Abstract

High Speed Sintering is an advanced powder bed fusion polymer Additive Manufacturing technique aimed at economical production of end-use parts in series manufacture. Surface finish is thus of high importance to end users. This study investigates the surface topography of High Speed Sintered parts produced using a range of different energy-related process parameters including sinter speed, lamp power and ink grey level. Areal surface texture was measured using Focus Variation microscopy and the sample porosity was systematically examined by the X-ray Computed Tomography technique. Surface topography was further characterised by Scanning Electron Microscopy, following which the samples were subject to tensile testing. Results showed that areal surface texture is strongly correlated with porosity, which can be further linked with mechanical properties. Certain texture parameters i.e. arithmetic mean height $Sa$, root-mean-square $Sq$ and maximum valley depth $Sv$ were identified as good indicators that can be used to compare porosity and/or mechanical properties between different samples, as well as distinguish up-, down-skins and side surfaces. $Sa$, $Sq$ and $Sv$ for up- and down-skins were found to correlate with the above energy-related process parameters. It was also revealed that skewness $Ssk$ and kurtosis $Sku$ are related to sphere-like protrusions, sub-surface porosity and re-entrant features. Energy input is the fundamental reason that causes varying porosity levels and consequently different surface topographies and mechanical properties, with a 10.07 $\mu$m and a 30.21% difference in $Sa$ and porosity, respectively, between the ‘low’ and ‘high’ energy input.

Keywords: Additive Manufacturing, High Speed Sintering, Areal Surface Texture, Porosity, X-ray Computed Tomography, Powder Bed Fusion

1. Introduction

Additive Manufacturing (AM) has been increasingly used to produce end-use components and products in recent years [1]. Continued technological advances have enabled certain AM processes such as powder bed fusion (PBF) based processes to make significant inroads into a broad market including aerospace, automotive, medical devices and consumer goods [2]. However, one of the main drawbacks that impedes the wide adoption of AM in industry is the surface roughness being at least an order of magnitude higher than other parts manufactured by traditional processes such as machining and injection moulding [3].
Defects on functional surfaces can eventually result in the failure of the component in service [4, 5]. Therefore, research has been undertaken to characterise surface topography of AM parts and to understand the influence of AM process parameters on surface roughness [6]. The research reported in the literature can be divided into two major areas, namely PBF metal and polymer AM related. In metal AM, Charles et al. [7, 8] assessed the impact of using different laser powers, scan speeds and hatch spacing on the generated surface roughness of the down-facing surfaces of the Selective Laser Melted (SLM) parts. Whip et al. [9] identified a strong correlation between surface average height (Sa), maximum valley depth (Sv) with laser powder in SLM. It was found that Sa and Sv decreased as the laser power increased. Similar findings were also reported by Koutiri et al. [10] and Calignano et al. [11] who also found that the scan speed had the greatest impact amongst laser power and hatch distance. Gockel et al. [4] attempted to correlate Sa and Sv with the fatigue strength of alloy 718 samples produced by SLM. Different laser contour parameters were used to first identify the trend of surface roughness variations, which were then correlated with the fatigue life. Increased Sv was found to correspond with a reduced fatigue life. The effect of build orientation on surface topography has also been researched. Fox et al. [12] reported that surface roughness (Ra) of overhanging features on SLM parts was not correlated with the build orientation. However, Sidambe [13] argued that the horizontal surfaces had a smoothest surface texture whereas the surfaces of the sample built in the vertical direction were found to be rough, attached with large volume of partially melted powder particles. Tian et al. [14] and Strano et al. [15] also found consistent results. In addition to laser power, scan speed, hatch spacing and build orientation, other process parameters that were studied include weld track width [16] in Electron Beam Melting (EBM) and laser scanning direction [17] in SLM. The research in the polymer AM field adopted approaches similar to metal AM to investigate the effect of process parameters on surface roughness. Mavoori [18] attempted to identify the appropriate laser power, layer thickness and bed temperature for Laser Sintering (LS) of polyamide-12 (PA12) parts. Sachdeva et al. [19] examined the surface roughness variations of PA12 parts fabricated by different laser powers, bed temperatures and hatch spacing in LS. The laser power between 28 to 32 W, 0.2 mm hatching and 175°C bed temperatures were found to result in the lowest surface roughness Ra (i.e. 5.46 µm). A similar study was conducted by Negi et al. [20], who identified that hatch spacing was the most significant factor, followed by laser power and scan speed for LS of glass-filled polyamide parts. Van Hooreweder et al. [21] pointed out that the layer-wise production manner and unmolten particles that stuck on the contour of LSed parts were considered to the main reasons that led to the surface roughness being an order of magnitude higher than that in injection moulding. Strano et al. [22] analysed the effect of build orientation on surface roughness Ra, whereby a computational model was developed to optimise build orientation and energy consumption.

As surfaces of additively manufactured parts are different from those produced by conventional processes, developing specific methods and surface parameters for AM surface characterisation has become a popular topic in recent years [6]. It is noted that, while most of these methods and parameters seem to be generic, the efficacy of these methods was usually demonstrated on metal AM surfaces, as reported in the literature. Pagani et al. [23] proposed a new method for measuring freeform surfaces and re-entrant features. A set of 3D surface texture parameters was defined based on triangular mesh, which was able to represent specific 3D surface topography features such as re-entrant features that cannot be precisely measured by traditional measurement techniques. Du Plessis and le Roux [24] proposed a method to standardise the procedures for measuring surface texture parameter Sa and dimensional accuracy of metal AM parts. Zanini et al. [25] investigated the
validity of using a set of generalised surface texture parameters to represent re-entrant features on the SLMed part surfaces. Lou et al. [26] developed a bespoke characterisation procedure for PBF metal surfaces where the robust Gaussian regression and the morphological filters were adopted to separate waviness component in roughness measurements. In the paper by Klingaa et al. [27], a new method for characterising surface texture of internal surfaces of SLMed conformal cooling helical channels was proposed. On the PBF polymer side, Vetterli et al. [28] proposed and evaluated a novel method for charactering surfaces processed via LS. An elastomeric gel pad was pressed onto the surface, enabling the reflective skin on the other side of the pad to form a positive imprint. The pressure depending on the surface topography was detected by a sensor, allowing a height map to be calculated. The results showed a consistent measurement repeatability and reproducibility within 4% and 6% error range, respectively.

