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Reviewed Paper

Surface Roughness Variation in Laser Powder Bed Fusion Additive Manufacturing

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Abstract

The surface roughness of an additively manufactured part produced through laser powder bed fusion has a significantly higher roughness than surfaces produced through traditional manufacturing processes. This roughness can have a significant impact on mechanical properties such as the fatigue life. Additionally, there is still a lack of understanding of the variation of the surface roughness and the appropriate metrics to represent the surface. This work presents line of sight measurements across several large surfaces with changing processing parameters and layer geometry. The measured areas are divided into regions where surface measurement metrics are calculated, and the surface variation within and across the surface is discussed. The calculated metrics and variation are related to the expected impact that the surface will have on the mechanical performance. Results from this research will provide guidance towards surface roughness metric specifications to ensure quality parts with consistent mechanical performance.

Introduction

Additive manufacturing (AM) is a fabrication process that creates parts in a layer-by-layer fashion. As opposed to traditional fabrication techniques, AM has the capability to reduce production time, material consumption, and energy usage. Additionally, AM possesses the unique ability to create parts with complex features at a high precision. Laser powder bed fusion (LPBF) is a metal AM process, during which thin layers of powdered metal are fused together by selectively melting the shape on a given layer. This process is popular for the creation of parts with complex designs due to its fine feature resolution.

Although LPBF offers many benefits, there is still much to be learned about its processing-structure-properties-performance (PSPP) relationships before it can be used to confidently create parts with sufficient structural integrity. One of the predominant disadvantages in LPBF is the low fatigue life, which is caused by process-induced defects such as subsurface pores, internal pores, and surface notches [1, 2]. Although any type of defect can weaken the performance of the part, rough surfaces have been shown in prior studies to be the leading cause in decreasing the fatigue life [3, 4, 5, 6, 7]. As a result, many parts created via AM go through post processing to eliminate or reduce the defects present on the surface. However, the surface quality is very difficult or even impossible to alter in components that contain complex internal geometries, such as the internal cooling channels of a turbine blade or the core of a heat exchanger. As a result, such features must be left in the as-built or unmachined stage. Therefore, it is important to understand both the causes of surface roughness and the influence that it has on the fatigue performance.

As AM applications become more popular, the relationship between surface roughness and fatigue is becoming increasingly important to understand. In previous research by Fatemi et al., it was determined that as-built surface roughness dominates the multiaxial fatigue behavior in additively manufactured Ti-6Al-4V [8]. The fatigue-dominating behavior of surface roughness was again reaffirmed by Sanaei et al., who used the average roughness (Ra) parameter to show that a decreased surface roughness generally increases the fatigue performance of AM Ti-6Al-4V [9]. In a study by Romano et al., it was shown that using a maximum defect size, the fatigue life of an AM specimen can be predicted with a reasonable degree of accuracy [10]. In addition to this, other research efforts have shown that downward-facing angled AM surfaces significantly reduce the fatigue life of components due to the increased roughness of these surfaces [11, 12, 13]. The surface roughness is known to control the fatigue performance of a component. The maximum surface notch, Rv or Sv has been shown to relate to the fatigue failure [14, 15]. However, this roughness varies significantly across AM surfaces, which is not often discussed in literature. Therefore, one of the main goals in this research is to investigate the variations in the surface roughness of AM metals.

In AM, layers are often created using a technique that combines both contour and bulk scans, as shown in Figure 1. The contour, shown in green, is essentially an outline of the layer geometry, while the bulk scan, shown in red, melts the internal area of the layer. The formation of surface features, such as notches, is controlled by the melt pool size of the contour scan, which is directly related to the contour processing parameters that are used throughout the build [16, 17]. Additionally, previous research has shown that the contour processing parameters strongly influence the surface features in as-built parts created with LPBF [14, 18, 19]. As a result, this study focuses on the relationships between contour processing parameters and the resulting surface roughness variations.

