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Characterisation of high speed sintering surface topography with re-entrant open surface pores using 3D surface texture parameters and material ratio curve

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Abstract
High Speed Sintering (HSS) is a polymer powder bed additive manufacturing process for economical volume production of end-use parts. The surface of HSS components often contains 3D features, e.g. re-entrant open surface pores. X-ray computed topography is capable of capturing these features, allowing measurement data to be used for surface texture characterisation. This paper focuses on characterising HSS surface topography based on the newly developed 3D surface texture parameters with a special interest in the re-entrant surface pores. In comparison to the conventional areal counterparts, the 3D surface texture parameters pioneered in this study have been proven to be able to fully characterise re-entrant features, and thus better reflect the 3D nature of HSS surface topography. The selected three 3D height parameters (i.e. Sa, Sq and Sv) and the three 3D hybrid parameters (i.e. Sdq, Sdr and Srf) are useful to quantify re-entrant open surface pores from different perspectives, e.g. variation, depth, gradient, area. The material ratio curves of HSS surfaces vary in their shapes and display recess shapes at the surface heights where the re-entrant pores start to build up. Furthermore, the volume parameter Vvv is utilised to characterise the volume density of open surface pores.

Keywords: Additive manufacturing; high speed sintering; surface topography; open surface pores; X-ray computed tomography; material ratio curve.

1. Introduction

High Speed Sintering (HSS) is a polymer additive manufacturing (AM) process aimed at economical series production of end-use parts. It uses powder as the feedstock material, which is spread onto the powder bed. A layer of the cross-section of the part is formed by jetting the ink onto the area of interest followed by the sintering process using the infrared lamp. The ink rapidly absorbs the thermal energy from the lamp, causing the underlying powder to sinter and solidify. A new layer of powder is then coated and this process continues until the part is fully built.

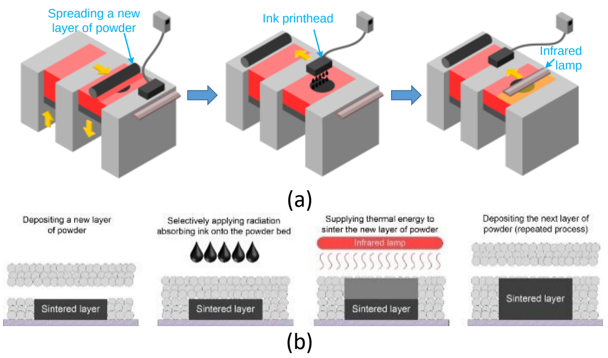


Figure 1. High Speed Sintering process: (a) schematic of the High Speed Sintering process; (b) Detailed view of the sintering process, adapted from [1].

HSS surface topography is three-dimensional in nature, comprised of open surface pores, see Figure 2. These 3D topography feature cannot be measured using conventional tactile and optical measurement techniques due to the line-of-sight limit, but can be instead captured by X-ray computed tomography (XCT) which has no constraint on surface geometry. The use of XCT for AM surface texture, in recent years, has been a focus of the AM metrology community [2-5], bringing in the advantages that enable not only the capture of 3D topography features, but also the non-destructive measurement of internal surfaces.

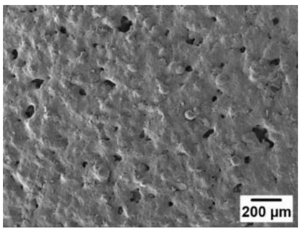


Figure 2. SEM micrographs of HSS surface.

This paper aims to characterise the 3D HSS surface topography measured by XCT. A special interest is dedicated to the re-entrant open surface pores, which are open pores on the surface and the near surface pores with the channels connected to the external surface.

2. Surface roughness, open surface pores relating to HSS process and mechanical properties

AM process and associated process variables have direct impacts on the quality of produced parts, including surface roughness, open surface pores and internal porosity, and the resultant mechanical properties.