In recent years, three-dimensional (3D) areal surface texture measurement has been progressively accepted as an appropriate way to characterise AM surfaces as compared to two-dimensional profile measurement [3]. Tactile and optical methods are the two industrially recognised mainstream techniques for texture measurements [29], and X-ray Computed Tomography (XCT) technique has also drawn significant attention due to the capability to measure hard-to-reach and internal surfaces [3, 30-32]. The majority of the effort was made in the PBF metal domain. Thompson et al. [33] conducted a quantitative comparison between optical and XCT techniques for areal surface topography measurements of SLMed parts. Results showed that XCT was the least repeatable. Townsend et al. [34] assessed the validity of using XCT for surface topography measurements, in terms of measurement deviation, repeatability and reproducibility. Triantaphyllou et al. [35] measured the areal surface texture of SLM and EBM parts using both optical and tactile methods, and claimed that the difference between them was of little significance. Cabanettes et al. [36] further added that the optical Focus Variation technique was well suited for measuring surface texture of SLMed parts built in different orientations. In addition to metal AM work, systematic comparisons between tactile profile and optical measurement techniques were also conducted to characterise surface texture of Laser Sintered polymer parts [29]. Launhardt et al. [29] found that the tactile method resulted in the most repeatable and reproducible results whereas it usually caused minor damages to the measured surfaces. By contrast, optical methods showed unique advantages in characterising and visualising 3D surface topography, with Focus Variation being the most reliable among other optical methods.

High Speed Sintering (HSS), as a novel and disruptive PBF based AM technique, was invented specifically for medium to high volume production of end-use components [37, 38]. The surface quality is therefore of high importance to end users. Areal surface texture measurement is increasingly gaining consensus as the current best way of characterising the 3D surface topography of an additively manufactured part [3]. However, the eventual surface topography is affected by a number of factors involved in the sintering process including energy source, feedstock material, fusion of powder particles etc. Thus, this study aims to understand this complex interaction between surface texture and the HSS energy-related process parameters through investigating areal surface texture, porosity and the resulting mechanical properties. Three process parameters (sinter speed, lamp power and ink grey level) were studied. The experimental methods are described in Section 2. The results are presented in Section 3, which is followed by in-depth discussion and conclusions in Sections 4 and 5.
2. Material and methods

2.1 Material

Virgin PA2200 (polyamide-12, also known as Nylon-12) supplied by EOS GmbH was used as the raw material powder to manufacture the test samples. This is the most ‘standard’ and repeatable material for powder bed polymer AM [39], and is the most well-documented material to date for HSS. The average powder size was 56 µm and D90 was 90 µm.

2.2 The High Speed Sintering process and machine

HSS, as shown in Figure 1a, uses an infrared lamp as a thermal energy source to melt a selectively-applied radiation absorbing ink, causing the underlying powder particles to sinter and coalesce [38]. The ink is first jetted from the inkjet printhead onto a fresh layer of pre-heated powder, as shown in Figure 1b. The entire powder bed is then exposed to infrared radiation using the infrared lamp, which causes the ink to rapidly absorb sufficient energy to sinter the underlying powder particles [40]. Areas without ink remains unsintered. This is followed by recoating a new layer of powder, and the process continues until the object is built. The HSS system used in this study was a Voxeljet VX200, which has a maximum build size of 300×200×150 mm³.

![Schematic of the High Speed Sintering process](image)

(a) Schematic of the High Speed Sintering process

![Detailed view of the sintering process](image)

(b) Detailed view of the sintering process, adapted from [41]

Figure 1: The High Speed Sintering process

2.3 Design of Experiments

2.3.1 HSS process parameters

From the literature review presented in Section 1, surface topography is the result of a series of complex interactions involved in the sintering process. Given that the sintering of powder particles are largely determined
by the thermal energy that is input into the part on the powder bed, three thermal energy-related process parameters were investigated in this study, which were sinter speed, infrared lamp power and ink grey level.

- **Sinter speed** – the speed at which the lamp passes over the bed. The lower the sinter speed, the higher thermal energy that is input into the powder bed per unit time.

- **Lamp power** – the power at which the lamp radiates infrared. With a constant sinter speed, changing the power of the infrared lamp can effectively result in increased and decreased energy input to the powder bed.

- **Ink grey level** – the amount of ink to be jetted onto the powder bed. The ink will absorb heat from the lamp radiation, causing powder particles to sinter. A higher ink grey level means a greater amount of ink to be dispensed.

It is noted that the ink, supplied by Sun Chemical Corp [42], contains carbon black in petroleum distillates. Carbon black is a strong infrared absorber, and a typical particle size is approximately 100 nm. The parameter ‘ink grey level’ (a dimensionless parameter) that is widely used in the inkjet industry describes the degree of coverage of the desired area by ink, which is determined by the volume of the droplet ejected from the printhead [37]. The printhead installed in the Voxeljet VX200 system is provided by Xaar® 3D Ltd, which is a native 360 nozzle per inch (npi) inkjet printhead that controls droplet volume by using different dot sizes [43]. The grey levels are set at linear increments of six picolitres at a set dot per inch (dpi) [43] (in this case, 1018 effective resolution dpi), ensuring a wide range of tonal values, from light shades, through mid-tones, to full solid coverage can be achieved. Grey level 0 means white where no dot is present, and grey level 1 represents six picolitres per dot size at 360 npi. Thus, a higher grey level means a greater amount of ink ejected from the printhead and as a result, the area covered by the ink is darker. The greater amount of radiation absorbing ink also theoretically means an increased amount of energy absorbed during the HSS process, leading to a higher degree of particle melt.

Other parameters that were kept constant included the layer thickness of 0.1 mm, powder bed pre-heat temperature of 160°C, 45 minutes pre-heat time prior to printing, and 60 minutes cooling time after printing. The samples were then post-processed in a bead blasting machine to remove surrounding powders.

### 2.3.2 The Taguchi experimental design

The experiments were designed with two objectives in mind:

(i) To systematically examine the effect of the above three process parameters on the resulting surface topography.

(ii) To investigate the relationships between the surface topography with porosity and mechanical properties of the produced samples, namely, whether mechanical properties are influenced by specific surface topographic characteristics.

The Taguchi Design of Experiments L9 array was thus employed and the three-level variables are defined in the following Table 1. Please note, although energy density calculation methods exist for some PBF processes [44-47], none currently exist for HSS. Energy input variations have therefore been assessed through use of combinations of a low, medium and high value of each parameter, as listed in Table 1. The parameter sets
chosen are within the most reliable process window for HSS, and based on recommendations from the HSS system manufacturer, i.e. sinter speed of 80 – 120 mm/s, lamp power of 750 – 1000 W and ink grey level of 2 – 4.

Table 1: The Taguchi L9 array for the investigation of areal surface texture in relation to HSS process parameters and porosity

| Set number | Energy-related parameter | Sinter speed (mm/s) | Lamp power (W) | Ink Grey level |
|------------|--------------------------|---------------------|----------------|----------------|
| 1          |                          | 80                  | 750            | 2              |
| 2          |                          | 80                  | 875            | 3              |
| 3          |                          | 80                  | 1000           | 4              |
| 4          |                          | 100                 | 750            | 3              |
| 5          |                          | 100                 | 875            | 4              |
| 6          |                          | 100                 | 1000           | 2              |
| 7          |                          | 120                 | 750            | 4              |
| 8          |                          | 120                 | 875            | 2              |
| 9          |                          | 120                 | 1000           | 3              |

2.3.3 Building process layout and test samples

Figure 2 shows the layout of the build. In each set of samples, there were five ASTM D638 Type I tensile bars [48] and two cuboids of 8×20×3.2 mm³ (XYZ). Samples were arranged at 5 mm spacing at least in order to minimise thermal interaction between neighbouring parts. All samples were at least 15 mm distance from the edge of the effective build area. Nine sets of samples were produced, in accordance with the Taguchi L9 array shown in Table 1. A set of produced samples is shown in Figure 3.

