

Layer Formation Studies in Selective Laser Melting of Steel Powders

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ABSTRACT

This paper advances the findings of the selective laser melting (SLM) of tool steel and stainless steel powders. The distinguishing feature is the melting of single layers in deep powder beds by a continuous CO₂ laser. First, effect of process parameters on the surface roughness for each material is investigated. Based on these results combined with visual observation of the solidified tracks, the question is then discussed as how the processability of various type of steels is changed. The results show that surface morphology of layers is affected strongly by scan spacing, thereby giving a lower average roughness at reduced scan spacing. The effect of scan speed is also remarkable. In addition, other roughness parameters such as the peak height and skewness are found to be useful tools for evaluation of laser melted surfaces.

1. INTRODUCTION

Selective laser sintering (SLS) of metals has been the subject of scientific research and commercial developments since the early 1990s, introducing significant findings in terms of process technology, systems, materials and application aspects [1-3]. Regarding the materials, however, only a limited number of commercial metallic powders have been already released and those materials also are restricted to be used with the dedicated SLS machines for their best performance. This weakness may threaten the further successes of SLS process as a worldwide manufacturing technology. As a result, it is a need to broaden the range of used materials either by examining the conventional alloys, or, developing the new material systems. With focusing on standard ferrous alloy powders, this paper is an attempt in this direction in which selective laser melting (SLM) of a number of selected steel powders is studied.

SLM is an emerged name for the direct route of selective laser sintering of metals when the complete melting of powder occurs rather than the sintering or partial melting [4]. Albeit, partial melting of powder mixtures can be also classified under SLM [5]. The aim is to create a strong part that is usable without further post processing other than surface finishing. Although, at the first view, all metals may be thought as possible candidate material, the practical limitations in the processing restrict the range of used materials as well as the process window. Processing window is affected by numerous parameters such as the energy density level, absorptivity, thermal diffusivity, melting point/range, surface tension and viscosity of melt, working atmosphere and so on [5,6]. In addition, the prevention of melt pool instability as well as overcoming the thermal effects are the key issues in the process success [7]. Moreover, the component shape is often a determining factor as bulk volume production is more affected by thermal gradients [8]. In the case of iron based materials, remarkable studies of processing iron [9], iron and alloying elements such as graphite and boron [10,11], steels (low alloy [12], stainless [4,7,13-15], tool [16-18], high speed [19-22]) and specially developed powder mixtures such as Fe-Fe₃P-Ni-Cu [23] have been performed. Not surprisingly, there are significant

differences in the reported results, but sometimes findings contradict each other. While, it is reported that 316L stainless steel can be routinely processed to densities greater than 99%, less success has so far been achieved with tool steels. Elsewhere, it was shown that H13 can be processed easier than M2 under the conditions investigated [18]. Densities up to 90% were reported with H13 powder compared with 70% for M2. In another attempt, a relative density of 85% was reported with M2 [22]. On the other hand, it is reported in [10] that processing of M2 would tend to jam the powder roller within the SLS machine, thereby making M2 powder almost unprocessable by this route. This study aims to provide an insight into processability of steel powders through studying the surface roughness. The surface roughness is not only a primary concern to the users, but also a key issue in completion of component during the fabrication. Firstly, the effect of process parameters on the surface texture is investigated. Based on these results combined with visual observation of the solidified tracks, the question is then discussed as how the processability of various type of steels is changed. Along with the average roughness, other roughness parameters are also investigated to determine any possible correlation between the laser melted surface feature and the parameters.

2. EXPERIMENTATION

The experiments aimed to investigate the surface roughness of a number of selected steel powders at various process parameters. Gas atomized M2 high speed steel, H13 tool steel, 314S-HC and 316L stainless steel powders were used in this study. 316L was selected because it has been found to be processed with relative ease. The composition and size fraction of the powders used are listed in Table 1. All tests were performed using a research SLS machine built at the University of Leeds. The laser used was a SINRAD 240W CO₂ laser in continuous mode with a beam diameter of 0.6 mm. Rectangular single layers 10 mm × 20 mm were produced on a 5 mm deep powder bed. The raster scans were parallel to the width of the layer, with scan spacing of 0.06, 0.3 and 0.6mm (10, 50 and 100% of the laser beam respectively). Laser power of 110W was used, with 12 levels of scan speed from 1 to 150mm/s. The process was performed under argon atmosphere to protect powders from oxidation. More details of experimental procedure has been described elsewhere [7].

