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LOCATION AND ORIENTATION DEPENDENCY IN SURFACE ROUGHNESS OF NICKEL SUPER ALLOY 625 PARTS: STATISTICAL AND DISTRIBUTIONAL ANALYSIS

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Abstract

Surface roughness is an important characteristic of additively manufactured parts, since it can impact various mechanical properties, such as friction or fatigue life. Further, surface roughness can change significantly depending on a number of factors: part geometry, location on the build platform, process parameters, or powder characteristics. Generally, it has been previously established that printing angle has a significant effect on surface roughness. In this study we reanalyze a dataset constructed based on Laser-Beam Powder Bed Fusion manufactured Nickel super alloy 625 parts. The goal is to evaluate the effect of location and print orientation on the variability of surface roughness, particularly relative to printing angle. Different combinations of location orientation-angles factors are tested using analysis of variance (ANOVA), with some significant findings. In addition, we further consider the question of characterizing surface roughness measures as applied to additive manufacturing and explore distributional analysis (particularly extreme value theory) as a way to qualify these measures.

Keywords: Additive manufacturing, Surface roughness, ANOVA test, Extreme value theory

Introduction

Additive manufacturing (AM), the process of layer-by-layer fabrication, has simplified the creation of highly complex and customized geometries and many of its advantages are well-documented in the literature, particularly for applications involving limited production quantities or peculiar shapes. Surface roughness of completed parts made through an AM process is one of the key issues that stand in the way of wider application of the technology. Particularly, roughness properties of the parts can be fundamental for applications, where 1) fit and structure are significantly critical or 2) at the point when parts have minuscule component sizes. The layer-wise nature of additive manufacturing naturally creates a mechanism for increased roughness. With the rise in prevalence of metal AM for advanced and complex designs, understanding the surface

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roughness characteristics in this process is essential [1], particularly since it is reliant upon complex interactions between process and design parameters.

Orientation of the surface has a crucial role in parametrizing the surface roughness [2]. To analyze the roughness, it is important to investigate the interdependencies among the laser angle, the part position, and the orientation of the surface, all of which may have an effect on the resulting built-part properties. Printing angle is the best-studied factor when applied to surface roughness properties. For example, Strano et al. have used selective laser melting to fabricate Steel 316L alloy parts and studied the effect of different rising angles on surface roughness. The surface investigation has showed an expanding thickness of extra particles situated along the edges, as the surface inclining point rises [3]. The position and angle dependencies were also explored by Kleszczynski et al. on surfaces away from the laser [4]. Overall, flat surfaces oriented parallel to the build plane have been shown to have lower surface roughness compared to the vertical ones [5]. It is well-established that surface roughness tends to increase with the increase in the surface angle towards the vertical [6]. Snyder et al. explored surface roughness for three different build directions with Inconel 718 parts and observed that vertical direction led to the lowest surface roughness [7]. Fox has studied the effect of surface orientation based on nine different angles on surface roughness parameters [8] and also observed a significant effect of printing angle.

In this work, we focus on other factors that may be relevant to surface roughness characterization, specifically, location and build-orientation dependency. We reanalyze the data collected on samples manufactured for one of the previously published studies [8]. The primary research question, then, is whether there exists evidence for location and/or orientation effect on surface roughness characteristics. Particularly, we are interested in making statistically significant claims to answer this question. Secondly, we are also aiming to perform a preliminary analysis into understanding distributional characteristics of additively manufactured parts. In a previous work, Fox et al. have established that extreme value analysis, specifically Gumbel distribution fitting, can be a useful tool in understanding and describing Sv particularly [9]. Here we consider another extreme-value distribution analysis based on generalized Pareto distribution as a way to characterize roughness profile.