Figure 2: The layout of the building process on the HSS system
Figure 3: A set of test samples produced by the HSS process

Cuboids were used for surface topography characterisation. It is noted that there are other artefacts discussed in the literature [3, 9, 33, 49] that have been proposed for measurements of AM surfaces, mainly for metal AM. Given that the cuboids will also be subject to XCT scans for porosity measurements and more importantly this study is aimed at exploring the effect of HSS process parameters on the variation of surface topography, the authors decided to use the above shape and dimensions. To reduce uncertainties e.g. noise and beam hardening in XCT scans, two cuboids in each set were scanned and the porosity levels were compared. For tensile testing, the five tensile bars in each set were used.

2.4 Measurements, characterisation and testing

The five activities presented below were undertaken in sequence to acquire quantitative and qualitative information on surface topography, porosity and mechanical properties.

2.4.1 Areal surface texture measurements

Areal surface topography was measured using a structured light Alicona InfiniteFocusSL [50] laser profilometer, which is Focus Variation (FV) microscopy that scans an area of interest in 3D. ISO 25178-2 [51] defines terms, definitions and areal parameters for surface texture characterisation. In general, areal parameters have distinct advantages compared with profile parameters e.g. arithmetic mean deviation of the profile $Ra$ in ISO 4287 [52]. This is because surface topography is three-dimensional whereas profiles parameters measured in 2D are unable to provide a complete description of the real surface [3]. The areal surface texture parameters chosen were $Sa$, $Sq$, $Sv$, $Sku$ and $Ssk$. The description of these parameters are provided in Table 2. $Sa$ and $Sq$ are the most common texture parameters [6]. $Sv$ was chosen as it was reported to have a potential impact on crack initiation causing reduced mechanical properties [4]. $Sku$ and $Ssk$ are recommended for AM surface characterisation [3].

Table 2: Areal surface texture parameters measured in this study
| Parameter | Description |
|-----------|-------------|
| Sa        | Arithmetic mean height of selected area |
| Sq        | Root-Mean-Square height of selected area |
| Sv        | Maximum valley depth of selected area |
| Ssk       | Skewness of selected area. It describes how the mass is distributed around the mean plane. |
| Sku       | Kurtosis of selected area. It is a measure of the sharpness of the surface roughness over the area. |

A total of five measurements at different positions were taken per surface (i.e. up-skin, down-skin and side surface) per sample. In each measurement, an area of 2.0×2.0 mm$^2$ was scanned and the data was processed in Alicona MeasureSuite 5.3. It is noted that there have not been established international standards on the size of the measured area specifically for AM surface metrology. In general, measuring lengths and cut-off wavelengths for a sequence of $Ra$ ranges are specified in ISO 4288 [53], which is applied to areal measurement per ISO 25178-3 [54]. Based on the above, the measuring length of 8mm for AM surface measurements was proposed by Townsend et al. [3] and Triantaphyllou et al. [35]. However, there have been some concerns and discussions as it is a rather large area for optical surface measurements compared with traditional tactile profilometry. In addition, due to AM parts being intrinsically small and complex, some AM surfaces are smaller than 8×8 mm$^2$. There is thus no conformance on AM measurement area and there are debates that current ISO standards, which were originally designed for machined surfaces, cannot directly be applied to AM surfaces without amendments. It is also noted that other lengths/sizes were also adopted in different studies reported in the literature (e.g. 2.9×2.9 mm$^2$ by Thompson et al. [33], 1.4×1.89 mm$^2$ by Whip et al. [9], 1.62×1.62 mm$^2$ by Newton et al. [55], 2.5×3.0 mm$^2$ by Koutiri et al. [10], 4mm long linear measurements by Brika et al. [56] and 5×3 mm$^2$ by Khorasani et al. [57]). Hence, in this study, an area of 2.0×2.0 mm$^2$ was scanned in each measurement, and five measurements in total were performed at different regions across the surface area, following which the average was used to present the surface topography.

### 2.4.2 X-ray computed tomography scans for porosity measurements

The cuboids were scanned using Nikon Metrology 225/320 kV Custom Bay system. An accelerating voltage of 100kV, power of 17.6V and 500 ms exposure were used in the scans. The achieved voxel size was 10.0 μm. 3D data was reconstructed from the 2D radiographs using a filtered back projection algorithm. The data was then analysed using FEI Avizo 9 software with segmentation by the Otsu method [58] to characterise porosity. Porosity in terms of pore volume fraction was calculated using a low pore size cut-off of 2×2×2 (8) voxels, which was in line with the related research work reported in the literature [59-61]. The porosity levels of the two cuboids in each set were compared for initial validation.

* Up-skin refers to the top surface of the sample along the build direction. Down-skin is the bottom surface of the sample.
2.4.3 Scanning electron microscopy (SEM)

Up-, down-skins and side surfaces of each cuboid were examined in SEM to acquire additional qualitative information on surface texture. The cuboids were gold coated in vacuum, and SEM was performed on a Tescan Vega3 system in 10 kV, with a maximum magnification of 3000x.

2.4.4 Tensile testing

Tensile tests were performed on Tinius Olsen tensile machine to quantify the Ultimate Tensile Strength (UTS) and Elongation at Break (EAB) of the test specimens. The test speed was 5 mm/min. Where possible, ASTM D638 Standards [48] were followed during testing.

2.4.5 Mercury intrusion porosimetry measurements for porosity validation

In order to cross-evaluate the results of porosity measurements obtained by XCT, additional mercury intrusion porosimetry (MIP) was conducted on a Micromeritics® AutoPore V system, as shown in Figure 4a. In each measurement, a cube was held in a section of the penetrometer cell shown in Figure 4b. The cube was subject to low and high pressure tests in sequence, with a starting pressure of 30.00 psia, pressure increments from 10.00 to 2500.00 psia at different stages, an ending pressure of $6.00 \times 10^4$ psia, advancing and receding mercury contact angle of 130°, and the equilibrium time of 10s.