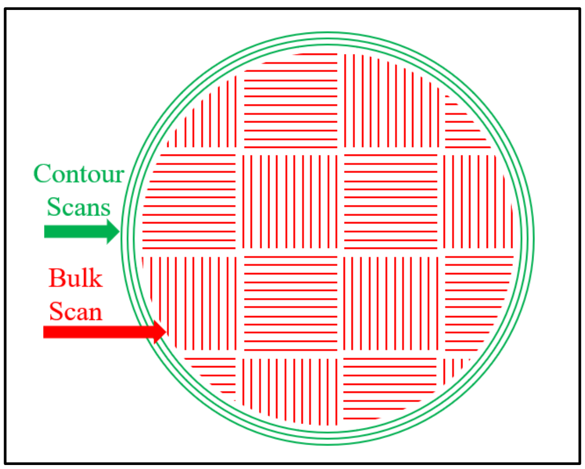

Figure 1: Contour scan versus bulk scan path in AM.

Prior research has shown that a decrease in the contour power increases the roughness of the AM surface [9, 14]. As shown in the plots in Figure 2, a low power specimen results in deeper valleys and higher peaks than a specimen produced with a higher contour power. In order to characterize AM surfaces, two classifications of metrics have been developed to quantify the roughness of the surface. These classes of surface metrics are known as line metrics and area metrics [20]. Line (or 2D) metrics utilize the height data from a single line on the surface of the specimen. As a result, a single line metric is unlikely to include the whole range of data of an entire surface. However, area (or 3D) metrics utilize the height data from a larger surface area on the specimen. As a result, area metrics are generally more reliable because they have the ability to capture more of the data in the surface. However, such scans require a significantly larger amount of time and data usage, making area metrics costlier and less feasible to calculate than line metrics. This research investigates the variation of line measurements, with the eventual goal of determining the necessary number of line measurements taken to accurately represent the surface without having to scan the entire surface.

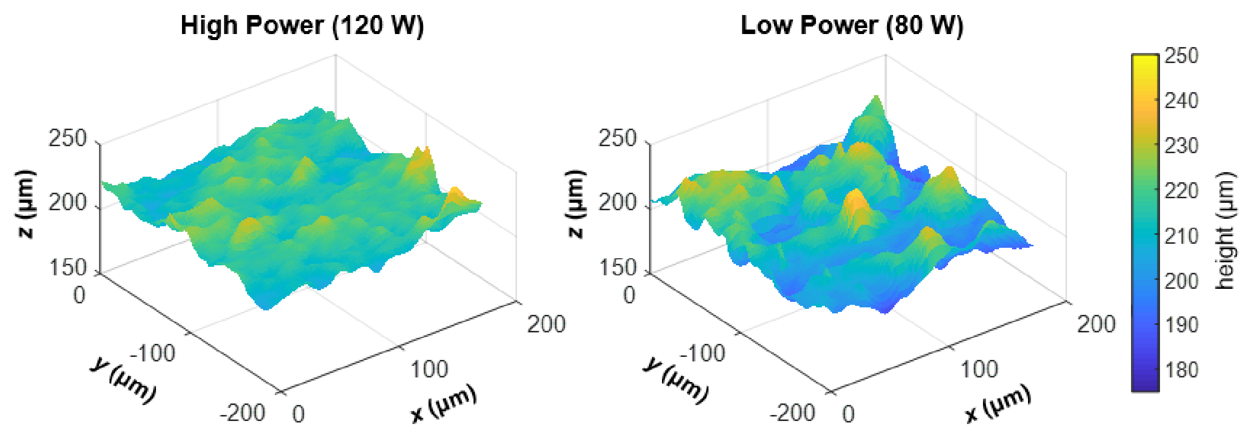

Figure 2: Sample surface roughness of both low power and high power AM surfaces.