Methodology and analysis

This research uses the data collected in a previously published paper by one of the co-authors [8]. The part design and dimensions are shown in the Figure 1. The parts were fabricated using Nickel Super Alloy 625 on an EOS M290 laser powder bed fusion machine at the National Institute of Standards and Technology (NIST). To quantify profile heights Alicona Infinite FocusXL200 G5 with Real3D Rotation Unit (focus variation microscope) was used. All details regarding the build setup, processing parameters, handling, and data measurements were presented in the original paper. Each sample contains eight ribs and each rib contain nine angled surfaces. Each surface is a 5 mm by 5 mm plane. Measurements of these surfaces were cropped to 4 mm by 4 mm images.

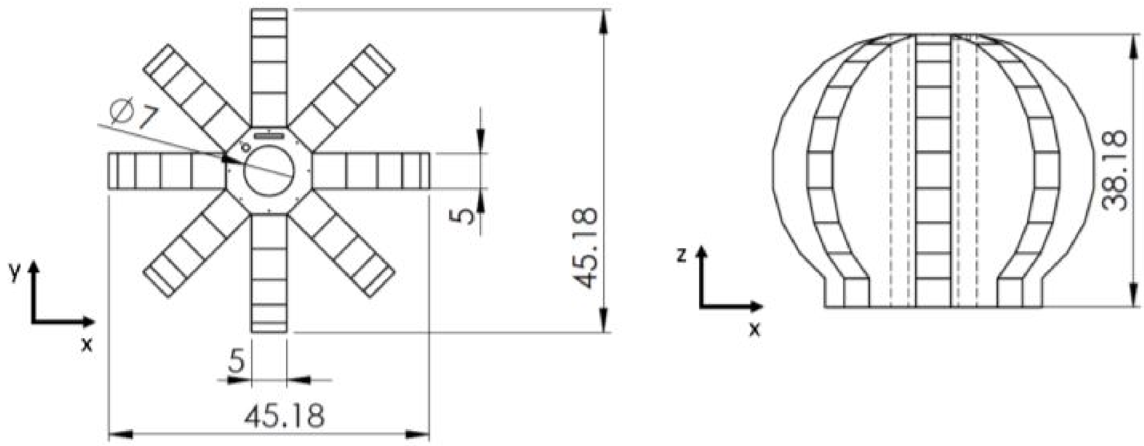


Figure 1 Schematic of the test artifact. Dimensions are in millimeters[8]

Surfaces start with angle of 165° and decrease by 15° per surface with the last surface having an angle of 45°. Table 1 summarizes the angles and surface labels. Figures 2 and 3 further depict the rib orientation and surface positioning. In all samples, Rib 1 faces the back and Rib 5 faces the front of the machine.

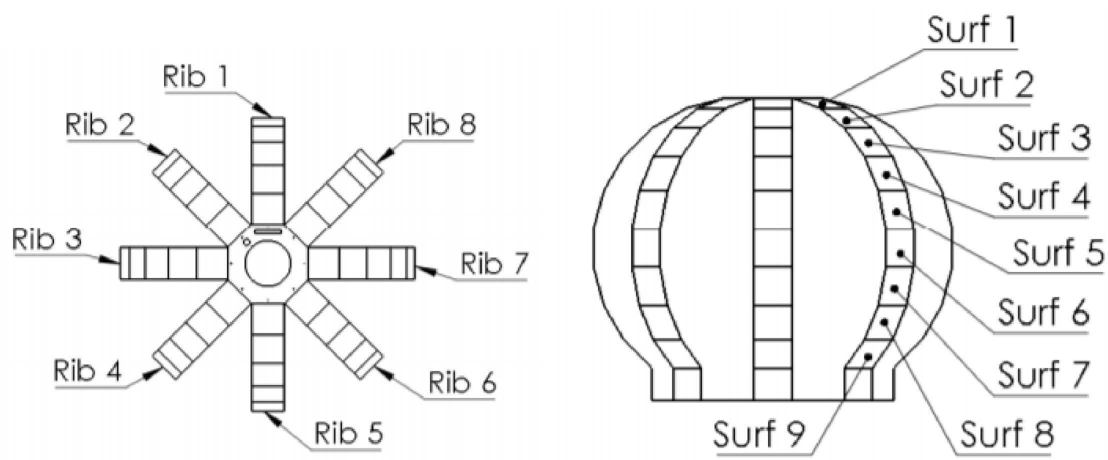


Figure 2 Identification of ribs and surfaces of the artifact [8]