In the HSS process, lamp powder and speed, and the ink grey level are the dominant process variables that have a substantial influence the surface quality and porosity of printed components. In principle, a greater amount of energy that is input into and/or absorbed by the part on the powder bed leads to a more complete melting of particles and subsequently particle coalescence and solidification, resulting in reduced voids. Given that the volume of material increases as it is melted from a solid to a liquid state, the melted particles flow outwards, generating a smoother surface. As the layer-by-layer melting process continues, the excess heat dissipates downwards and penetrates through the current layer, whereby the previous layer is remelted. This further closes down the voids between particles, leading to a reduced level of open surface pores on the layer surface. The reduced porosity enhances the bonding strength between particles, as a result, reduces the tendency of crack initiation and propagation between melted particles, which consequently improves mechanical properties of the printed part. A good correlation was found between surface texture parameters (e.g. Sa, Sq, Sv) and the internal porosity as well as the tensile strength [6]. AM's rough surface texture, particularly surface notches, some of which are open surface pores, could lead to a shortened fatigue life [7,8].

3. HSS Samples and 3D Surface Measurement

3.1. HSS samples

Night sets of HSS samples were fabricated using different combination of primary process parameters, i.e. sinter speed, lamp power, and ink grey level. Figure 3 shows a set of the fabricated samples. These samples were used to investigate surface texture, porosity and tensile strength, and an effort was made to correlate these three properties [6].

Figure 3. A set of test samples produced by the HSS process [6].

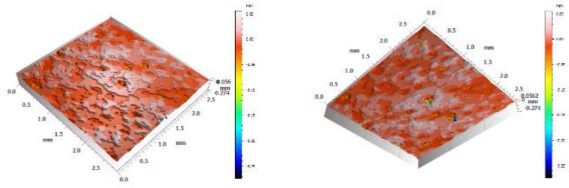
3.2 HSS sample surfaces measured by XCT

HSS samples developed in [6] were scanned by XCT (Nikon Custom Bay 225/320, voxel size 10 µm, exposure time 500 ms, voltage 100 kV, Otsu surface determination provided by FEI Avizo 9), whereby the 3D surface topographies were extracted. Three sets of samples are employed in this paper. Set 1 indicates the sample produced using industrially established HSS process parameters, while Set 2 and Set 3 are two sets of samples produced from less appropriate parameters i.e. reduced amount of energy input (please note that Set 1, Set 2, and Set 3 in this work are identical to Set 2, Set 6 and Set 7 in [6] respectively). All these surfaces present open surface pores, despite different levels, see Figure 4-6. Table 1 lists their surface roughness Sa measured by the focus variation (FV) microscope and the overall porosity by XCT. Please note that the roughness parameters are the averaged value from five measurements on the top surface of each sample set.

Table 1. Surface roughness and porosity of three sets of HSS samples.

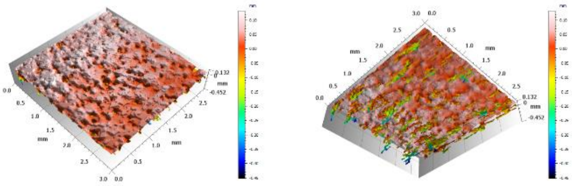
Set No.	Set 1	Set 2	Set 3
Sa (µm)	10.5	16.0	18.6
Sq (µm)	13.9	21.3	24.5
Sv (µm)	84.6	132.2	138.7
Porosity (%)	6.9	15.3	34.5

The surface topography of Set 1 is smooth with only a few visible surface pores, see Figure 4(b). Surface topographies of Set 2 and Set 3 are rougher than that of Set 1. Although Sa of Set 2 and Set 3 measured by FV microscope are close (difference less than 3 µm), their 3D surface topographies show that Set 3 has a much higher density of open surface pores than Set 2, see Figure 5(b) and 6(b).



