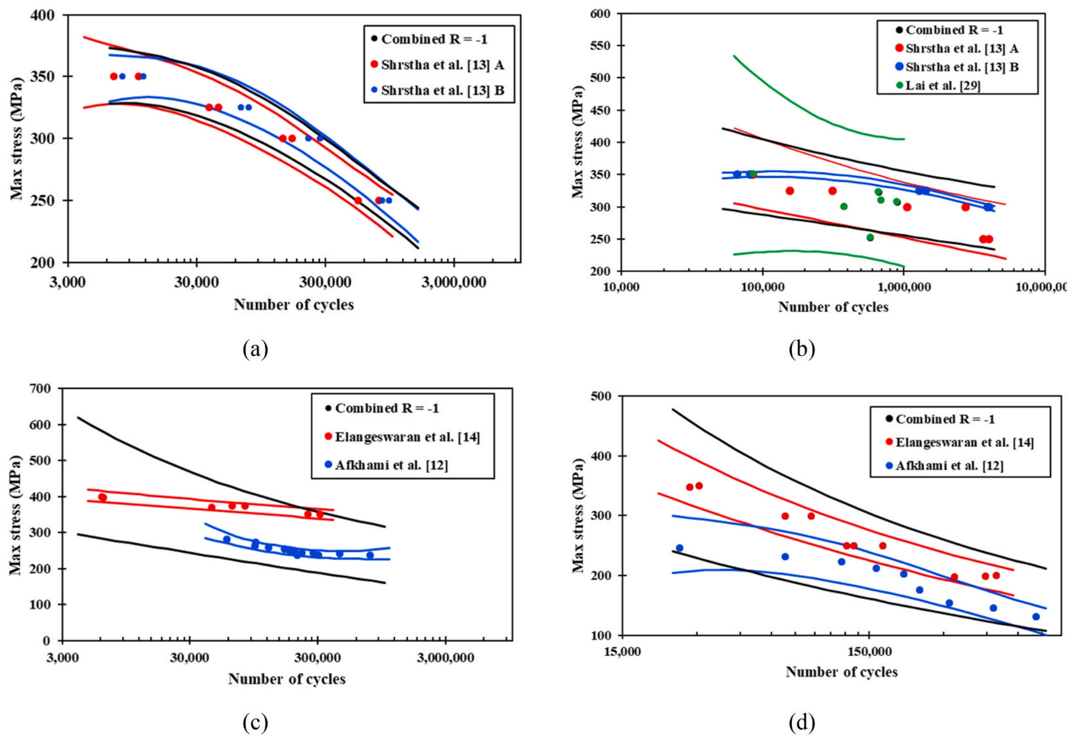


Fig. 8. 316L stainless steel samples (a) Vertical-AB-HT, (b) Vertical-*M*-P -HT, (c) Vertical-M, and (d) Vertical-AB.

Table 4
Percentage difference variation in fatigue strength for 316L Vertical-As-built-HT samples under LCF and HCF from same author.

	Low	LCF	High	Low	HCF	High
Shrestha et al. Machine (A) [13]	328.322	354.160	373.938	281.644	297.852	316.592
Shrestha et al. Machine (B) [13]	348.097	363.915	381.505	292.415	307.185	320.848
Combined Stress (C)	340.957	356.697	382.913	284.512	302.204	320.406
Error A - B	5.68%	2.68%	1.98%	3.82%	3.13%	1.34%
Error A - C	3.71%	0.71%	2.34%	1.01%	1.44%	1.19%
Error B - C	2.09%	2.02%	0.37%	2.78%	1.65%	0.14%

Table 5
Percentage difference for 316L vertical-machined-polished-HT samples under LCF and HCF conditions by different authors.

	Low	LCF	High	Low	HCF	High
Shrestha et al. Machine (A) [13]	353.346	411.529	479.292	297.989	346.897	403.831
Shrestha et al. Machine (B) [13]	379.315	378.355	389.135	349.462	348.418	358.179
Lai et al. Machined (D) [29]	247.970	392.735	621.727	231.579	337.520	491.700
Combined (C)	326.062	386.812	458.564	288.403	341.586	404.203
Error A - B	6.85%	8.77%	23.17%	14.73%	0.44%	12.75%
Error A - D	42.50%	4.79%	22.91%	28.68%	2.78%	17.87%
Error A - C	8.37%	6.39%	4.52%	3.32%	1.55%	0.09%
Error B - C	16.33%	2.19%	15.14%	21.17%	2.00%	11.39%
Error D - C	23.95%	1.53%	35.58%	19.70%	1.19%	21.65%

Table 6
Percentage difference in fatigue strength for 316L vertical-machined under LCF and HCF conditions from different authors.

