INVESTIGATION ON OCCURRENCE OF ELEVATED EDGES IN SELECTIVE LASER MELTING

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Abstract

Selective laser melting (SLM) is a layer-wise material additive process for the direct fabrication of functional metallic parts. During the process, successive layers of metal powder are fully molten and consolidated on top of each other by the energy of a high intensity laser beam. The process is capable of producing almost fully dense three-dimensional parts having mechanical properties comparable to those of bulk materials. However, one of the problems encountered in SLM process is the occurrence of the elevated ridges of the solidified material at the edges of the successive layers. Those ridges reduce the dimensional accuracy and deteriorate topology of the top surface. The edge-effect problem is encountered not only in SLM, but also in other production techniques applying melting processes such as LENS™ (The Laser Engineered Net Shaping) and EBM (Electron Beam Melting). In this study, the reasons for the elevated edges and solutions to this problem are investigated and reported. Different scan strategies as well as different hatching and contour parameters are tested to reduce the edge-effect problem. Besides, the influence of applying laser re-melting in combination to selective laser melting has been investigated. It turns out that re-melting layers deposited by SLM improves the part density and surface roughness, but creates on its own elevated edges.

1. INTRODUCTION

The technology of Selective Laser Melting (SLM) is an additive production process providing fully functional, three-dimensional models, parts and tools by selectively consolidating successive layers of powdered metal material on top of each other [1]. During the process, a solid state laser source such as an Nd:YAG or fiber laser is used to fully melt powder particles, thereby making dense parts without a need for any post-process densification [2]. A schematic view of the process is shown in Figure 1a.

The process offers many advantages compared to the conventional manufacturing techniques: shorter time to market, mass customization, geometrical freedom and an ability to produce more functionality in the parts with unique design and intrinsic engineered features. Compared to other layer manufacturing technologies, SLM has the advantage to produce parts that have good mechanical properties comparable to those of bulk materials. SLM is now well established in production of complex parts, dental frames as well as for tooling.

Despite significant progress in terms of the process, material flexibility and part quality in recent years, there are still some major drawbacks accompanying the process such as insufficient surface quality, stair-stepping effect, balling, residual stresses and poor dimensional accuracy [3]. Other than these problems, the formation of elevated edges of the solidified material may be a serious problem since it deteriorates the surface topology and dimensional accuracy (See edges of part in Figure 1b). The existence of the elevated edges, on the other hand, may also worsen the stair-stepping effect that is inherent to all layer manufacturing techniques. One of the important disadvantages of having elevated edges on the contours of the parts is the likely collision of these edges with the powder coater blades. Since the height of the produced edges is generally higher than one layer thickness, the coater blades may hit the edges causing vibrations during powder deposition. This results in a waviness on the surface of deposited powder layer, thereby causing aligned porosity in the produced SLM parts, which in turn, may yield anisotropy in mechanical properties.

This paper takes an experimental approach to investigate this phenomenon in detail. It has both a fundamental and an application purpose. The fundamental purpose is to gain better understanding of the underlying physical mechanisms of the incident. The application is to seek solutions to combat or reduce the edge-effect without sacrificing part properties.