Methodology

Previous research efforts have provided the samples and measurement data under investigation in this work [14, 21]. This provided the samples and height data for two triangular samples created via LPBF of alloy 718. Both samples utilized the same contour speed (560 mm/s); however, both a high power (120 W) and a low power (80 W) were used for comparison against one another. After these samples were fabricated, the specimens were scanned using a Keyence VR-3200 wide area 3D measurement macroscope which uses a structured light technique. Twelve regions of the specimen were scanned, six on the bottom and six on the top. The specimen geometry with the twelve scanning regions are shown in Figure 3. Each of these twelve regions were then scanned using structured light surface scanning, which provided the height data for the surface metric calculations.

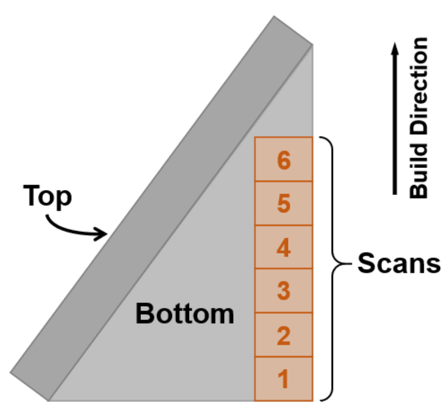

Figure 3: A representation of the geometry under investigation in this work.

The maximum valley depth is a common metric reported to describe the roughness of a surface because it is shown to heavily influence the fatigue life of the material [12, 14]. This metric is denoted with either Rv or Sv, which correspond to the line measurement and the area measurement, respectively. Rv is calculated by finding the distance between the mean of the height data and the maximum valley depth across the measurement line [22]. Sv is essentially a three-dimensional extension of Rv; that is, Sv is calculated by finding the distance between the mean surface and the maximum valley depth across the entire areal surface [23]. Because line measurements only measure a very small fraction of the surface, using a single Rv measurement may not adequately describe the surface of the specimen. However, evaluating the surface at a statistically significant number of Rv measurements allows for the possibility of obtaining a sufficient amount of data, without having to scan the entire surface. As a result, this work investigates the variations of these metrics in AM surfaces.

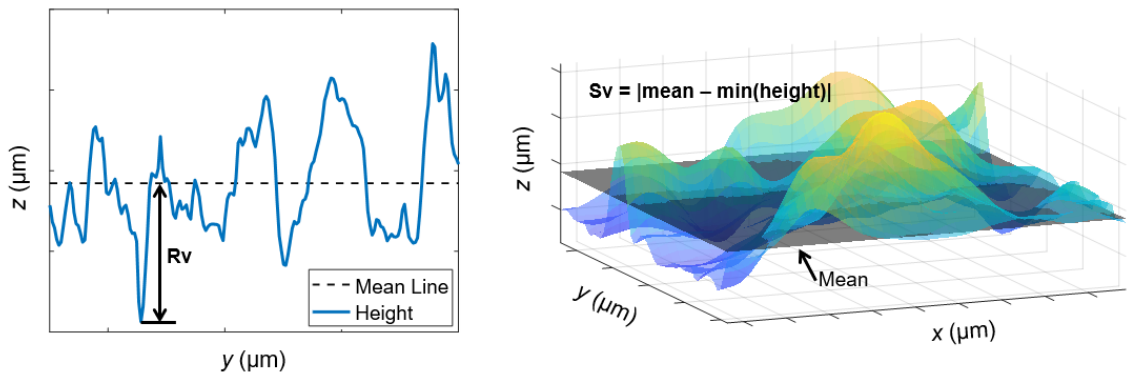

Figure 4: Comparison of Rv (left) and Sv (right) surface metrics.

Results and Discussion

The variations in the surface roughness metrics can be compared both across and within the samples. Across the samples, the area surface metrics are varied due to the change in power; the high power specimen exhibits smaller notches than the low power specimen, as shown in Figure 5. The Sv values in the low power specimen also exhibit more variation than the high power specimen. These Sv variations shown here are in good agreement with the findings in [14].