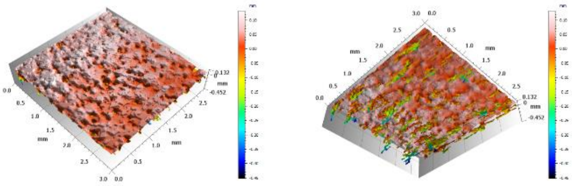
(a) (b)

Figure 4. 3D surface topography of Set 1 top surface: (a) top view; (b) bottom view.



(a) (b)

Figure 5. 3D surface topography of Set 1 top surface: (a) top view; (b) bottom view.



(a) (b)

Figure 6. 3D surface topography of Set 1 top surface: (a) top view; (b) bottom view.

4. Use of 3D Surface Texture Parameters and Material Ratio Curve for 3D HSS Surface Characterisation

3D surface texture parameters were recently developed by the University of Huddersfield, which allow XCT measurement data to be used for the assessment of 3D surface topography. The 3D surface parameters include height parameters [9, 10], hybrid parameters [9], volume parameters [11] as well as feature parameters based on 3D watershed segmentation [12, 13]. Different from the traditional areal surface texture parameters calculated on the base of surface height maps, 3D parameters are resulted from the 3D surface topography (usually measured by XCT and presented by triangular mesh). The impact of re-entrant features is considered while calculating these 3D parameters. A sequence of height parameters, hybrid parameters and volume parameters are selected for HSS surface characterisation. Please note that surface filtration is not applied before the computation of 3D parameters. This is to avoid the suppression of topographical features with certain wavelength bandwidths.

4.1. 3D height parameters

Sa (arithmetical mean height) and Sq (root mean square height) are the two most popular height parameters used to represent an overall measure of surface texture. The 3D Sa and Sq are computed by

$$Sa = \frac{1}{A_{form}} \iint_{\Sigma_{form}} |r_{sl}(u,v)| \, d\sigma_{form}$$

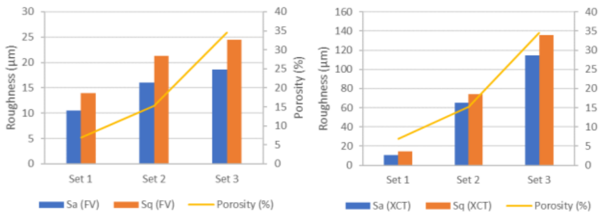
$$Sq = \sqrt{\frac{1}{A_{form}} \iint_{\Sigma_{form}} r_{sl}^2(u,v) \, d\sigma_{form}}$$

where $r_{sl}(u,v)$ represents the scale limited surface, $d\sigma_{form}$ is the infinitesimal areal element, and A_{form} is the area of the form surface. More details can be referred to [9]. Sv is simply the deepest valley of the measured surface.

Sa, Sq and Sv values of three sets of HSS samples are listed in Table 2. The 3D Sa and Sq take re-entrant features into consideration of their computation. This feature is not possible with the conventional areal counterpart. It, therefore, generates much higher values for the surfaces with a large number of open surface pores, e.g. the Set 2 and Set 3 surfaces. The 3D Sa and Sq of the three sample surfaces also quantitatively reflect the characteristics of the open pore clusters. It is, however, not quite evident from the conventional roughness values in Table 2. It is also interesting to find out that the change trend of 3D Sa and Sq, in comparison to the conventional counterparts, aligns better with the general porosity, see Figure 7. Sv, although based on a single extreme value, could indicate the deepest height of open surface pores of three surfaces.

Table 2. 3D Sa, Sq and Sv of three sets of HSS samples.

Set No.	Set 1	Set 2	Set 3
Sa (µm)	10.4	65.0	114.6
Sq (µm)	14.6	74.1	136.1
Sv (µm)	271.8	487.1	789.0



(a) (b)

Figure 7. Comparison of the alignment of Surface Texture with Porosity: (a) areal parameters based on FV measurement; (b) 3D parameters based on XCT measurement.