Table 1 Angle of each surface as measured from the build plate [8]

Surface	Angle (°)
Surface 1	165
Surface 2	150
Surface 3	135
Surface 4	120
Surface 5	105
Surface 6	90
Surface 7	75
Surface 8	60
Surface 9	45

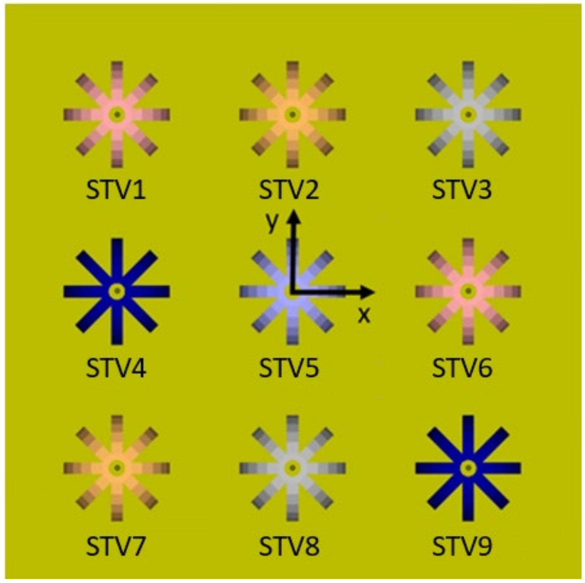


Figure 3 Top view rendering of the part positioning [8]

Given that surface data contains the height of the profile, form removal and leveling were performed on the data. Gaussian filter was applied to the data with a short cut off equal to 2.5 μm and a long cut off equal to 2.5 mm. We focus on surface roughness parameters Sa and Sq, which are calculated as

$$Sa = \frac{1}{L}\int_0^L |z| \quad (1)$$

$$Sq = [\frac{1}{L} \int_0^L z^2]^{1/2}, \quad (2)$$

where, L is the evaluation length and z is the profile height.

<u>Orientation and location dependency results</u>

As noted earlier, the effect of surface angle on roughness has been previously established, including observations made on this dataset. Figure 4 depicts the surface roughness parameters based on the angle of the plane for all surfaces. It can be observed that surfaces at 45º and 65º angle are the roughest in both parameters, while the surfaces at 90º and 105º angle are the smoothest. Recall that the former two are downward facing, while the latter two are close to perpendicular to the build plate.

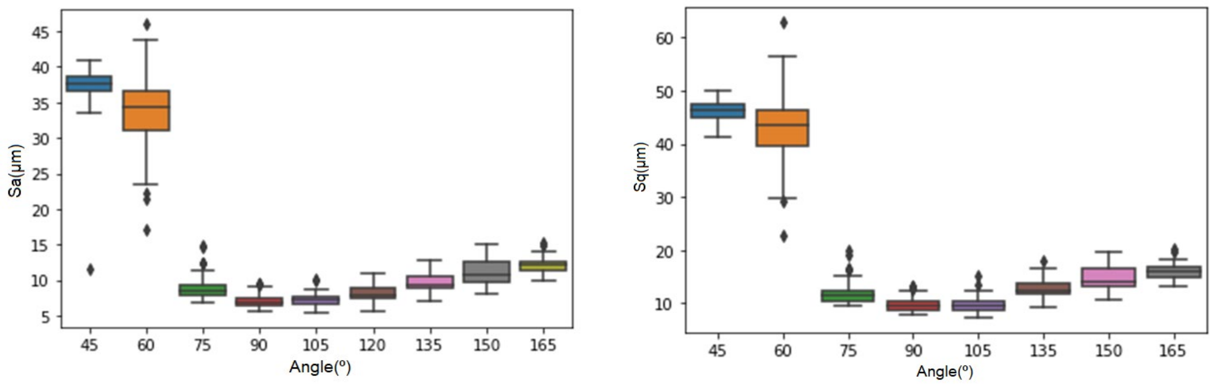


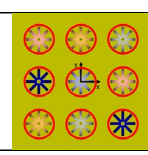
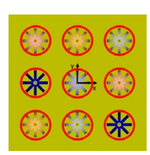
Figure 4 Surface Roughness (Sa, Sq) vs Angle