![Figure 4a: Micromeritics® AutoPore V system](image1)

![Figure 4b: Placing an HSS sample into the low pressure chamber](image2)

Figure 4: Mercury intrusion porosimetry: (a) the Micromeritics® AutoPore V system and (b) placing an HSS sample into the low pressure chamber

3. Results

This section presents the variations of areal surface texture parameters in relation to porosity levels, mechanical properties and the HSS process parameters i.e. sinter speed, lamp power and ink grey level.
3.1 Relationships of surface texture and porosity

3.1.1 Arithmetic mean and root mean square heights (Sa and Sq)

The variations of arithmetic mean height (Sa) for up-, down-skins and side surfaces in relation to porosity is shown in Figure 5. The X-axis shows nine sets of samples across all the experiments, and the yellow bar attached to each set shows the porosity level, of which the value can be read on the primary Y-axis on the left. The points in each set are the corresponding Sa values, which can be read on the secondary Y-axis on the right. The error bars represent the standard deviation across the five measurements. For up- and down-skins, Sa was found to be strongly correlated with porosity. Sa decreased as the porosity reduced, and vice versa. Sa for side surface can also be linked with porosity, and the slight inconsistency (i.e. set 9) was likely due to the limitation of the FV measurement technique incapable of measuring re-entrant features which are rather common on side surfaces (please refer to Section 4.3.1 and Figure 22). It was also found that down-skin surfaces are the smoothest and side surfaces are the roughest. Root mean square height (Sq) in relation to the porosity level shown in Figure 6 was found to follow the same pattern as Sa. Table 3 provides some examples of surface topographies of up-skins and the porosities (measured by XCT and MIP techniques) of the nine sets of samples.

![Figure 5: Relation of Sa to porosity level](image-url)
Figure 6: Relation of $Sq$ to porosity level

Table 3: Surface topographies of up-skins and porosities. The XCT images show the front view of a projection slice, and the build direction is from bottom to top.

| Set number | Height map | Porosity tomography image |
|------------|------------|----------------------------|
| **Set 1**  | ![Image](image1.png) | ![Image](image2.png) |
| $Sa = 13.71 \mu m$ | Porosity = 14.54% (measured by XCT), 14.77% (measured by MIP) |
| **Set 2**  | ![Image](image3.png) | ![Image](image4.png) |
| $Sa = 10.54 \mu m$ | Porosity = 6.79% (XCT), 6.94% (MIP) |
| Set 3 | $S_a = 8.56 \, \mu m$  
|      | Porosity = 4.71\% (XCT), 4.55\% (MIP) |
| Set 4 | $S_a = 14.62 \, \mu m$  
|      | Porosity = 24.11\% (XCT), 24.68\% (MIP) |
| Set 5 | $S_a = 12.90 \, \mu m$  
|      | Porosity = 11.13\% (XCT), 10.96\% (MIP) |
| Set 6 | $S_a = 16.00 \, \mu m$  
|      | Porosity = 14.95\% (XCT), 15.27\% (MIP) |
3.1.2 Maximum valley depth (Sv)

The graph in Figure 7 shows the variation of the depth of the deepest valley $S_v$ in relation to porosity. $S_v$ was reported to be a metric that is related to mechanical properties [4] as a deep valley could potentially cause stress concentration acting similarly as a notch. For both up- and down-skins, $S_v$ varied in accordance with porosity levels, exhibiting a strong correlation. A close relationship between $S_v$ of side surfaces and porosity was also observed in most cases except sets 8 and 9. It is also noted that $S_v$ is significantly higher compared with $S_a$, by up to six times higher. Again, down-skin $S_v$ is in the lowest level and side surface is in the highest level. In addition, there is a large extent of scatter in $S_v$ indicated by the standard deviation, particularly for samples with a high level of porosity (e.g. sets 1, 4, 7 & 8), suggesting a high degree of variability on the surface.
Figure 7: Variation of $Sv$ in relation to porosity.

3.1.3 Skewness and kurtosis ($Ssk$ and $Sku$)

Skewness ($Ssk$) and kurtosis ($Sku$) are parameters describing the distribution of the heights/depths of peaks and valleys. They are typically considered to be discriminating parameters to differentiate up- and down-skins if the sample is built at an inclined angle to the powder bed [13, 35]. In this study, all samples were built horizontally and thus Figure 8 and Figure 9 examine the variation of up- and down-skin $Ssk$ and $Sku$ in response to porosity. Please note that $Ssk$ and $Sku$ for side surface are excluded due to the presence of re-entrant features making $Ssk$ and $Sku$ values invalid to a certain extent, which will be discussed in Sections 4.3.1 and 4.4.

$Ssk$ describes the symmetry of peaks and valleys around the mean plane. If $Ssk = 0$, it means peaks and valleys are evenly distributed around the mean plane. If $Ssk < 0$, the surface is predominated by valleys. By contrast, the surface is dominated by peaks if $Ssk > 0$.

No clear pattern relating to $Ssk$ and porosity was found in Figure 8. By comparing up- and down-skins, down-skin $Ssk$ is always higher than up-skin $Ssk$. Therefore, $Ssk$ can potentially be used to as an indicator to discriminate up- and down-skins. Additionally, for down-skins, over half of the samples has a positive $Ssk$ (i.e. sets 2, 3, 4, 6 & 9), meaning that there are greater number of peaks than valleys. Whereas, most of the up-skins (except set 3) have a negative $Ssk$ value, indicating valleys dominate the surface. Negative $Ssk$ is likely caused by the presence of open pores and are related to sub-surface porosity (please see Figure 15, and Sections 4.3 and 4.4).
Set number
Porosity (%)
Porosity and skewness Ssk
Set number
Porosity (%)
Porosity and kurtosis Sku

Figure 8: Skewness Ssk and porosity

Kurtosis Sku is a measure of the expansion and distribution of heights, namely, the sharpness of a surface. In general, Sku = 3 is the nominal cut-off value, which represents the surface having an equal distribution of soft and sharp peaks and valleys. If Sku < 3, the surface is considered to primarily consist of squashed peaks and valleys with a relatively large edge radius, which, for AM surfaces, can be interpreted as less likely to initiate cracks under loads as compared to spiked peaks and valleys. On the other hand, if Sku > 3, the surface is characterised by sharp peaks and valleys with a relatively small edge radius.

Sku for both up- and down-skins is greater than 3 as shown in Figure 9, indicating that the majority of peaks and valleys is sharp. For samples with a low level of porosity (i.e. sets 2 and 3 with a porosity of 6.79% and 4.71%, respectively), up- and down-skins have similar Sku values. However, there is a significant difference in Sku for samples that are of high porosity. This is likely due to sub-surface porosities of up- and down-skins being different. For instance, in sets 5 and 6, it appears that the bottom layers of the sample is significantly less porous than the top layers (shown in Table 3), resulting in a large discrepancy in up- and down-skins Sku values. Further discussion can be found in Section 4.4.
3.2 Relationships between surface texture and HSS process parameters.

The varying HSS process parameters with the associated surface texture of up-, down-skins and side surfaces are plotted in Figures 10 – 13.

3.2.1 Arithmetic mean and root mean square heights (Sa and Sq) in relation to process parameters

Sa for all up-skin, down-skin and side surfaces increased as the sinter speed increased, shown in Figure 10. In particular, Sa for the up-skin showed a significant trend with the sinter speed with a P-value lower than 0.05. An inverse trend was found for the ink grey level. Sa for all up-, down-skins and side surfaces increased with a decrease in ink grey level, indicating an improved surface roughness. Increasing lamp powers also led to a decreased Sa for both up- and down-skins, but using a high power might potentially be detrimental to the side surface Sa, as shown in Figure 10c. Having said that, it is well known that side surfaces of AM parts have re-entrant features [25, 35] that result in measurement inaccuracies potentially in a large extent in FV measurements. This will be further discussed in Section 4.3.1. The P-values for down-skin and side surface Sa suggest that they are more susceptible to ink grey level compared with up-skin. Additionally, Sq, which is the root mean square height, was found to be in a trend consistent with the above.