After processing, layers were lifted from the bed, strongly brushed to remove loose powder, and weighed. Surface roughness perpendicular to the scanning direction (i.e. along the longer side of the layer) was measured with a Talysurf instrument, a contact surface profilometry, with a tip radius of 2.5 μm. A cut off length of 2.5mm and a total evaluation length of 15mm was used. Besides measuring the average roughness (R_a), different measures of roughness such as R_q, R_p, R_t and R_v were recorded to assess which might be correlated with surface feature. For each sample the measurements were carried out three times: along the centre line, 2mm up and down of the centre line of sample. In addition each processing condition was

Material	Composition (wt. %) (balance Fe)									Size range (μm)
	C	Si	S	Mn	Ni	Cr	Mo	W	V	
M2	0.88	0.27	0.004	0.28	-	3.9	4.8	5.8	1.9	-53
H13	0.38	0.93	-	0.32	-	4.9	1.7	-	1.0	-75/+38
316L	0.029	0.23	0.009	1.4	11.8	16.9	2.3	-	-	-45
314S-HC	0.44	1.4	-	0.91	20.3	24.7	-	-	-	-53

Table 1 Composition and size ranges of stainless, tool and high speed steel powders

repeated at least twice and the mean surface roughness and the standard deviation were calculated. Extremely rough surfacing or the large holes that observed in the produced samples at some experimental conditions, made the contact method of roughness testing impossible. Instead, a non-contact surface profiling system, Wykoo NT3300 optical profiler, was used to scan an area of 16×4 mm in such cases. The optical profiling system is a 3D surface topography measurement instrument, in which the interference of two beams from a broad spectrum light source is used to measure surface feature. However, the reported results in this paper are limited to the contact measuring method. Layers topography was recorded using scanning electron microscopy (SEM) and optical microscopy equipped with a digital camera.

3. RESULTS AND DISCUSSION

3.1 Reduced Scan Spacing

Figure 1(a) reveals the effect of scan speed on the measured average roughness, R_a , of 316L stainless steel processed at scan spacing of 0.06 mm (90% beam overlap). The results show that the roughest surface is produced at the lowest scan speed. This is due to the fact that the high delivered energy to the powder bed at low level of speed forms an enlarged molten pool, thereby increasing the surface roughness. As shown in this figure, there is a low scan speed range, here 2 to 15 mm/s and marked AB, in which R_a , reduces rapidly with increasing speed. There is then a range BC in which R_a varies with speed. Then at higher speeds, range CD, the average roughness is affected slightly by the scan speed and even appears to be independent of speed at $U \geq 100$ mm/s. At these speeds relatively smooth layers with good repetition are produced. However, further increasing of scan speed results in producing porous and fragile samples, thereby giving higher roughness. The BC speed range, the range of variation of R_a with speed, is likely correlated to that reported in reference [16], in which there existed a speed range that the layer mass increased with scan speed. In other word, the more powders melt, the more rough surface forms. Here, the mentioned range occurs at around 15 to 50 mm/s.