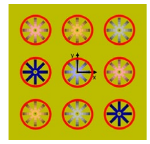
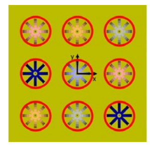
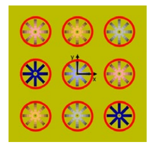
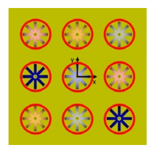
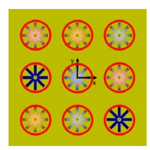
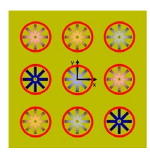
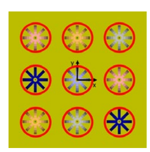
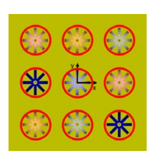
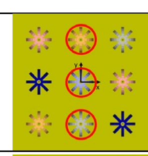
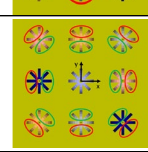
Observe that the conclusion above reflects an effect that is relatively substantial, and hence can be observed visually without advanced statistical analysis. At the same time, as far as orientation or location dependency are concerned, the expected effect is less pronounced and hence a more careful analysis may be required. Specifically, since we are looking to evaluate whether either orientation or build-plate location have an effect on either of the roughness parameters, we perform a family of analysis of variance (ANOVA) tests as follows. Different combinations of the surfaces and ribs are selected. The hypothesis for the ANOVA test is constructed as follows:

$$H_0: \mu_1 = \mu_2 = \mu_3 = \cdots = \mu_9$$
$$H_1: At\ least\ one\ is\ different,$$

where μ_i is the mean of the specified surface profile for sample STV_i. A significant result (usually, p<=0.05) based on the p-value in any of the cases then indicates that the corresponding means are different, i.e., the corresponding factor has a significant effect on roughness. Table 2 provides the description of tests performed and corresponding p-values.

Table 2 ANOVA test results

Test #	Tested surfaces	Locations	P-Value	Significance
1	All surfaces, All ribs, All specimen		S_a: 0.996	Not Significant
			S_q: 0.994	
2	Surface number 1 (165º) of all ribs, All specimen		S_a: 0.067	Not Significant
			S_q: 0.096	
3			S_a: 0.887	

	Surface number 2 (150°) of all ribs, All specimen		$S_q: 0.872$	Not Significant
4	Surface number 3 (135°) of all ribs, All specimen		$S_a: 0.718$ $S_q: 0.572$	Not Significant
5	Surface number 4 (120°) of all ribs, All specimen		$S_a: 0.289$ $S_q: 0.204$	Not Significant
6	Surface number 5 (105°) of all ribs, All specimen		$S_a: \approx 0.0$ $S_q: \approx 0.0$	Significant
7	Surface number 6 (90°) of all ribs, All specimen		$S_a: \approx 0.0$ $S_q: \approx 0.0$	Significant
8	Surface number 7 (75°) of all ribs, All specimen		$S_a: 0.001$ $S_q: \approx 0.0$	Significant
9	Surface number 8 (60°) of all ribs, All specimen		$S_a: 0.165$ $S_q: 0.429$	Not Significant
10	Surface number 9 (45°) of all ribs, All specimen		$S_a: 0.131$ $S_q: 0.290$	Not Significant
11	Surfaces 5, 6, 7 of all ribs of STV2, STV5, STV8		$S_a: 0.003$ $S_q: 0.005$	Significant
12	Opposite ribs, Toward center and away from center		$S_a: 0.273$ $S_q: 0.952$	Not Significant