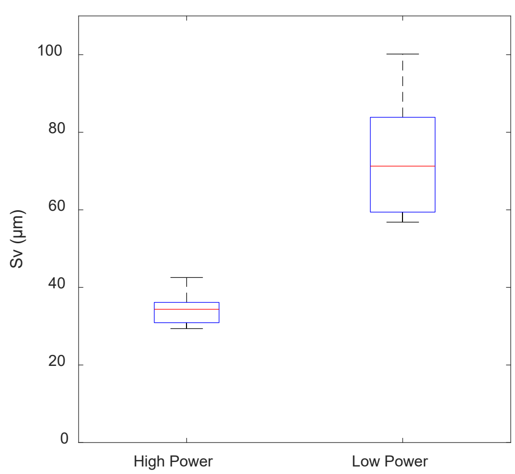

Figure 5: Comparison of Sv values for both high power and low power specimens, using the data from each of the twelve regions on the specimens.

Next, the variations of Rv values within the samples are plotted in the histograms in Figure 6. Here, it can be seen that the distribution of the Rv values are weighted more towards the smaller values, with only a few data points representing the most extreme notches. A more detailed statistical analysis will need to be conducted to determine the number of line measurements needed to capture an acceptable amount of data to appropriately represent the surface.

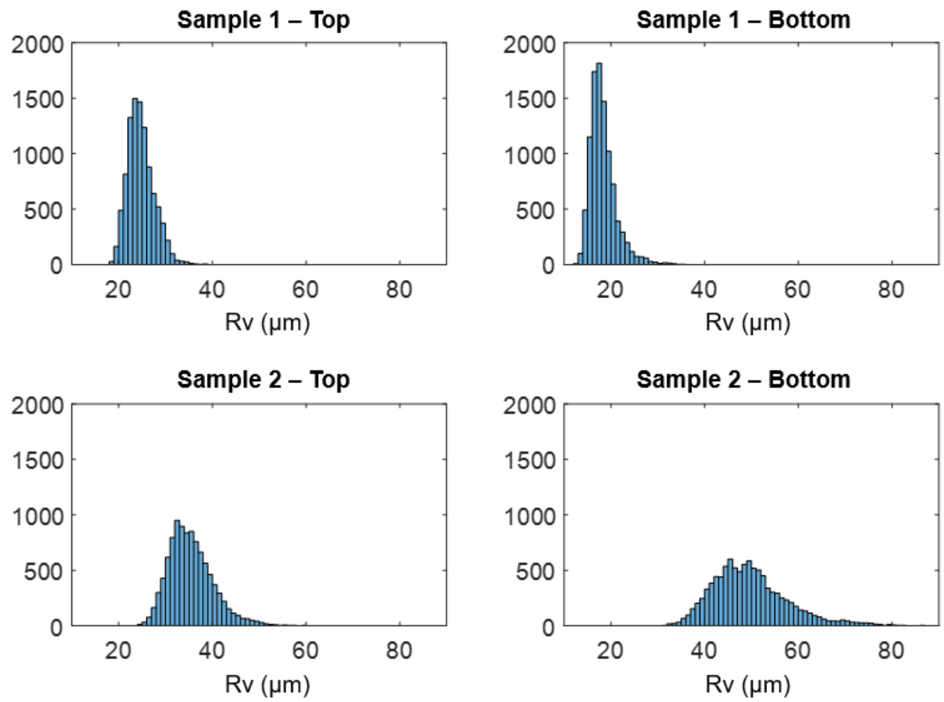

Figure 6: Histograms showing the variation of Rv within each of the samples.

In order to determine the amount of variation within each sample, the Rv metric has been calculated incrementally across each of the scanning regions as defined above. These roughness metric values are plotted in Figure 7 through Figure 10 along with the constant Sv value for each scanning region. In these plots, the *x*-axis represents the line measurement number, and the *y*-axis represents the roughness parameter in µm. For each side of the sample, there are six separate scanning regions that are displayed. Each of the red points shown on the plots represent the Rv measurement for the appropriate line measurement number, while the black dashed line corresponds to the constant Sv measurement for the entire scan. Here, it can be observed that Rv varies significantly within each of the scans, with more variation seen in the lower power sample. Additionally, it is important to note that Sv is not just a simple maximum value of Rv; each Rv value is shifted by its own mean value, while Sv is shifted by a different mean value. The maximum Rv is often very close to the Sv value; however, they are not necessarily the same.