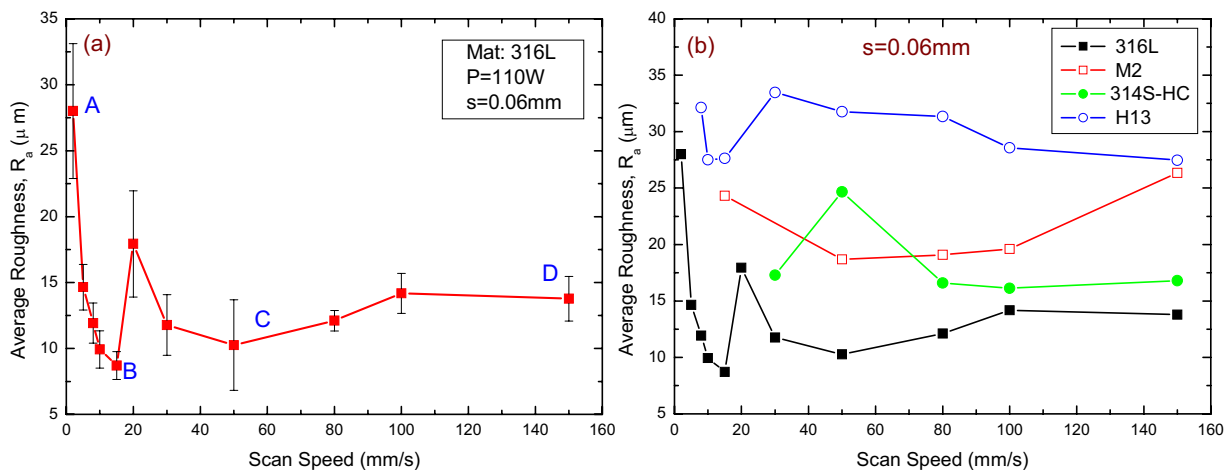


Figure 1 Measured average roughness at $s=0.06$ mm, (a) 316L, (b) all batch of powders

The recorded average roughness for all four batch of steel powders are shown in Figure 1(b). All samples were produced at the same parameters and with scan spacing of 0.06 mm. Except for the case 316L, there was a speed range in which the measuring surface texture was

impossible by the stylus method. This is discussed in further paragraphs. The results indicate that the average surface roughness is not importantly affected by the material at this scan spacing and almost all materials show the same trend as discussed for 316L former. At high speeds, particularly all materials except M2 reveal that their roughness is independent of scan speed. However, the overall findings show that H13 and 316L samples are appeared to became the roughest and smoothest surfaces respectively.

Figure 2 shows the typical surface morphology of layers formed at power of 110W and a scan spacing of 0.06mm. At speed of 5mm/s, a fully dense 316L without any pores in the structure was formed (Figure 2(a)). Although, a relatively smooth surface is produced and there is no evidence of individual track formation, the rippling associated with the tracks appears in Figure 2(b). For the H13 and M2 powders, on the other hand, processing at the same scan speed resulted in the formation of columnar agglomerates parallel to the scan direction and irregular large pores in the surfaces as shown in Figure 2(c) and (d). As a result, surfaces became too rough to evaluate their surface finish. As the speed is raised to 20mm/s, Figure 2(e) and (f), a relatively more smooth, compared to 5mm/s speed, and almost fully dense surface of 316L is generated (Figure 2(e)). While, the produced surface of M2 layer is still accompanied with pores (Figure 2(f)). The pores are more regular in shape and mainly are appeared along a line parallel to the scanning direction. This situation is shown in Figure 2(g) where 314S-HC processed at a speed of 20mm/s. Additionally, the appearance of pores are less pronounced near the layer edges. As speed is raised to 100mm/s, as shown for M2 in Figure 2(h), a smooth surface with small distributed bores around the surface of layer is formed. The latter phenomenon was observed for all batch of powders processed at this scan speed. However, compared with findings at low scan speed, processing at higher speed resulted in the formation of finer surface structure, small agglomerates and reduced pore size, the same as reported by others [21,22].

In raster scanning when the laser interacts with the powder bed, the layer formation is performed by localised melting and bonding of particles in a row line by line. Consequently, a molten track is formed in which its shape and length is a function of process parameters. Depending on the material composition, its physical properties and working atmosphere, these tracks may interrupt somehow or other. Track instability phenomenon has been discussed in detail elsewhere [7] (Also in [9,20]). Breaking up of tracks is associated with formation of agglomerates and pores in the surface. On the other hand, bed surface temperature is decreased with increasing scan speed, causing the higher melt viscosity and surface tension. Consequently, the melt cannot fill the spaces between particles and large pores are formed. It means the porosity in the scanned surface generally increases with increasing scan speed. However, a closed look at the measured R_a in Figure 1(b) demonstrate that there is a low speed range in which the formation of large agglomerate and pores made the surface texture testing impossible. Niu and Chang, [20], have proposed that this phenomenon may be caused by the competition between coursening and densification. Laser melting at low speed range tends to cause the formation of the coarse and dense agglomerates because of the highly localised heat input and greater heat affected zone around the laser beam, thereby increasing agglomeration of the powder particles outside the laser beam. While processing at a high speed gives a relatively low heat input and smaller heat affected zone, thereby giving less agglomeration outside the laser beam, with relatively small agglomerates and pores. In the current study, the measurement of