The first 10 tests evaluate the effect of specimen location on the build plate on the mean of the roughness profile, either across all surfaces together (Test #1) or for each surface angle separately (Tests #2-#10). Observe that of these the only significant results correspond to the approximately vertical angles (surfaces 5-7), which have also been found to be relatively smooth. We can then conclude that for these effects, there exists evidence of location dependence for both roughness measures. On the other hand, rougher downward facing surfaces did not exhibit statistically significant dependency. Test #11 further evaluates this aspect by considering samples STV2, STV5 and STV8 only. We again observe a significant difference. Finally, Test #12 evaluates whether orientation of the surface (i.e., towards (green ovals) or away (red ovals) from center) has a significant effect. Results for opposite ribs were not significant for any of the combinations. We then conclude that while there is evidence for some location dependency, it is only limited to some of the tested cases. On the other hand, it should be emphasized that relatively small sample sizes limit the potential for making significant conclusions.

Distributional analysis of surface roughness.

Generalized Pareto Distribution (GPD) is a continuous distribution normally applied to the model tail of a distribution. Consequently, we surmise that it can be directly relevant for characterizing surface roughness, especially for AM parts that can exhibit significantly non-normal surface profiles. Specifically, we expect that GPD-based modeling can help to distinguish between heavy-tailed surface profiles (i.e., rough surfaces) from light-tailed profiles (i.e., smooth surfaces), which can then streamline the location-dependency analysis of interest.

GPD is generally identified by its shape parameter k, particularly, the sign of the parameter primary distinguishes between the heavy-tailed vs light-tailed distributions [10]. Pickands first introduced a generalized Pareto distribution in the context of statistical inference concerning the tail of a distribution [11]. The method based on analysis of exceedances relative to a pre-set threshold was developed by Davison [12]. Exceedances, which are the values greater than a threshold subtracted from a pre-defined threshold, are presumed to follow a generalized Pareto distribution with cumulative distribution function given as follows [13]:

$$F(x;k,\sigma) = \begin{cases} 1-\left(1-\frac{kx}{\sigma}\right)^{\frac{1}{k}}; \;\; k \neq 0, \sigma > 0 \\ 1-\exp\left(-\frac{x}{\sigma}\right); \;\; k = 0, \sigma > 0 \end{cases}, \tag{3}$$

where σ is the scale parameter and k is the shape parameter. Both are estimated with the maximum likelihood method. In this study, threshold is selected to be equal to 95 percent.

Figure 5 depicts surface profile for surfaces 1, 6, and 9 for Rib1 of specimen 1 and their relative fitted GPDs for exceedances. To streamline the computations, here we sampled 10,000 data points for each profile. Exceedances are calculated based on the threshold and a generalized Pareto distribution was fitted on the exceedances. The Anderson-Darling test was used to evaluate goodness of fit [14]. All the results were not significant; this means that all samples’ exceedances can be modeled as following generalized Pareto distribution with the specified threshold.