In looking at these Rv and Sv plots, there are multiple instances in which a very sharp notch appears to occur with a magnitude that far exceeds the height of the rest of the scanning region. For example, scans 1, 4, and 5 in Figure 10 contain such peaks. These large spikes in the height data are only a few micrometers wide, however, and are unlikely to be indicative of real surface notches within the material. It is expected that these data spikes are caused by the structured light surface scanning method, either from the angle of the light rays or from a phenomenon within the reflection of the material. However, more investigation is needed to determine whether these data points actually indicate a steep notch in the surface of the material.

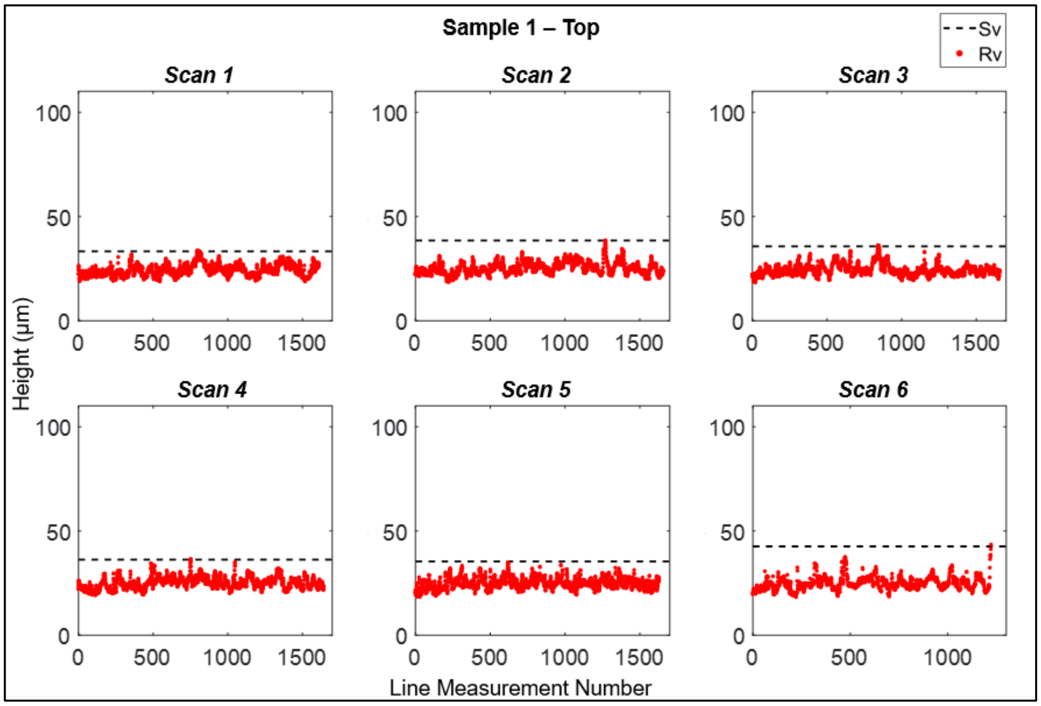

Figure 7: Rv and Sv measurements across the top of Sample 1.