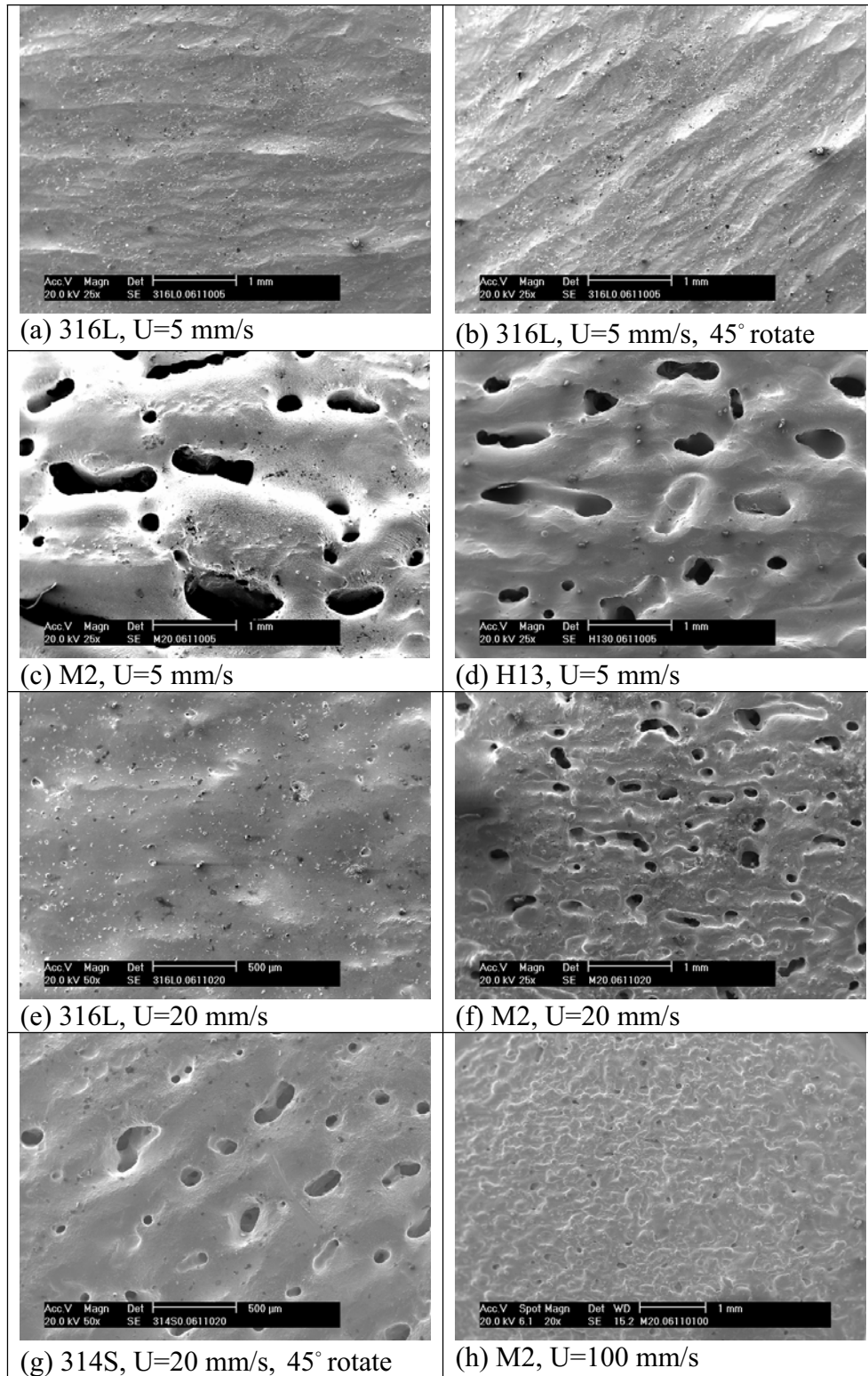


Figure 2 SEM images of laser melted 316L, M2,314S and H13 surfaces at s=0.06mm

316L surface finish was carried out from a speed of 2mm/s, while for the other batch of powders it was accomplished at higher speed levels. The two possible explanations of the differences between 316L and the other powders in the measurable speed level are that firstly, the existence of higher percentages of silicon in H13 and 314S-HC, and carbon in M2, decreases the viscosity of melt, thereby facilitating flow of melt pool. Secondly, all other three batch of powders are found to have a wider melting temperature range than that of 316L in which greater mushy zone are formed. Moreover, the effect of absorptivity is worthy of mention.

3.2 Moderate Scan Spacing

The measured average roughness of the samples as a function of scan speed, for the scan spacing of 0.30mm, are shown in Figure 3(a). At this scan spacing, full dense layers were formed at a lower speed level, thereby performing the surface texture testing from a speed of 2mm/s. The highest R_a was recorded for M2 when processed at 2mm/s. For all the powder batches, R_a is affected by speed in a similar way. However, appearances of through holes on the 316L samples processed at $U > 8$ mm/s made the roughness measuring impossible for those layers (see Figure 4(d)). While, the