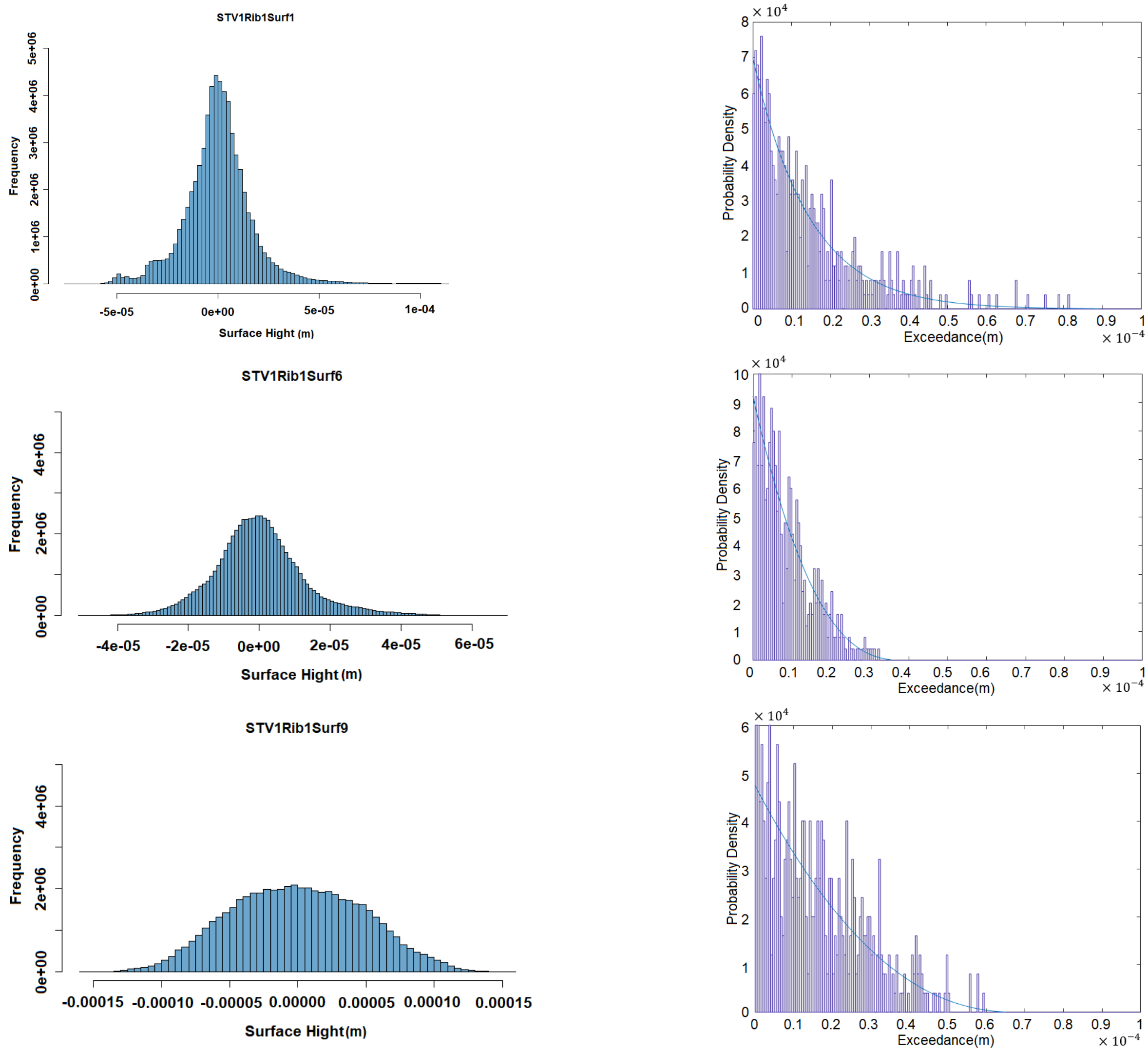


Figure 5 Surface profile and relative GPD fit

Recall that based on the previous analysis of the effect of surface angle on roughness, we already observed that the three surfaces do exhibit significantly different behavior, with surface 9 being the roughest and surface 6 the smoothest. Shape parameters were calculated for the three surfaces in order to make a comparison among the roughest surface (surface number 9 with 45º), the smoothest surface (surface number 6 with 90º), and the surface with medium roughness (surface number 1 with 165º). The results presented for three samples (STV1, STV5, STV9) and ten times resampling are given in Figure 6.