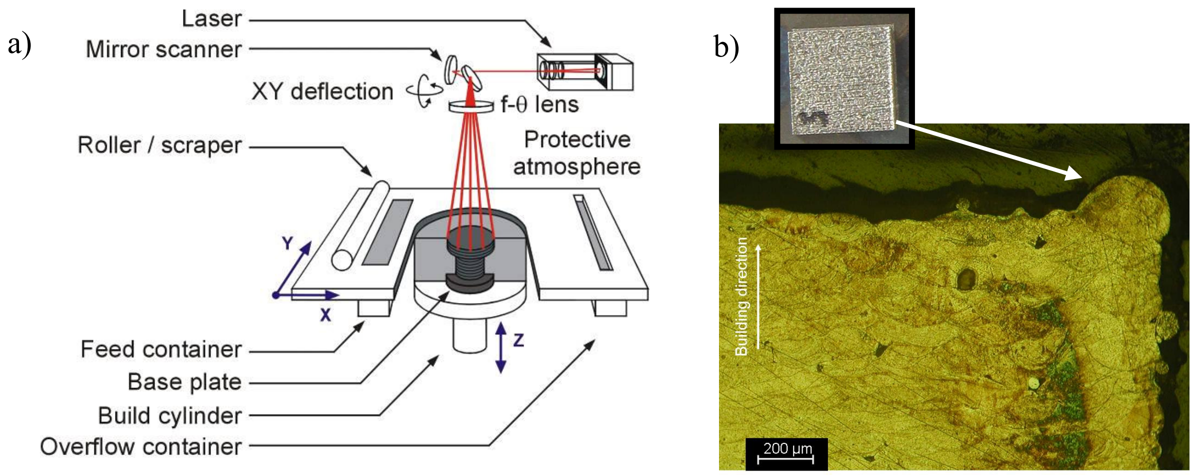


Figure 1: a) A typical SLM machine layout b) Edge-effect seen on a cross-section of an SLM part

2. OVERVIEW OF THE PROBLEM

The problem of elevated edges is not only encountered in selective laser melting [4], but also in laser engineered net shaping (LENS™) [5, 6] and electron beam melting (EBM) [7]. In fact, the generation of circular cross-section tracks is a well known observation in metal melting technologies at some processing conditions. This phenomenon can be understood as the consequence of surface tension effect so that the melt track will assume a form such that its surface area will be a minimum and its volume a maximum i.e. cylindrical in shape with a rounded cross section. The latter incident may speed up through the absence of good wetting between the molten track and the underlying surface [2, 8, 9].

During the SLM process, the first scan line of the layer that is being scanned (part's border) is surrounded at both sides with powder particles with very low thermal conductivity. Due to the change of shape of the melt pool in most cases, more powder particles are dragged to the melt volume thereby increasing the size of melt pool as well as affecting the solidification rate of the melt. In addition, insufficient amount of powder remains for the subsequent scans. The first track then acts as a heat sink when the second is scanned, resulting in a significantly smaller track [10, 11].

Within the melt pool, on the other hand, surface tension gradients coupled with temperature gradients in the surface, result in a rapid flow of melt known as thermo-capillary or Marangoni flow [2, 12]. This flow might be large enough to push the melt back while the laser scans the powder bed.

3. EXPERIMENTATION

The test specimens have been produced from two commercially available alloys of steel and titanium powders. A Concept Laser M3 Linear machine was used to produce the parts from AISI 316L stainless steel. The machine is equipped with a 100 W Nd:YAG laser and a laser beam diameter of about 180 µm at the powder bed surface. The titanium alloy Ti6Al4V was processed using an SLM apparatus, the LM machine, developed at K.U.Leuven. The LM machine employs a 300 W Yb-fiber laser with a focus diameter of 80 µm, and has been described elsewhere [13].

In order to study the influence of the effective parameters on the edge-effect, series of cubic parts with various process parameters and scanning strategies were produced on both machines. The ultimate aim was to find a solution to produce parts having no significant edges, and without a density reduction either in the outer shell or in the core of the produced parts. Generally, decreasing the laser power or increasing the scan speed when approaching the edges results in a better surface flatness as the consequence of a reduced energy input. However, this has a potential to weaken the connection between the contours and the part's core.