In general, a greater amount of energy input can be obtained, as introduced in Section 2.3.1, by reducing sinter speed, increasing lamp power and/or ink grey level. The trend of Sa/Sq variation in Figure 10 reveals that increasing energy input can result in a smoother surface. Section 4.2.1 provides an in-depth discussion on the effect of energy input on surface topography.

Figure 9: Kurtosis Sku and porosity

![Main Effects Plot for Sa_Up-skin (μm)](image)

![Main Effects Plot for Sa_Down-skin (μm)](image)
Figure 10: Main effects plots for surface arithmetic mean (Sa) in relation to the HSS process parameters.

3.2.2 Maximum valley depth (Sv) in relation to process parameters

Figure 11 shows the variations of Sv in relation to sinter speed, lamp power and ink grey level. Sv shows a clear trend of increasing Sv with the increased sinter speed, reduced lamp power and ink grey level in most cases. As using a higher speed, a lower power and a lower grey level essentially indicate a lower energy input, Sv can be linked with the degree of powder fusion, which will be discussed in detail in Section 4.2.1.
Figure 11: Main effects plots for maximum valley depth ($S_v$) in relation to the HSS process parameters

3.2.3 Skewness and kurtosis ($S_{sk}$ and $S_{ku}$) in relation to process parameters

Results in Figure 12 showed that $S_{sk}$ is of a negative value for up-skin, indicating that the up-skin primarily consists of valleys rather than peaks, which is likely due to the presence of open pores (please see Figure 15b and c). For down-skins, $S_{sk}$ varies between approximately 0.5 and -0.5 depending on the process parameters used. Using a sinter speed of 100 mm/s, together with 875W lamp power and ink grey level of 4 resulted in peaks and valleys being evenly distributed around the mean plane for down-skin.

With respect to $S_{ku}$, the trend for up-skin is that it decreased along with an increase in sinter speed, lamp power and ink grey level, as shown in Figure 13. The decreased $S_{ku}$ towards the nominal value of 3 indicates a reduced randomness of the surface heights. As for down-skin $S_{ku}$, it also reduced towards the nominal value of 3 as the lamp power increased. This suggested that peaks and valleys on the down-skins became less sharp when using a higher lamp power. More discussion is given in Sections 4.2.1 and 4.4.
3.3 Porosity and mechanical properties

Tensile testing was performed according to Section 2.4.4 to determine the mechanical properties of the samples. The results presented in Figure 14 revealed that both UTS and EAB are strongly correlated with the level of porosity. Reduced porosity resulted in an increase in UTS and EAB. The porosity for set 3 is 4.71%, which is the lowest amongst other sets of builds, resulting in the UTS being the highest. In contrast, increased porosity, which means the sample was of a lower density with enlarged voids within the material, led to the reduced UTS and EAB. Both UTS and EAB are in the lowest level in set 7 where the porosity is the highest. Given that surface texture (e.g. $S_a$, $S_q$ and $S_v$) is closely correlated with porosity, and porosity is strongly correlated with the resultant mechanical properties, a link can be established between surface texture and mechanical properties, which will be presented in Sections 4.1, 4.2 and 4.5.

4. Discussion

4.1 Correlation of areal surface texture with porosity and mechanical properties

Upon analysing the results presented in Section 3, the correlation between areal surface texture, porosity and mechanical properties can be derived as follows, and the reasons behind the correlation are discussed in the proceeding subsections.

- $S_a$ and $S_q$ strongly correlate with porosity (Figure 5 and Figure 6) and hence, measuring $S_a$ and/or $S_q$ will provide an indication of the porosity level.
- Since porosity is closely correlated with mechanical properties (Figure 14), areal surface texture can be further linked with mechanical properties, in particular $S_a$ and $S_q$.  

• A general trend for $S_a$, $S_q$ and $S_v$ is that they increased as the sinter speed increased, lamp power and ink grey level reduced (Figure 10 and Figure 11). This means surface roughness increased as the amount of input energy reduced, and vice versa.

• $S_{sk}$ increased as the lamp power increased (Figure 12), indicating that the surface was less dominated by valleys, primarily due to reduced number of open pores on the surface.

• $S_{ku}$ decreased towards the nominal cut-off value of 3 as the lamp power increased (Figure 13), suggesting that peaks and valleys were less sharp, in other words, surface became relatively smoother.

4.2 Effect of energy input on surface topography

4.2.1 Fusion of powder particles

One of the most critical underlying reasons that causes the varying surface topographies is the amount of thermal energy involved in the sintering process. It is understandable that using a slow sinter speed and a high lamp power will effectively introduce an increased amount of energy into the build. Figure 10 demonstrates that $S_a$ reduced as the sinter speed decreased and lamp power increased, indicating an improved surface roughness for up- and down-skins. Increasing the ink grey level resulted in a greater amount of ink jetted onto the part, which enhanced the absorption of heat radiation of the lamp, leading to a smoother surface $S_a$, shown in Figure 10. Combinations of sinter speed, lamp power and ink grey level are most likely to have a greater impact on surface texture (i.e. a lower $P$-value) but this requires further experiments to be carried out.

It has been reported by other researchers that energy input is critical to porosity [46, 59]. A higher degree of sintering can be obtained with higher lamp powers resulting in formation of parts with enhanced mechanical strength. A higher degree of sintering also leads to parts with a higher density. A greater amount of energy input (to a certain level) on the top layer of powder particles can cause a more uniform and flat surface, and thus a better surface finish [38]. Therefore, areal surface texture is closely related to energy input that has a direct effect on porosity and mechanical properties. This is further evidenced by examining SEM micrographs of the up-skins of the samples in sets 3, 5 and 7 with varying porosity levels of 4.71%, 11.13% and 34.92% in Figure 15a, b and c, respectively.

(a) $S_a = 8.56 \, \mu m$, sample porosity 4.71%
(b) $S_a = 12.90 \, \mu m$, sample porosity 11.13%
Thermal energy from the lamp causes powder particles to fuse and consolidate, as illustrated in Figure 16a. In general, the shell of the powder melts, causing the molten polymer to form necks between neighbouring particles. The difference between the average pressure on the contact area and the surface tension along the peripheries of the two adjacent particles induces a sintering force, which is the thermodynamic force that drives neck growth and shrinkage [62, 63]. Low input energy, caused by reducing lamp powers, increasing sinter speed or decreasing amount of ink, results in incomplete fusion, leaving voids between particles, as depicted in Figure 16b. Partially sintered particles and voids as a result of lack of fusion can be clearly seen in Figure 15, which led to increased surface roughness. Moreover, an example of the comparison of the top surface profiles of sets 3 and 5 are shown in Figure 17, demonstrating that a higher input energy directly leads to a smoother surface.