average roughness of H13 is scarcely affected by the speed, R_a generally reduces with increasing scan speed for the other powder batches. This is consistent with R_a values at the reduced scan spacing. Compared to the results in Figure 1(b), the average roughness for the all powder batches, except H13, are found to increase with scan spacing. Increasing the average roughness with speed has been also reported in [24]. This might be due to formation of a wider melt pool as more fresh powder melts at increased scan spacing. Along the average surface roughness, Figure 4 gathers typical images of layers formed at these process parameters. Formation of individual tracks is clearly observed for all the imaged samples. In addition, they reveal the form of rather more rounded tracks than they formed in the decreased scan spacing.

3.3 Increased Scan Spacing

By increasing the scan spacing to 0.60mm, the more extended width tracks are formed, thereby, making more rougher surfaces. This situation corresponds to the single track formation where continuous rounded tracks at low speed and broken tracks at slightly higher speeds where formed. Figure 3(b) shows the measured average roughness for the four powder batches

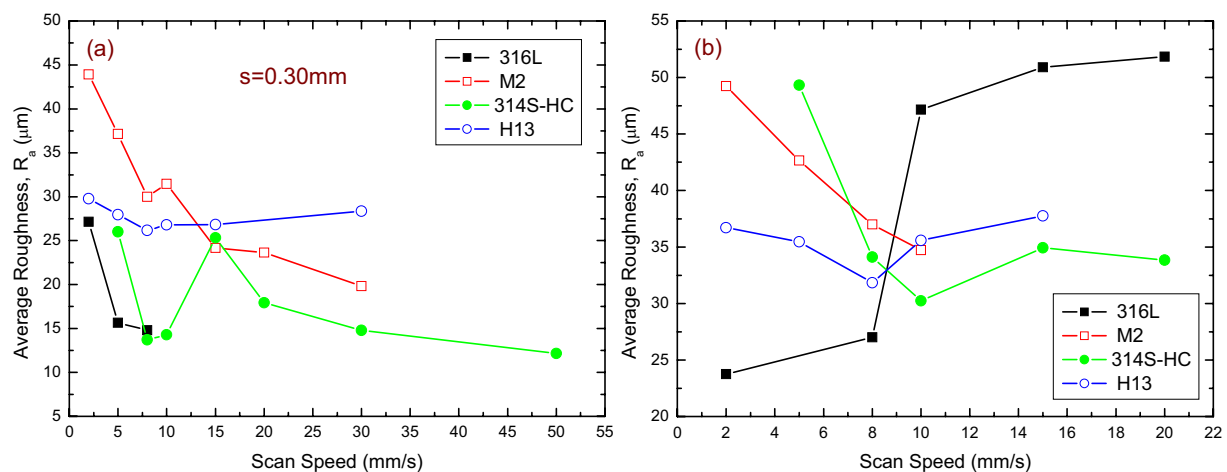


Figure 3 Measured average roughness for all powders, (a) $s=0.30\text{mm}$, (b) $s=0.60\text{mm}$