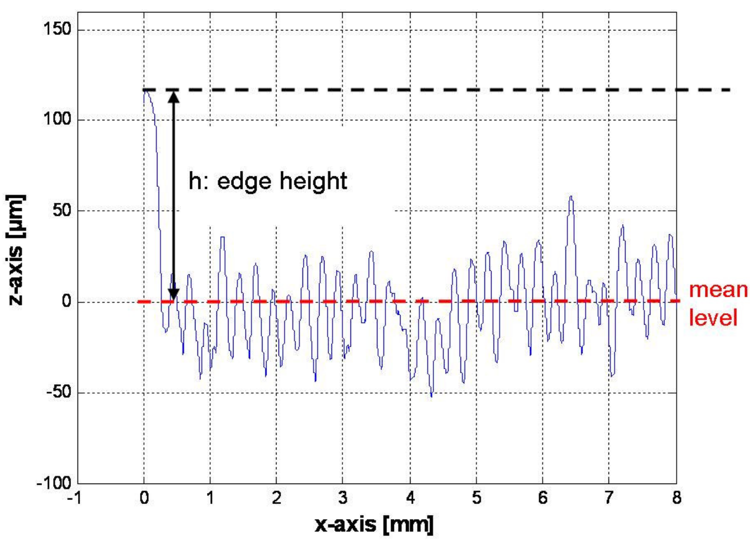


Figure 2: The edge height shown on an average cross-section

While the M3 Linear equipment allows applying a few numbers of dedicated scanning strategies such as island scanning, it is easier to program any desired scanning strategy with a complete freedom in the LM machine. This paper reports the most promising tested scan strategies. The studied factors can be summarized as changing the contour or overall SLM processing parameters, applying multiple or no contours, island scanning, various filling strategies with uni- and bi-directional scanning, applying different profiles for the power in one scan vector and making one part as a combination of two parts such as core and shell made with different parameters.

After production of sample parts, a contact surface profilometer, Talysurf 120L from Taylor Hobson Ltd., was used to measure the edge height of the top surface of as-processed parts. These measurements were carried out by scanning an area of 8 mm x 1 mm along parallel lines taken each 50 µm in y direction. Based on the individual surface profiles taken at an interval of 50 µm, an average profile of the top surface was then determined. Parts' cross-sectional topography was also recorded using an optical microscope.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Following the experimental method described in the previous section and from the average profile of the top surface, the edge height is determined as the distance between the first peak located on the edge of the part and the mean value of the flat surface. An example is shown in Figure 2 where *h* denotes the edge height. The remainder of this section presents results and discussion concerning the work on edge height in the conducted SLM experiments as individual sub-sections.

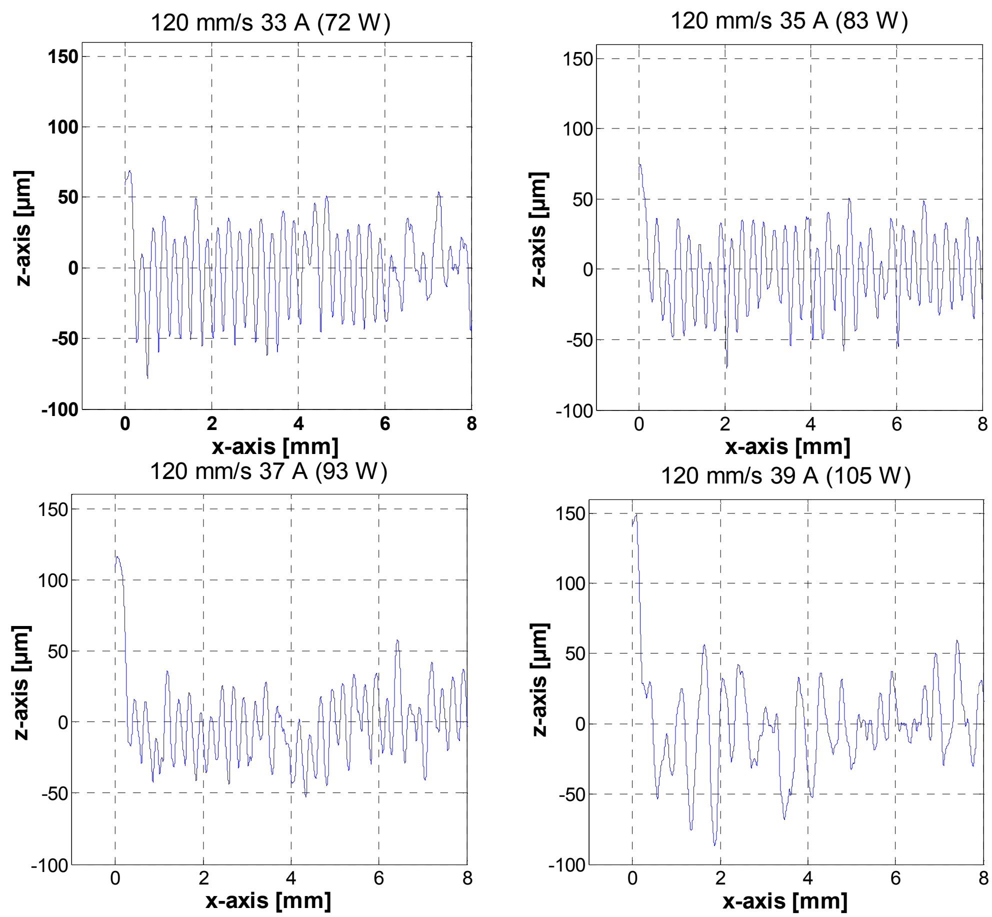


Figure 3: Different profiles derived with 120 mm/s with various laser power values