4.2. 3D hybrid parameters

Hybrid parameters incorporates both height and spatial information. Three hybrid parameters Sdq, Sdr and Srf are particularly useful for the characterisation of HSS 3D surface topography.

Sdq is the weighted mean of the squares of the gradient of a function defined on a surface. Please refer to [9] for the details of its computation. A greater Sdq value indicates steeper topographical features.

Sdr indicates the developed interfacial area ratio, representing the ratio of the increased surface area in comparison to the normal form surface. Sdr is computed as:

$$Sdr = \frac{A - A_{form}}{A_{form}}$$

where A is the area of the actual surface and A_{form} is the area of the form surface.

Srf indicates the percentage of the re-entrant features on the form surface and is defined as

$$Srf = \frac{A_{form} - A_{shadow}}{2 \cdot A_{shadow}}$$

where A_{shadow} is the area of the shadow on the form surface.

Table 3 lists the results of three hybrid parameters. The open surface pores have sharp flanks, resulting the Sdq values of Set 2 and Set 3 nearly double of that of Set 1. Sdr reflects the increase of surface area. The Set 3 surface having the largest number of open surface pores results in 131% increment of surface area. In comparison, the Set 1 surface only generates 8.9% surface area increment due to having only a few open surface pores. Srf offers a quantification of the percentage of re-entrant features. The Set 3 surface results in the highest Srf 57%, followed by the Set 2 13%, while the Set 1 surface only generates 0.5%.

Table 3. 3D Sdq, Sdr and Srf of three sets of HSS samples.

Set No.	Set 1	Set 2	Set 3
Sdq	2.4	4.5	4.9
Sdr (%)	8.9	61.3	130.9
Srf (%)	0.5	12.9	57.4

4.3. 3D material ratio curves and volume parameters

The Abbott-Firestone curve is also named as the material ratio curve or bearing area curve. Mathematically it is the cumulative probability density function of the surface profile's height and can be calculated by integrating the profile traces, see Figure 8.

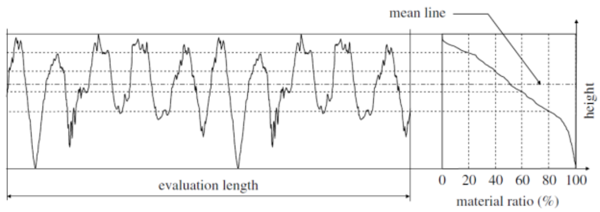


Figure 8. Material ratio curve.

The material ratio curves of the three sample surfaces are illustrated in Figure 9. Recesses are found on the curves of Set 2 and 3 (more significant on Set 3). In the valley zone, the void volume shows big differences among three sets: the curve of Set 1 drops down sharply when approaching to the end, i.e. at the ratio of 98%; Set 2 starts decreasing rapidly at the ratio of 90%; the dramatic drop of Set 3 starts even earlier, at around the ratio of 78%. This indicates that material ratio curve can provide rich information of the development of open surface pores.

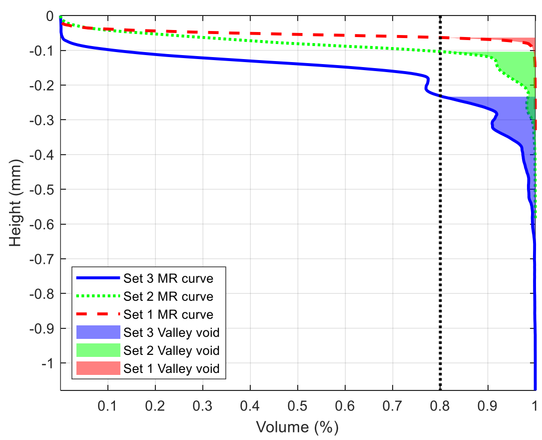


Figure 9. Set Mr2 based on the default value of ISO 25178-2 [14].