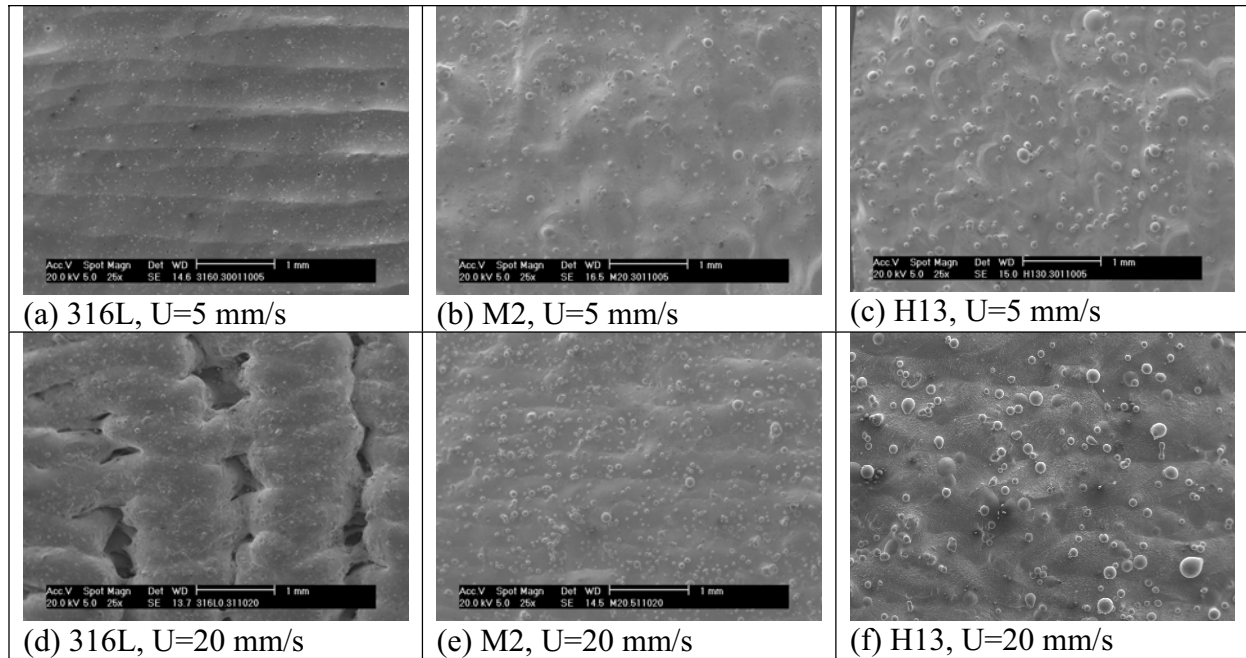


Figure 4 SEM images of laser melted 316L, M2 and H13 surfaces at $s=0.30\text{mm}$

processed at the increased scan spacing. Formation of undulating surface morphology and weak bonding between adjoining tracks, thereby causing areas of porosity, limited the testing speed range to 20mm/s . Compared to the reduced and moderate scan spacing results, higher R_a values were recorded. The results trends almost are similar to those observed at lower scan spacings. However, there is no explanation for significant increase of R_a in the case of 316L powder at higher speeds. It seems R_a can not evaluate solely the surface texture at this experimental condition. This is discussed next.