Figure 16: Schematic representation of the sintering of particles based on the Frenkel-Eshelby model [64-66]: (a) sintering sequence for two spherical particles and (b) sintering of multiple particles, adapted from [63, 67]
With respect to porosity and mechanical properties, as presented above, a higher amount of energy input enables a more complete fusion of powder particles, and hence a reduced porosity. The relationship between porosity and mechanical properties of HSS parts is plotted in Figure 14 as well as Figure 18 below, demonstrating a strong correlation. Porosity is known to influence mechanical properties and it was found that cracks tended to initiate from pores by unfused powder particles [68, 69]. Increased energy input improves fusion of powder particles, allowing a more complete liquid phase sintering and/or partial melting, even full melting in some circumstances to be achieved [67], and thus significantly less number of lack of fusion pores and better resulting mechanical properties. Based on the above, the link between surface roughness, porosity and UTS is illustrated in Figure 19. A greater amount of energy input results in lower surface roughness and porosity, and better resulting mechanical properties. Additionally, it should be noted that particle packing density on the powder bed may also affect porosity and surface quality, which will be elaborated in Section 4.2.2.

Figure 17: Comparison of the surface profiles of the samples in sets 3 and 5

Figure 18: Relationship between porosity and mechanical properties
As for side surfaces, they were found to be of consistently higher $S_a$, $S_q$ and $S_v$ values than those of up- and down-skins, as shown in Figure 5 to Figure 7. This is due to the nature of the HSS process i.e. the layer-by-layer manner. The top and bottom surfaces are formed during a single stroke of the lamp followed by a rapid solidification on a single layer. However, by contrast, side surfaces are formed as a result of multiple layers joining together in consecutive sintering and solidification, leading to an increased surface roughness. In addition, surrounding powder particles that are partially sintered adhere to the side surfaces, which further diminishes the surface quality. Therefore, side surfaces usually exhibit significantly more peaks and deep valleys indicated by a higher $S_v$ value.

In addition, despite higher input energy generally being considered to be beneficial to surface quality, an excess amount of energy can have a negative effect on surface roughness [70]. The reason behind this phenomenon is the excess heat over-melts the current layer and dissipates downwards, leading to remelting of previous layers. Polymer pyrolysis occurs, which consequently creates a porous structure [71]. The excess heat also dissipates outwards to the surrounding powder, resulting in the melting of excess particles adjacent to those intended to be fused by the lamp. This eventually causes the formation of clusters of excess particles that adhere to the side surfaces of the part, which increases surface roughness. However, it is worth mentioning that, for processes such as LS or SLM for metals where a laser beam provides intensive energy to the area of interest to sinter or melt particles, overly high energy can easily cause over-melting of powders and thus evaporation and formation of defects (e.g. keyholes), which eventually affect surface roughness and porosity [57, 70]. Whereas, in HSS, the infrared lamp is used as the energy source that irradiates the entire powder bed as it moves across, shown in Figure 1 and Figure 2. While the area that is covered by ink absorbs significantly more energy supplied from the lamp, a proportion of the energy is also absorbed by the un-printed powder. Above a certain level, this leads to unwanted ‘hardening’ of this powder, preventing reliable part removal without damage. This restricts the possibility to further increase energy input into the parts themselves whilst still being able to remove them successfully.
In comparison to $Sa$, $Sq$ and $Sv$ that can be directly indicated by the porosity level, skewness $Ssk$ and kurtosis $Sku$ were not found to be in the same relationship with porosity. This is due to the nature of $Ssk$ and $Sku$ parameters, which are generally more suited for differentiating up- and down-skins of the samples that are produced in different build orientations [13, 35], as well as for characterising surfaces of SLM/EBM parts where intensive energy (i.e. laser/electron beam) interacts with powder, creating a number of weld tracks i.e. rippling effect [9]. However, all samples were built horizontally in this study, and the lamp enabled particle coalescence in one lamp strike rather than multiple scans as in SLM. Having said that, certain trends can still be observed. As the lamp passes over the powder bed, insufficient energy input leads to lack of fusion pores. $Ssk$ value was lower than zero for the majority of the up-skins of the samples shown in Figure 8, expect for set 3 (the highest density), indicating that up-skins primarily consisted of valleys largely due to the presence of open pores on the surface. This supports the finding that energy input is one of the fundamental reasons that causes varying surface topographies. When inputting a higher amount of energy (by using a lower sinter speed, a higher lamp power and/or a higher ink grey level, as shown in Figure 12a), there were less number of open pores/valleys and $Ssk$ (negative value) increased towards zero. Similarly, for down-skin $Ssk$, increasing sinter speed and decreasing lamp power effectively reduced input energy, leading to a decreased negative $Ssk$ value, namely, more open pores on the surface (Figure 12b).

Kurtosis $Sku$ characterises the sharpness of a surface and the nominal cut-off value is 3. All surfaces measured were found to have a $Sku$ value greater than 3, indicating that the majority of peaks and valleys was sharp. Despite all that, both up- and down-skins $Sku$ values reduced towards 3 as the lamp power increased, as presented in Figure 13. It demonstrates that higher lamp powers enabled a more complete fusion of particles, producing a smoother surface i.e. peaks and valleys became less sharp. This is also consistent with the surface profiles plotted in Figure 17 where peaks and valleys on set 3 are smoother than those on set 5. Furthermore, it should be noted that both up- and down-skin $Ssk$ and $Sku$ involve a series of complications, particularly for down-skin, as it undergoes under a number of heating cycles when the layers above it are melted and solidifies. Therefore, $Ssk$ and $Sku$ are more related to sub-surface porosity, which will be discussed in Section 4.4.