4.1 SLM process parameters effect

The purpose of carrying out the first set of tests is to investigate the influence of SLM process parameters such as the scan speed and laser power on the edge effect. These experiments were conducted using stainless steel powder of which the nominal scan speed and laser power are given as 360 mm/s and around 100 W respectively. During these tests, the scan speed was varied between 120 to 360 mm/s while the laser power was changed from 72 to 105 W. The contour of the parts was also scanned before the core, at the same processing parameters used for fill vectors. One set of the measured profiles for the scan speed of 120 mm/s, at the four laser powers of 72, 83, 93 and 105 W is illustrated in Figure 3. The recorded profiles in all cases are qualitatively similar so that each part reveals an elevated edge regardless of the used parameters even though the edge height is significantly affected by the laser power.

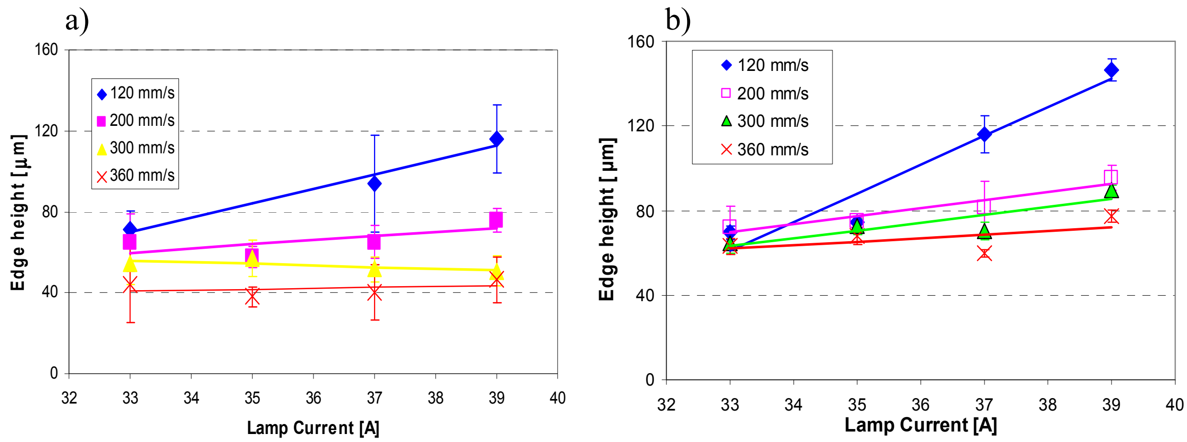


Figure 4: Profiles derived with various scan speeds and laser powers:
a) from top to bottom, b) from side to side

Figure 4 shows the measured edge heights of the parts as a function of laser pump current (laser power), for the two measured directions of side to side and top to bottom (Figure 5), at the four scan speeds from 120 to 360 mm/s. When the laser power is increased, the edges become more pronounced especially at low scan speeds (120 mm/s). At higher scan speeds, the effect of the laser power becomes less significant. The higher energy input entered to the powder bed, the higher the edges become. As the figures suggest different combinations of laser power and scan speed neither solve the edge problem, nor exhibit a significantly lower edge height than the nominal scan speed and laser power values.

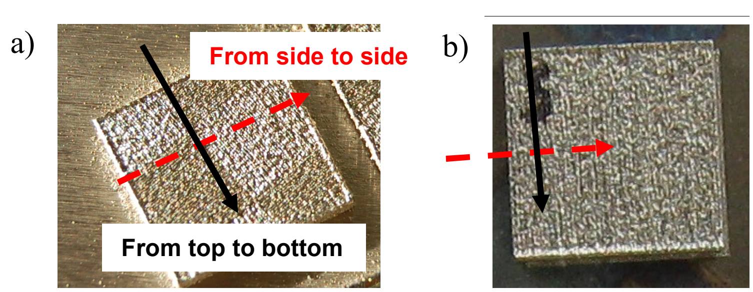


Figure 5: The measurement directions shown on a sample a) produced on Concept Laser M3 Linear with island scanning from 316L stainless steel b) produced on in-house built machine from Ti6Al4V