3.4 Other Roughness Parameters

Table 2 presents the measured roughness parameters of H13 samples, for the three tested scan spacings of 0.06 , 0.30 and 0.60mm , at a speed of 15mm/s . A mean of all readings is given for each case, together with the standard deviation of values. The results show the highest value of average roughness is recorded, as expected, at the greatest scan spacing. However, the both samples with the reduced and moderate scan spacings are found to have approximately the same R_a value ($27\text{--}28\ \mu\text{m}$). On the other hand, it is observed that surface feature quite differs with variation of scan spacing. It means R_a is not an adequate tool here to distinguish between the surfaces. In fact, while R_a remains useful as a general guideline of surface texture, it typically proves too general to describe the surface's functional nature. R_a makes no distinction between peaks and valley, nor does it prove information about spatial structure. Therefore, it is a need to consider the other roughness parameters to evaluate the surface. Table 2 shows R_p and R_t to vary more with spacing than R_a . The peak roughness R_p , the distance between the highest point of the surface and the mean surface over the evaluation length, were measured 58.7 and $84.5\ \mu\text{m}$ for scan spacings of 0.06 and 0.30mm respectively. Consequently, at these conditions, the total roughness R_t , the distance between the highest and lowest points over the evaluation length, were recorded 174.1 and $236.3\ \mu\text{m}$ respectively. It means by increasing s from 0.06 to 0.3mm , R_p and

Parameters	Scan spacing (s)		
	Reduced (0.06mm)	Moderate (0.30mm)	Increased (0.60mm)
R_a (μ m)	27.7 ± 1.0	26.9 ± 3.1	37.7 ± 4.7
R_q (μ m)	35.1 ± 1.1	35.2 ± 4.9	46.9 ± 5.3
R_p (μ m)	58.7 ± 1.9	84.5 ± 11.4	91.5 ± 7.8
R_{p1max} (μ m)	75.9 ± 11.1	135.8 ± 50.1	122.0 ± 8.9
R_v (μ m)	88.1 ± 12.5	70.0 ± 5.9	112.0 ± 25.8
R_{v1max} (μ m)	98.2 ± 11.8	100.5 ± 13.8	134.5 ± 24.1
R_t (μ m)	174.1 ± 22.9	236.3 ± 61.3	256.6 ± 23.4
R_{sk}	-0.73 ± 0.14	0.65 ± 0.14	0.14 ± 0.05
R_{ku}	3.30 ± 0.66	4.79 ± 1.42	2.83 ± 0.18
R_z (μ m)	146.8 ± 14.4	154.5 ± 13.6	203.5 ± 28.7
R_{sm} (μ m)	748.0 ± 63.8	762.1 ± 168.5	775.3 ± 105.7
R_c	96.7 ± 2.8	98.3 ± 14.7	144.4 ± 18.7

Table 2 Surface parameters of H13 tool steel processed at a speed of 15mm/s

R_t values increased by 44 and 36% respectively. Increasing these parameters show that appearance of unusual conditions, such as sharp spikes or burrs on the surface is more pronounced. Actually, it seems that these parameters play a key role in the SLM as each new layer processing needs the fresh powder to be deposited on the previously scanned surface. Perhaps, in some experimental conditions the peak roughness may dominate the powder deposition system. However, as R_t is based on two peak height values (or a single peak height for R_p), it is not a very repeatable parameter.

Among the other roughness parameters, R_{sk} , skewness and R_{ku} , kurtosis, are found also to be relevant in the SLM process. Skewness is a measure of the asymmetry of the profile about the mean line. The sign of the skewness will tell whether the farther points are above or below the mean surface level. Negative skew indicates a predominance of valleys, while positive skew is seen on surface with peaks. More random surfaces have a skew near zero. For the H13 powder processed at speed of 15mm/s, a negative recorded value of R_{sk} at $s=0.06$ mm, became positive when scan spacing increased to 0.30mm. It means that surfaces processed at a higher scan spacing are found to have more spikes on their surfaces. As scan spacing is raised to 0.6mm, R_{sk} is still positive but its magnitude tends near zero. In other word, the surface became more random (the less repetitive).