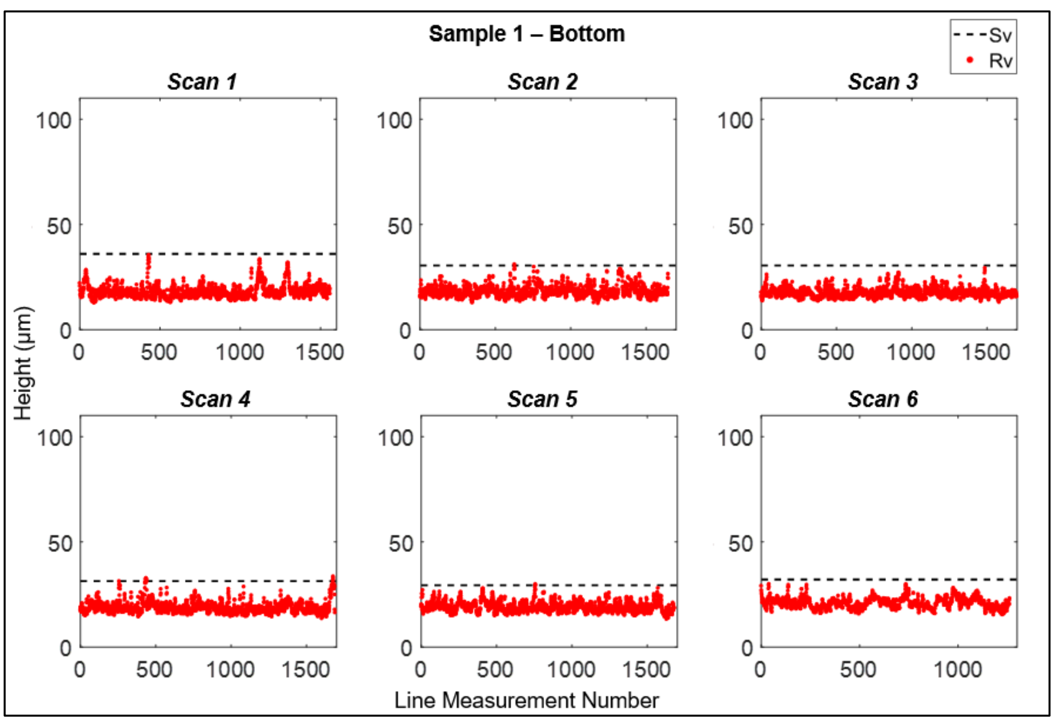

Figure 8: Rv and Sv measurements across the bottom of Sample 1.

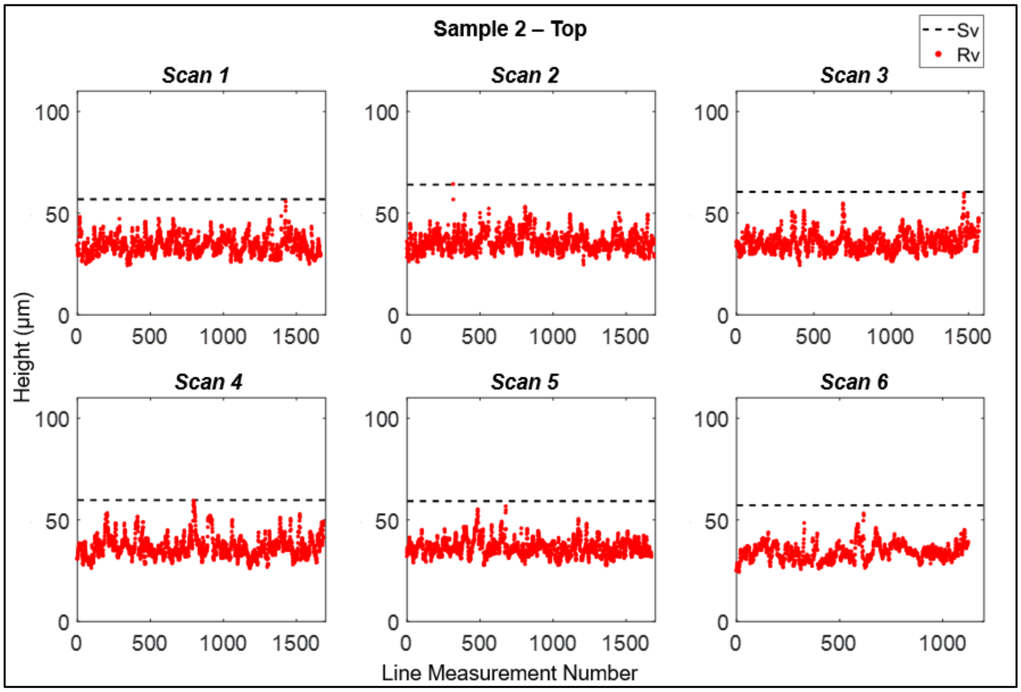

Figure 9: Rv and Sv measurements across the top of Sample 2.