	Low	LCF	High	Low	HCF	High
Elangeswaran et al. (E) [14]	379.315	393.550	408.319	351.884	364.920	378.443
Afkhami et al. (F) [12]	301.093	307.044	328.020	257.158	262.241	280.092
Combined (C)	272.333	383.796	541.502	211.739	294.171	409.261
Error E-F	25.98%	28.17%	24.48%	36.84%	39.16%	35.11%
Error E-C	39.28%	2.54%	24.60%	66.19%	24.05%	7.53%
Error E-C	10.56%	20.00%	39.42%	21.45%	10.85%	31.56%

Table 7
Percentage difference variation in fatigue strength for 316L vertical-as-built under LCF and HCF conditions.

	Low	LCF	High	Low	HCF	High
Elangeswaran et al. (E) [14]	398.107	443.813	494.880	244.174	271.394	301.717
Afkhami et al. (F) [12]	284.512	338.065	395.822	178.402	210.523	244.399
Combined stress (C)	298.263	414.954	576.766	175.186	242.885	336.822
Error E-F	39.93%	31.28%	25.03%	36.87%	28.91%	23.45%
Error E-C	33.48%	6.95%	14.20%	39.38%	11.74%	10.42%
Error F–C	4.61%	18.53%	31.37%	1.84%	13.32%	27.44%

space, and scanning speed.

It is also important to analyze the reproducibility of fatigue results from different authors under similar conditions. This analysis is also important for quality control of LPBF parts under cyclic loading. In this regard, another data set from a different author with the same conditions was combined with the 316L fatigue data shown in Fig. 8a and is presented in Fig. 8b [29]. Results show that the data points for the specimens produced by two different authors as well as those produced by same author but with different machines had different confidence intervals due to the scatter in the data. The confidence intervals from the combined data set (black) captured all the data points from Shrestha et al. [13] (Data A and B), however, one data point from Lai et al. [29] (Data D - green) was not captured along the HCF. Comparison between the Data A and D data sets showed a 4.79% difference under LCF and a 2.78% difference under HCF as shown in Fig. 8b. These differences highlight the lack of repeatability. However, the combined data can be used as a predictor since its confidence intervals captured almost all data points from the 3 data sets. A similar conclusion, however, cannot be derived about the confidence intervals. The high variance in Ref. [29] resulted in a very high confidence interval bounds (much higher than the combined data). A maximum of 35% difference was observed in the LCF regime while a maximum of 20% difference was observed in HCF for the combined and Data D (Table 5). This significant variation between the confidence intervals and combined data shows the importance of statistical analysis to capture the complete material behavior. In addition, this analysis highlights the importance of capturing enough data to deduce the correct conclusions.

Fig. 8c also shows the assessment of the process reproducibility for 316L, from two different authors (Elangeswaran et al. [14], and

Afkhami et al. [12]). All fatigue data used in this analysis was for vertical – machined samples under $R = -1$. The results show that the data points for the specimens produced by two different authors had varying confidence intervals as shown in Fig. 8c. Data from Afkhami et al. [12] (blue) exhibited a more conservative response. Although, the confidence intervals from the combined data set (black) captured all the data points from both data sources [12,14]. Comparison between the two data sets showed a 28.14% difference under LCF and a 39.16% under HCF as shown in Table 7. These high percentage differences could be due to the process parameters. A higher surface roughness (0.5 μm) observed by Elangeswaran et al. [14] compared to Afkhami et al. [12] (2.0 μm) could also be the reason for this difference. It should be noted that unlike Fig. 8b, the combined data for Fig. 8c captured the overall response. However, selecting any individual results show a 40% difference for LCF and a 66% difference for HCF (Table 6). These results reiterate the importance of studying the combined data as well as confidence intervals for correct fatigue predictions.

Similar to Fig. 8c and. d shows the assessment of the process reproducibility for 316L, from two authors [12,14] for vertical as-built samples under $R = -1$. The results show a minor difference between individual and combined data points. In addition, the combined data captured all data points from the two data sets. However, comparison between the two data sets showed a 31.28% difference under LCF and a 28.91% under HCF as shown in Table 7. These differences between the data sets and confidence intervals could be due to the large difference in the surface roughness of the samples (7.3 μm [14], and 6.0 μm [12]).