Figure 5 compares the values of skewness for the four batch of powders processed at scan spacing 0.06 and 0.60mm. The processing at the reduced scan spacing in all speed ranges, except for the very low speed, resulted in a negative R_{sk} as shown in Figure 5(a). However, the M2 samples are found to have a tendency to more random surfaces at higher speeds that means they are less repetitive than the other processed batches. Perhaps, this issue may address apparent contradictions in the processability of M2 powder. In other word, as M2 are found to have the least repeatability, success of its processing strongly depends on the used process parameters. However, as the current study is limited to the single layer formation, its findings can not comprise the situation of 3D parts production. Further increment of the scan spacing to 0.60mm,

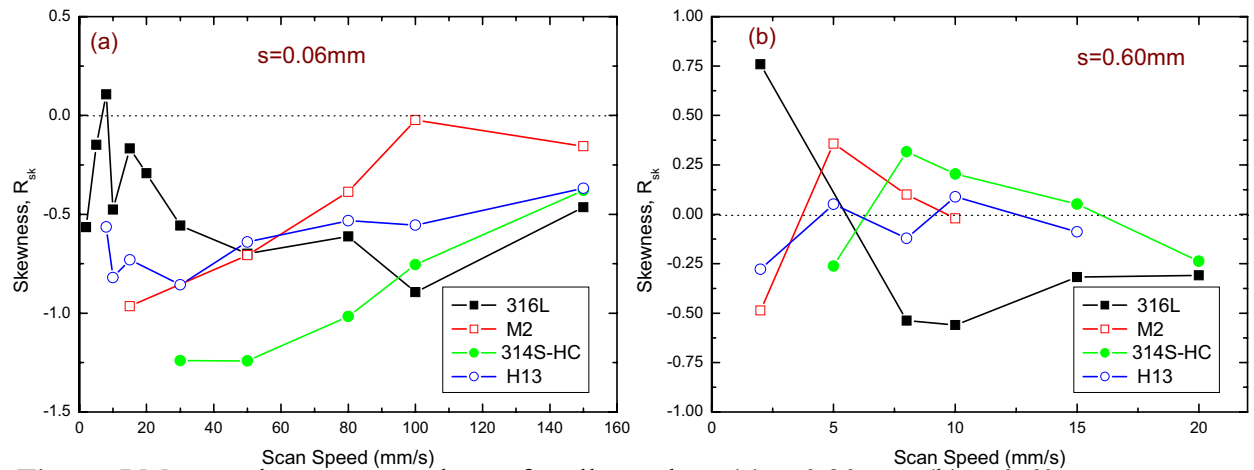


Figure 5 Measured average roughness for all powders, (a) $s=0.30\text{mm}$, (b) $s=0.60\text{mm}$

resulted in mainly positive or near zero values of skewness (Figure 5(b)). These results are consistent with earlier reported values of surface roughness, and also with the observation of surface morphology in which less smooth and more rough samples are produced at increased scan spacing. The overall values of R_{sk} , for all batch of powders at entire process parameters are found to be between nearly -1 and +1. On the other hand, although a negative skewness is a sign of valleys dominance in the surface, R_{sk} specified from -1.6 to -2 is really indicating the presence of comparatively few spikes which should wear away quickly. Ground surfaces often have skewness as low as -3. It means that compared with the other manufacturing processes SLM produces parts, at least in this study, with less repeatability. In fact, this is an inherent problem in the SLM process as it deals with the powders without any post processing other than surface finishing. However, proper selection of materials, processing parameters (smaller layer thickness, smaller laser beam, and so on), energy source and working atmosphere, as well as the part shape, may lead to production of good quality parts. Finally, how does someone answer to the question “Will selective laser melting, for example, have a quicker or immediate success?” [1] ?

4. CONCLUSIONS

Selective laser melting of 316L and 314S stainless, M2 high speed and H13 tool steels was investigated. Single layers were produced on loose powder bed. The findings can be summarized as follow.

1. Surface morphology of layers is affected strongly by scan spacing.
2. Excessive heat input at low speed ranges, as well as instability of molten tracks at higher speeds give rise to porosity.
3. A reduced scan spacing and higher scan speed led to a lower average roughness for the all powder batches examined in this study.
4. Roughness parameters R_p , R_t , R_{sk} and R_{ku} were found to be useful tools for evaluation of laser melted surfaces.
5. M2 high speed steel was found to have the most random surface, i.e. the lowest repeatability.

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