4.2 Scanning direction effect

In order to investigate the influence of vector scanning direction on the elevated edges of SLM parts, a number of specimens were built from Ti6Al4V material using uni-directional as well bi-directional scanning (raster) patterns. These samples were produced without contour scanning to eliminate the other parameters' effects on the results. Figure 6 compares parts' elevated edges for two scanning patterns. While uni-directional scanning causes a very high edge on one side of the part and a rounded corner on the other side (Figure 6a), bi-directional scanning is found to be a better scanning option lowering the edge height at both sides (Figure 6b). The rapid flow motion towards the sides and back of the melt pool caused by the surface tension gradient (thermal gradient) within the melt pool might be responsible for expelling the melt pool thereby forming high edges at the starting points of the scan lines.

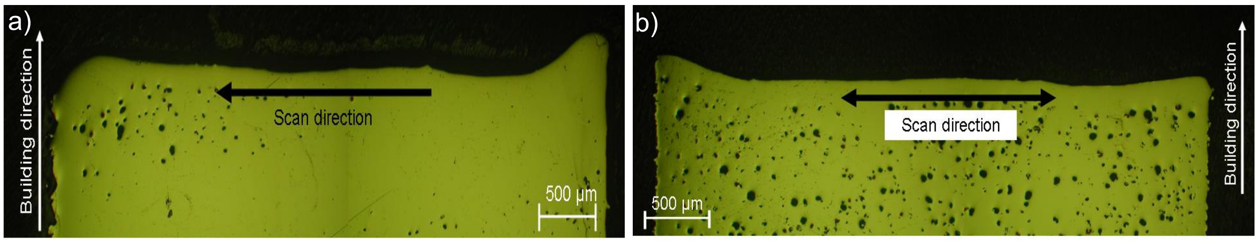


Figure 6: Effect of uni-directional scanning versus bi-directional scanning

4.3 Middle-fill and random-fill scan strategies

This section is concerned with the first scan line conditions, in order to verify the hypothesis of formation of elevated ridges as a consequence of first line scanning. A number of test specimens were produced using Ti6Al4V powder at its nominal SLM parameters (laser power 42 W, scan speed 225 mm/s and scan spacing 74 µm) and without contour scanning. The scanning strategy comprised of starting with first line being scanned at the middle of the layer, followed by filling the area to the right and then to the left of the middle line as depicted in Figure 7a. A scan speed of 750 mm/s for the first scan line was also used to avoid any peak in the middle of the part.

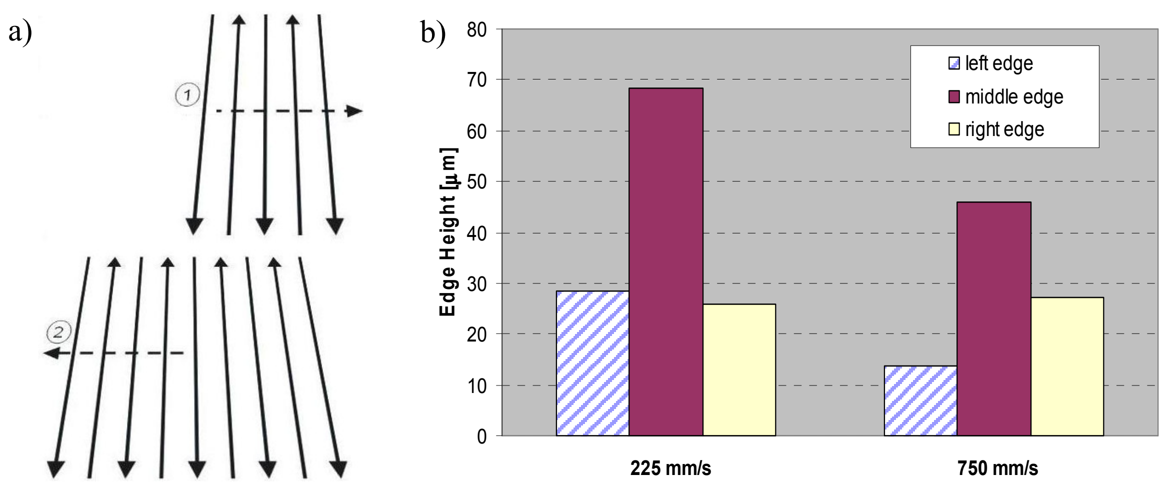
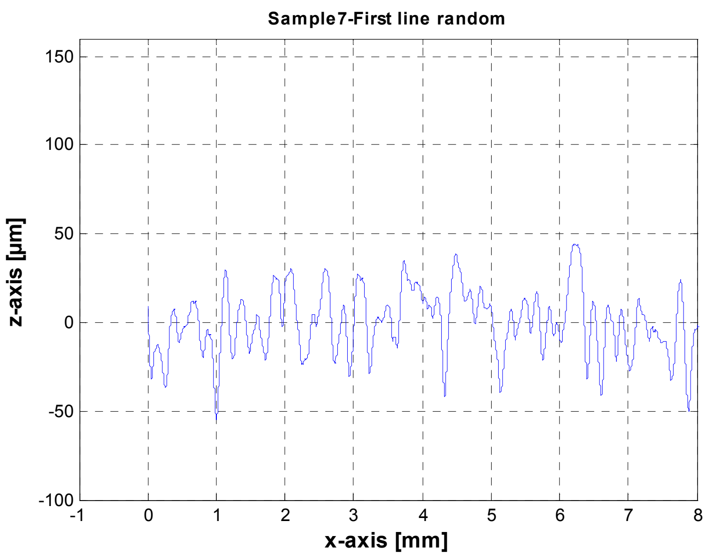