### 4.2.2 Powder rheological characteristics

An important aspect that affects surface topography is powder rheological characteristics. Surface topography of as-build parts is associated with thermal phenomena and the resulting powder flow properties [72]. It is well known that powder physical properties (e.g. particle shape, size, stiffness and surface texture) influence the powder flowability, hence the packing/compaction density of the powder bed [73]. This will eventually affect the surface roughness of the as-built part [74-76], as well as other properties including porosity and tensile strength [56, 77]. Basic flowability energy (BFE), which quantifies the energy required to displace a powder during non-gravitational forced flow, and specific energy (SE), which measures how easily a powder flows in an unconstrained environment, are the two indicators for powder permeability that is influential to the thermal environment/energy input during the HSS process. Reduced permeability indicated by an increased SE has been found to link to poor layer uniformity [78]. Low permeability causes air to be retained in the bulk while dispensing a new layer of powder, leading to inconsistency in powder spreading, as a result, imperfections in the sintered part surface.
An SEM image of the PA2200 virgin powders used in this study is shown in Figure 20. It can be identified that particles are of different sizes and irregular shapes. This will lead to an increased amount of BFE (increased inter-particles surface friction and cohesion forces) and consequently decreased flowability and powder packing density, compared with spherical particles. Moreover, varying particle sizes and shapes require higher aeration energy during powder spreading, in other words, increased resistance to air flow, which negatively affects the packing density [74]. While the particle size distribution is considered to be consistent in this study (all powders used were commercial virgin powders provided by EOS GmbH), the influence of varying particle sizes and shapes on powder rheological behaviours at different thermal phenomena, caused by different levels of energy input, is currently unknown, and that requires further investigation. In addition, Figure 20 also shows there are small quantities of flow additive. It was reported by Clayton et al. [78] that adding flow additive resulted in a higher BFE and generated a higher pressure drop (PD), enabling powders to flow easily and achieving a denser packing within the bulk. However, powder flowability with flow additive may vary significantly in different thermal environments. Again, further effort will need to be made on understanding the effect of flow additive on powder rheology at varying amount of input energy in HSS. This includes dynamic flow, aeration, permeability, compressibility and shear testing. This will identify critical parameters in relation to varying temperatures, such as aeration energy, cohesion coefficient, BFE, SE and PD, which are effective indicators to characterise powder flowability.

![Figure 20: Micrograph of the virgin PA2200 powders used in this study](image)

It is apparent that powder thermal conductivity of bulk powders directly affects energy absorption and temperature distribution of the powder bed. It is also apparent that thermal conductivity is directly influenced by the powder packing density, which highly depends on the above-mentioned powder characteristics (e.g. powder morphology). The variation of surface roughness values can be attributed to the presence of voids and partially sintered particles, as shown in Figure 15, that is partially caused by the incompact powder bed density [56]. Therefore, it is believed that there is a link between powder rheology and surface roughness. A better rheological behaviour will result in a better flowability during powder spreading, leading to a more efficient packing and associated energy absorption. This will eventually favour the formation of parts with an increased density and improved surface roughness.
Another thing to note is that, uniformity of each layer during a build may also be influential to the surface roughness of a final part in addition to powder packing density. An uneven layer, which is largely due to insufficient energy input, may result in variations in the dynamics of powder-infrared lamp interactions and packing density for the next layer. An example of the complications caused by an uneven layer is illustrated in Figure 21. Large and deep voids on the previous uneven layer can easily trap particles of certain sizes and shapes when spreading a new layer of powder. This introduces additional complexity in powder rheological behaviour and thus potentially negatively affects powder packing density for the next layer. Less amount of energy input, a more uneven layer (e.g. the set 5 surface shown in Figure 17), and as a result, more complex powder rheology issues and reduced surface roughness.

Figure 21: Demonstration of the impact of layer uniformity on powder rheological behaviour and powder bed packing density

In addition, it is worth noting that materials generally exhibit different rheological behaviours in solid and liquid states. Even in the same powder packing density condition, varying amounts of energy input can result in different thermal phenomena. This will affect the rheological characteristics of material being melted, causing variations in surface roughness. Temperature distribution is a direct result of energy density that is the combinational effect of lamp power, sinter speed and ink grey level. When the interface of the powders is subject to localised heat, surface tension reduces. This interface between the hot (current layer, liquid/semi-liquid state) and cool (previous layers, solid state) area induces a gradient of surface tension that rapidly propagates towards the surrounding area. An excess amount of input energy leads to a high gradient of surface tension, causing a slight motion of the liquid and thus forming irregularity on the surface during rapid solidification [57]. As a result, the surface roughness is negatively affected. However, a thorough understanding on rheological behaviours is yet to be acquired, especially for interactions of surface energy, capillary force, intermolecular forces and work adhesion involved in the HSS process.

4.3 Measurement limitations and discrepancies

4.3.1 Re-entrant features

AM surfaces are known with re-entrant features which place a significant challenge for metrology [9, 25]. The measurement technique used in this study is FV, which relies on the reflection of the light from the surface.
However, highly porous samples (e.g. sets 4, 7, 8 & 9) usually have re-entrant features on the side surfaces, which increases measurement discrepancies, especially in measuring $S_v$, $S_{sk}$ and $S_{ku}$. Some typical re-entrant features are shown in Figure 22 that were not detectable in the FV measurements due to its line-of-sight restriction. Therefore, $S_{sk}$ and $S_{ku}$ for side surfaces were not analysed in the paper. The implication of $S_v$ on mechanical properties is also inconclusive, despite the fact that $S_v$ appears to correlate with porosity shown in Figure 7. XCT is a promising technique to acquire a more precise surface topography as X-rays can travel through re-entrant features [6]. However, XCT is also constrained by other factors such as voxel size, scan time and surface determination etc. It is possible, though time-consuming, to XCT scan (in-situ) the entire gauge length of the tensile bar under tension to identify the maximum valley depth and the position, and to match it with the location where the crack started to initiate.

Figure 22: Re-entrant features on the side surface of the set 4 sample, imaged and processed by XCT (sample is in blue and air is in black)

4.3.2 Sphere-like protrusions and recesses

Surface topography in PBF AM is a result of fusion and subsequent solidification of powder particles. HSS is different from LS, SLM and EBM where a laser or electron beam is used to scan the surface of the part resulting in surface topography being typically dominated by weld tracks. However, certain singularities were observed on HSS part surfaces, typically consisting of sphere-like protrusions and deep recesses.

Figure 23 compares the surface topographies between sphere-like protrusions (Figure 23a) and a more ‘normal’ down-skin surface (Figure 23b). It is apparent that the dense population of sphere-like protrusions significantly affected the measured surface texture parameters. Protrusions are formed either from unsintered or partially-sintered powder particles that stuck on the surface, particularly due to insufficient heat. Therefore, they can appear alone and in clusters as shown in Figure 23a. It was further noticed that sphere-like protrusions were usually found at edges where two surfaces of the part intersect, in particular in sets 4, 7 & 8 where the amount of energy input was low. The reason that caused the inhabitancy of protrusions at edges is unknown in this study, which might be linked with the presence of slight thermal gradients at surface edges. In order to obtain consistent and less discrepant results, sphere-like protrusion were excluded to the authors’ best knowledge by visual examination of the scanned surfaces.
Deep recesses are another typical feature observed. Increased number of recesses was found on surfaces of the samples with a higher porosity level e.g. set 7 in Figure 15c. It was believed that deep recesses were open pores at the micro level, and they were formed as a result of lack of fusion. The surfaces of a part are in contact with surrounding unsintered powders that are inherently of low temperature. This leads to more open pores to form, eventually becoming deep recesses, some of which develop into re-entrant recesses that have a large and negative impact on surface topography as well as measurement reliability. This is also potentially the reason for side surface’s $Sa$, $Sq$ and $Sv$ that were found not to closely correlate with the process parameters in Figure 10 and Figure 11.