3.4. Effects of different sample conditions

The main effect plot is a quantitative graphical representation that shows the effect of different conditions on the fatigue life of 316L and 17-4 PH LPBF parts. This includes post-processing steps such as heat and surface treatments. This analysis was performed to understand the contribution of various sample conditions on the fatigue life, Fig. 9a shows the main effect plot of all conditions listed in Table 1 for 316L. It can be observed that Machined-Heat Treated (M-HT) condition had the highest effect on the resulting maximum stress (σ_{max}), while As-built-Polished (AB-P) had the lowest effect on the maximum stress of all the conditions studied. Therefore, results show that the longest fatigue life can be achieved by a M-HT sample. It should be noted that samples with M-HT, HFMI, M-P-HT, M − P conditions show near similar behavior in fatigue performance. These results show that the effect of machining and polishing is similar to heat treatment as M − P enhances the surface condition and therefore results in higher fatigue life.

Similarly, for 17-4 PH, Fig. 9b shows the main effect plot for the conditions listed in Table 2, with M − P having the highest effect on the maximum stress (σ_{max}). Comparing the two materials (316L and 17-4 PH) it can be observed that M − P condition had the higher effect in both cases compared to M-P-HT conditions.

4. Conclusions

In this study, fatigue parameters (Orientation, Condition, Number of cycles (to failure), Authors, and R-ratio) were analyzed statistically using experimental cyclic data for laser powder-bed fusion (LPBF) stainless steel 316L and 17-4 PH additively manufactured (AM) parts. The main findings from this study are as follows:

1. All fatigue data was subjected to normality tests and both (316L and 17-4 PH) data sets passed the normality assumption. Results from the order plot showed data independence for both materials while scatter plots displayed a higher variance for 316L. Similarly, histogram of residuals showed near normal distribution for both materials.
2. Statistical results for 316L showed that the Number of cycles to failure had the highest significance, while the R-ratio had the lowest. In addition, Orientation was not found to be a significant factor (P-value = 0.826) for 316L as the statistical variance observed within the vertical samples captured the fatigue response from all orientations.
3. Results for 17-4 PH showed that the Number of cycles and Orientation were significant (P-value <0.05), with the Number of cycles being the most significant.

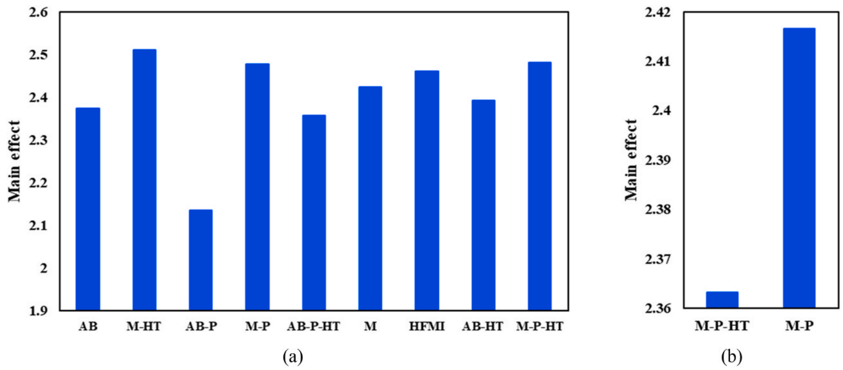


Fig. 9. Conditions main effect for (a) 316L and (b) 17-4 PH stainless steel samples.

4. Repeatability assessment with different machines (316L) was performed and showed minor deviations between low cycle fatigue (LCF - 2.75%) and high cycle fatigue (HCF - 3.13%) results.
5. Reproducibility assessment of 316L between different authors showed significant differences (28.14% difference under LCF and a 39.16% under HCF) between different datasets. However, combined datasets were able to capture the overall trend with higher accuracy
6. Condition assessment highlighted the contributions of various surface conditions on the fatigue strength and showed that Machined-Heat treated (Condition) samples had the highest effect (main effect = 2.5) while, As-built-Polished (main effect = 2.1) had the lowest effect for 316L samples. Machined –Polished (main effect = 2.4) had the highest effect for 17-4 PH.
7. The statistical analysis results presented in this work suggest a combined approach to get reliable predictions and confidence bounds under cyclic loading. In addition, a higher fatigue life can be guaranteed by Machined-Polished samples.

Disclosure statement

There are no relevant financial or non-financial competing interests to report from the authors.

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

CRediT authorship contribution statement

Ali Alhajeri: Writing – original draft, Visualization, Formal analysis. **Oluwatobi Aremu:** Writing – original draft, Formal analysis, Conceptualization. **Mosa Almutahhar:** Writing – review & editing, Methodology, Formal analysis. **Mohammed Yousif:** Methodology, Formal analysis, Data curation. **Jafar Albinmousa:** Writing – review & editing, Validation, Supervision. **Usman Ali:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Usman ali reports financial support was provided by King Fahd University of Petroleum & Minerals.

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