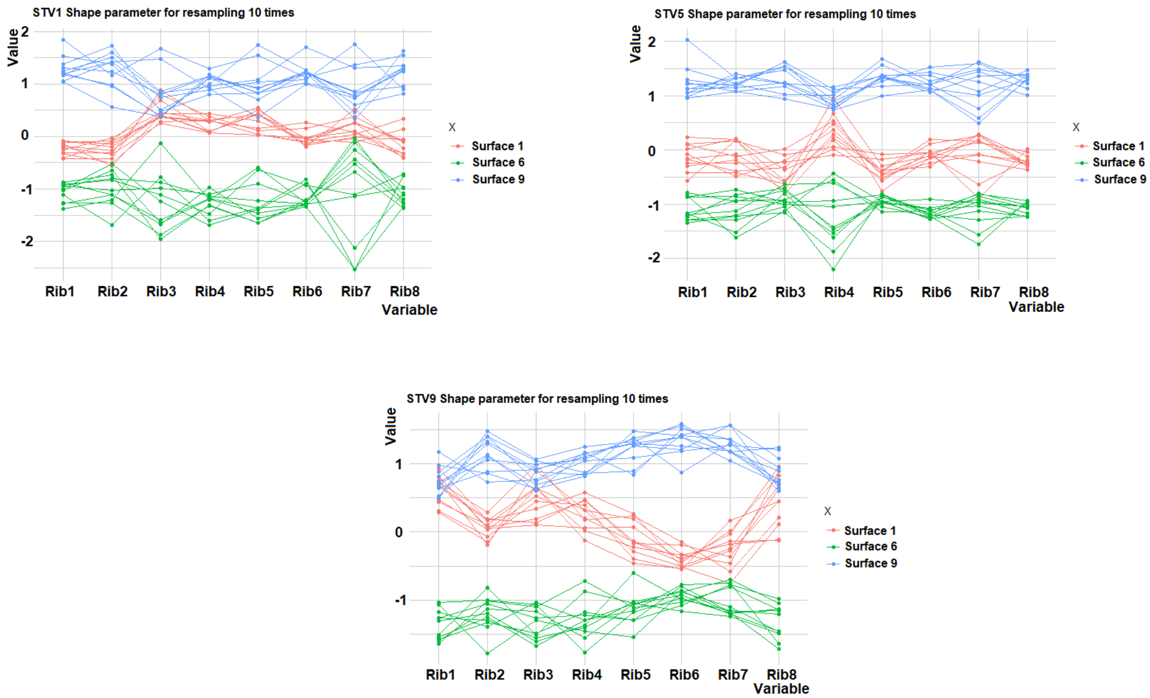


Figure 6 Shape parameter for three samples and three surfaces with ten resampling

Specifically, we observe that the three surfaces consistently correspond to three different classes based on the sign of the shape parameter. Particularly, surfaces known to be rough are characterized by a highly heavy-tailed distribution of the tail of exceedances, while smoother surfaces correspond to light tailed distribution of exceedances. This observation, by itself, is not surprising, since a heavy-tailed exceedance distribution directly translates into higher roughness. At the same time, we surmise that such an analysis may be interesting for better characterizing roughness of the surface as a whole, since it explicitly addresses the non-normal behavior of surface profile for AM parts.

Conclusions

Surface roughness varies based on various conditions like the geometry and part orientations. In this study, in phase one diverse combinations of ribs and surfaces were tested using ANOVA test to assess the dependencies of the surface roughness based on the angle of the surface and the orientation of the part on the build plate. For phase two of this study extreme value analysis was adopted to analyze the exceedance of the surface distribution and model the samples based on generalized Pareto distribution.

Results of phase one showed a significant difference between means of some of the samples for surfaces at vertical angles (105º, 90º, and 75º). This also applies for all samples on mentioned surfaces independently. On the other hand, no significant results were observed for other angles. Note though that this lack of significance may be due to relatively low samples sizes. Consequently, we conclude that while we observe some evidence of location and orientation dependency, more research is needed to unambiguously determine precise cases where this effect is significant.

Results of phase two indicate that GPD can be representative of the tail distribution of the profile and the shape parameter can be applied as a roughness measure. The shape parameter is higher for rougher surfaces and is lower for smoother surfaces. Since in AM parts particularly, the tail end of the roughness profile may be especially important, we surmise that such an analysis may be important in terms of relating roughness characteristics with part performance properties, which we intend to study in future research.

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