4.4 Sub-surface porosity

$Sa$, $Sq$ and $Sv$ for up- and down-skins have shown a strong correlation with energy input and the resulting porosity, as demonstrated in a number of graphs in Figures 5-7, 10, 11 & 19. They increased or decreased in a good consistency with the changes in the HSS process parameters and porosity levels. However, no clear trend was found for skewness $Ssk$ and kurtosis $Sku$ in relation to porosity in Figure 8 and Figure 9. They are the parameters characterising the distribution and sharpness of peaks and valleys on the surface, and thus are more susceptible not only to process parameters but also to other factors such as sphere-like protrusions.

However, the overall porosity of the entire sample is most unlikely to be adequate as an independent factor to link with $Ssk$ and $Sku$. It is seen that, for samples with a high level of overall porosity (e.g. set 4 shown in Table 3), there is a visible difference between the sub-surface porosities of up- and down-skins. Hence, in comparison to the overall porosity, sub-surface porosity potentially has a greater impact on $Ssk$ and $Sku$ values, and some observations are discussed below.

- Figure 8 shows the variation of up-skin $Ssk$ is not consistent with that of down-skin $Ssk$. Similarly, the variation of up-skin $Sku$ is not consistent with that of down-skin $Sku$ either, as shown in Figure 9.
- Neither up- nor down-skin $Ssk$ and $Sku$ was found to be in a good relation to the overall porosity of the entire sample in Figure 8 and Figure 9.
- Most of the up-skin $Ssk$ and $Sku$ values were largely different to the down-skin $Ssk$ and $Sku$ values, respectively, in Figure 8 and Figure 9. By visual examination of the XCT tomography images in Table

Figure 23: The down-skin surfaces (2×2 mm$^2$) of the set 8 sample. (a) shows sphere-like protrusions on the surface and (b) shows a more ‘normal’ down-skin surface.
3, it was found that the up-skin sub-surface showed a more porous structure than the down-skin sub-surface. Some examples are sets 4, 5, 6 and 9.

- Volume rendering of the sub-surface porosities of the up- and down-skins of the set 6 sample is shown in Figure 24. A noticeable difference between the two sub-surface porosities can be identified, which led to the difference in up- and down-skin $S_{sk}$ and $S_{ku}$ values.

- For sets 4, 5, 6 and 9, down-skin $S_{ku}$ had similar values, shown in Figure 9. Down-skin $S_{sk}$ was also found to have similar values for these sets. Given that the down-skin of these sets showed similar sub-surface porosities in Table 3, this suggests $S_{sk}$ and $S_{ku}$ are more closely related to sub-surface porosity as opposed to the overall porosity of the sample.

- All up-skin $S_{sk}$ had a negative value (except for set 3), and was lower than the corresponding down-skin $S_{sk}$ value, as shown in Figure 8, suggesting that up-skins were predominated by valleys due to the existence of micro open pores. As presented above, up-skin sub-surface was generally more porous than down-skin sub-surface. This was because down-skin was subject to a number of heating cycles when the subsequent layers were melted by the lamp. This resulted in additional thermal energy dissipating into the down-skin and the adjacent layers, enhancing the fusion of powder particles. Whereas, the up-skin (the top layer of the part) was subject to a gradual cooling process as soon as it was printed, leading to the sub-surface being more porous.

Although $S_{sk}/S_{ku}$ can potentially be linked with sub-surface porosity, further work is required to investigate the correlation between surface topography and sub-surface porosity.

![Figure 24: Volume rendering of the sub-surface porosity (in red) of the up- and down-skins of the set 6 sample, showing a visible difference.](image)

### 4.5 Areal surface texture and mechanical properties

Despite correlations between surface texture parameters ($S_a$, $S_q$ and $S_v$) and porosity, as well as porosity and mechanical properties having been established, the direct effect of certain surface texture features on the mechanical properties cannot be quantified. The mechanical properties are the consequence of a series of interactions between thermal energy, bonding between layers and consolidated part as well as surrounding unsintered powders. Measuring $S_a$, $S_q$ and $S_v$ may provide an indication of possible mechanical properties directly, i.e. an increasing $S_a$, $S_q$ and $S_v$ indicates the part having a reduced UTS and EAB in general. Nevertheless, the failure of a tensile bar in tensile testing is never simply caused by the maximum valley depth $S_v$ alone, or the highest $S_a$, as discussed in Sections 4.2 and 4.3.1.
A failure takes place in the location where is likely caused by a combined influence of a surface notch (e.g. high value of $S_v$ and $S_{ku} > 3$ sharp valleys) and a cluster of sub-surface pores making the structure inherently weak [4]. A typical example can be found in Figure 25a and b where the sample in set 7 shows a highly porous side surface adhered with partially sintered powder particles (protrusions). Large and deep recesses were present, that were considered as defects for mechanical properties. A fracture surface is shown in Figure 25c consisting of existing internal pores prior to tensile testing, which were also detrimental to the mechanical strength, resulting in the reduced capability to withstand the tensile load.

![Figure 25: SEM micrographs: (a) and (b) the side surface topography, and (c) fracture surface of the sample in set 7.](image)

5. Concluding remarks

This study investigated the areal surface texture of High Speed Sintered parts and correlated it with the process parameters (sinter speed, lamp power and ink grey level), porosity and mechanical properties. The FV surface measurement technique was used to systematically examine the surface topography of up-, down-skins and side surfaces, and the porosity was quantified by using XCT and MIP techniques. Based on the results presented and discussed in the preceding sections, the following conclusions are derived.
Surface arithmetic mean height (Sa), root-mean-square height (Sq) and maximum valley depth (Sv) have shown to be strongly correlated with the porosity levels. A higher value of Sa, Sq or Sv indicates a high level of porosity. Reduced porosity also reflects on a decrease in Sa, Sq and Sv, leading to a smoother surface. In terms of process parameters, a clear trend was identified for Sa, Sq and Sv for up and down-skins. They increased as the sinter speed increased, and they decreased as the lamp power and ink grey level increased. This suggests that a higher level of energy input can effectively result in improved surface roughness. Up- and down-skin kurtosis Sku was found to be greater than 3, indicating that the surface is characterised by spiked surface roughness with peaks and valleys having relatively sharp edges with small edge radius.

Porosity was further found to be closely correlated with UTS and EAB. The fundamental reason is the energy input. A higher degree of fusion of powder particles was caused by a greater amount of energy, resulting in formation of parts with reduced porosity and improved mechanical properties. A sufficiently high amount of energy input enables powder particle to fuse and consolidate, leading to a more uniform and smoother surface. Surface texture parameters Sa, Sq and Sv were found to be good indicators for porosity, UTS and EAB. However, it should be noted that mechanical properties are the result of a series of complex interactions between thermal energy, particle coalescence, layer bonding and surrounding powders. Thus, the mechanical properties of a finished part are the combinational influences of overall porosity, sub-surface porosity, material properties and surface topography. Future work will focus on characterising and correlating sub-surface porosity with surface topography. The influence of rheological behaviours of powders as well as melted material in different thermal phenomena on surface roughness of the finished part will also be investigated, which will provide a thorough understanding of the formation of surface topography.

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