The material ratio curve is often divided into three zones, i.e. the peak zone, the core zone, and the valley zone, to match three tribology stage of automotive engineering surfaces, e.g. cylinder liner surfaces, see Figure 10. To adopt this concept into the context of AM, the valley zone is where open surface pores reside. Therefore, it is natural to employ the valley void volume Vvv parameter among the volume parameter family, which is used to indicate the void volume per unit area, to characterise open surface pores. ISO 25178-2 [14] assumes that void valley ranges from 80% to 100% of the material ratio. This 80% Mr2 ratio (used to determine valley void areas), however, is to a large extent proposed based on the experience of automotive industry, and might not be directly applicable to AM. Figure 9 illustrates the valley void areas of three HSS samples. It is evident on the material ratio curve of Set 3 that the surface height corresponding to Mr2 80% is below the first recess position (-0.2 mm), and thus its valley void area only covers part of open surface pores, leading to an inadequate assessment of these pores.

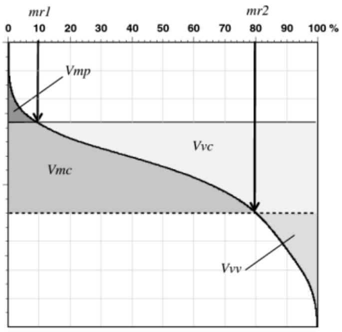


Figure 10. Volume parameters in ISO 25178-2 [15].

To determine a reasonable value of Mr2 for HSS open surface pores, alternative methods must be explored instead of fixing it to 80%. This complies with the statement that Mr2 can be set flexibly upon specific application [16]. With a careful observation of 3D surface topography of Set 3, a large portion of open surface pores starts to develop near the surface height on the material ratio curve where it experiences the first dramatic fall. Therefore, setting Mr2 ratios on the first sharp drop of material ratio curves yields a good covering of open surface pores, see Figure 10. The Mr2 ratios and their corresponding Vvv values of the material ratio curves of HSS surfaces using this approach are listed in Table 4. Vvv is a quantitative indicator to reflect the volume density of open surface pores. This parameter is potentially very useful for HSS process optimisation and HSS product performance assessment.

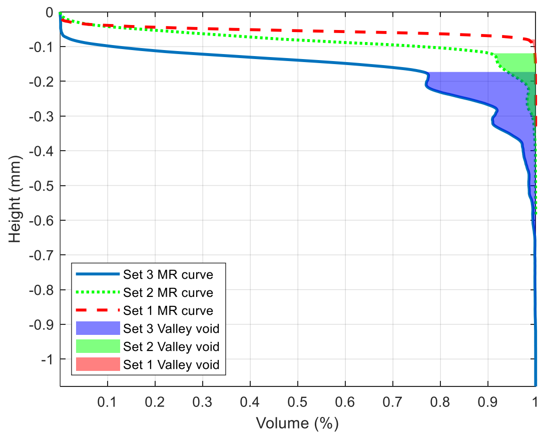


Figure 11. Determination of Mr2 based on the first sharp drop on the material ratio curve.

Table 4. Mr2 ratios and Vvv values of the HSS material ratio curves.

Set No.	Set 1	Set 2	Set 3
$\boldsymbol{Mr2}$ (%)	90.1%	90.2%	77.4%
$\boldsymbol{Vvv}$ (mm^3/mm)	2.172x10^{-7}	3.79 x10^{-6}	7.491x10^{-5}

5. Conclusion

HSS surface topography is in nature 3D, comprised of re-entrant open surface pores. An advantage of 3D surface texture parameters over the conventional counterpart is the ability to address re-entrant features. The selected 3D height parameters, 3D hybrid parameters and the volume parameter based on the material ratio curve enable the quantitative evaluation of the HSS open surface pores from various perspectives, e.g. variation, depth, gradient, area and volume. This makes 3D surface texture parameters an effective analysis tool to address the 3D nature of HSS surface topography, and thus enables surface texture to better link with HSS process optimisation and product performance evaluation.

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