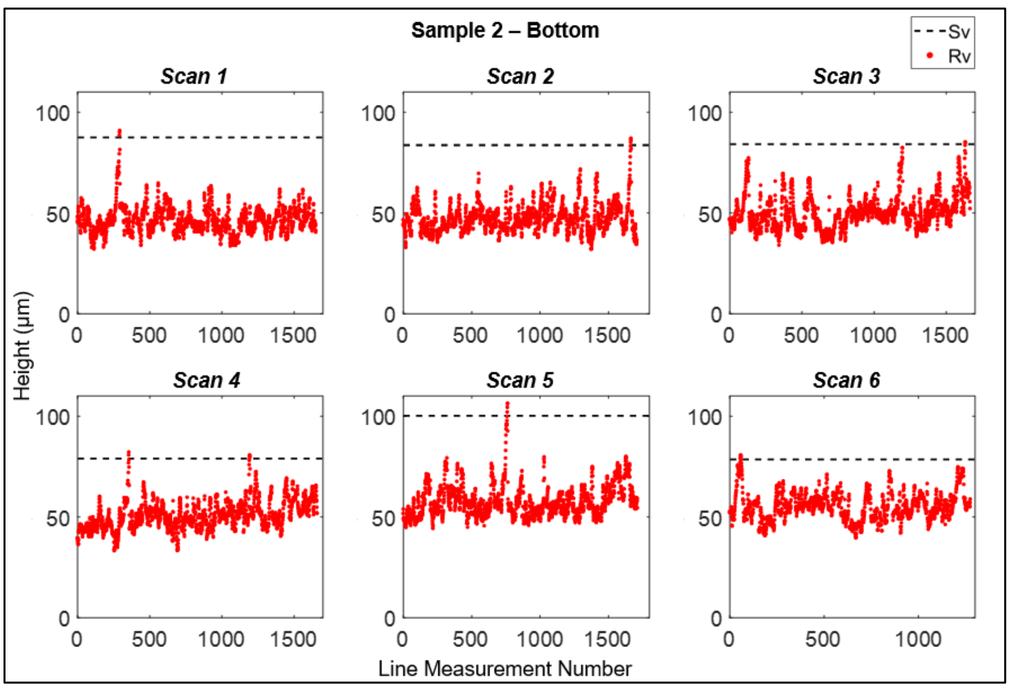

Figure 10: Rv and Sv measurements across the bottom of Sample 2.

Conclusions and Future Work

This work investigated the surface roughness of two specimens with constant contour speeds and varying contour powers. It was found that the sample with low power resulted in higher notches and thus, rougher surfaces. These results agree with the conclusions drawn in prior research. In addition, the variations in the surface roughness metrics were investigated, both across and within the samples. It was found that the low power sample exhibited higher variations in both the Sv and Rv surface metrics. Additionally, the variations of the Rv measurements within the samples were compared to the Sv value for each of the scanning segments. As expected, it was shown that Rv varies significantly across the samples, while Sv remains constant. Therefore, a small number of measurements may miss the largest notch in the surface. Further investigation of additional samples is needed to determine the minimum amount of surface that needs to be measured to capture the maximum notches that are present in the sample.

Although this study uses a small sample size that is not statistically significant, the results here still provide insightful information that is useful in determining the relationships between processing parameters and surface roughness variations in as-built parts created via LPBF. The results of this research provide a framework for future statistical studies to determine an appropriate amount of data that needs to be obtained in order to sufficiently represent the surface without the need to characterize the entire surface. Additionally, these results can be further enhanced in the future to predict the fatigue effects due to the surface roughness of the AM material.

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