Figure 7: a) Fill middle scan strategy, the arrows represent the direction and order in which the surface was scanned, b) measured heights at left, middle and the right side of part

Figure 7b shows the obtained elevated ridges that were measured in the direction perpendicular to the scan direction (from side to side). The measured profiles show no significant edges anymore at the left and the right borders of the part. Instead a big ridge is visible at the middle of the top surface. The middle ridge height decreases with increasing scan speed. This is in good agreement with the above mentioned hypothesis advancing the thesis that for every scanned layer, the first scan track is the largest and causes the edge effect.

In the foregoing experiments, the first scan line position was always remained at the middle of successive layers. For the next series of tests, the first line of each layer was scanned at a randomly chosen position. The recorded profile and the measured ridge height are depicted in Figure 8. Here the entire part was produced at 225 mm/s. It can be seen that not only no edge was formed in the part, but also the highest peak height (highest first scan line height) was comparable with previous series when the first line was scanned at 750 mm/s. These findings imply that random-fill strategy may reduce the edge-effect without weakening the attainable density.



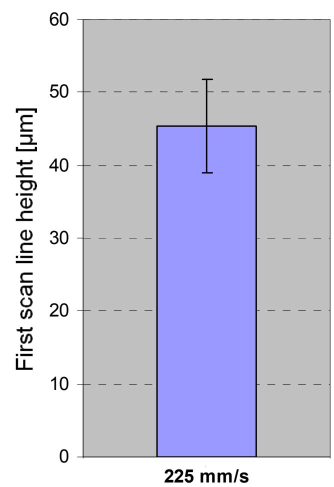


Figure 8: Profile derived with a random-fill scan strategy alongside with the peak ridge

4.4 Island scanning strategy and contour scanning

In this set of 316L stainless steel experiments, the influence of “island scanning”, a patented scanning pattern from Concept Laser, was investigated as well as the effect of contour scanning. In order to decrease the thermal residual stresses, the area to be scanned is divided into smaller sectors (5 mm x 5 mm), and these sectors are raster scanned with shorter scan tracks in a random order (Figure 5). The locations of the sectors are displaced by 1 mm in both x and y directions and the scan vectors are rotated by 90° in each sector from layer to layer. Figure 9 compares the results of island scanning to long vector raster scanning. The figure shows that the island scanning does not worsen or improve the edge-effect, which means the vector length does not play any role on the edge height. The figure is also concerned with the effect of contour scanning on the edge height. The parts made without contours have lower edges regardless of being scanned in islands or with long scan vectors. The production of parts without contours mostly solves the problem of edges but that cannot be used as an ultimate solution since the dimensional accuracy is highly affected by contour scanning. During SLM, the contours of a part are scanned on the powder bed firstly to define the borders of the melt pool, and then the inside the contours is scanned. Therefore, contours are necessary for the dimensional accuracy and cannot be left out during SLM.

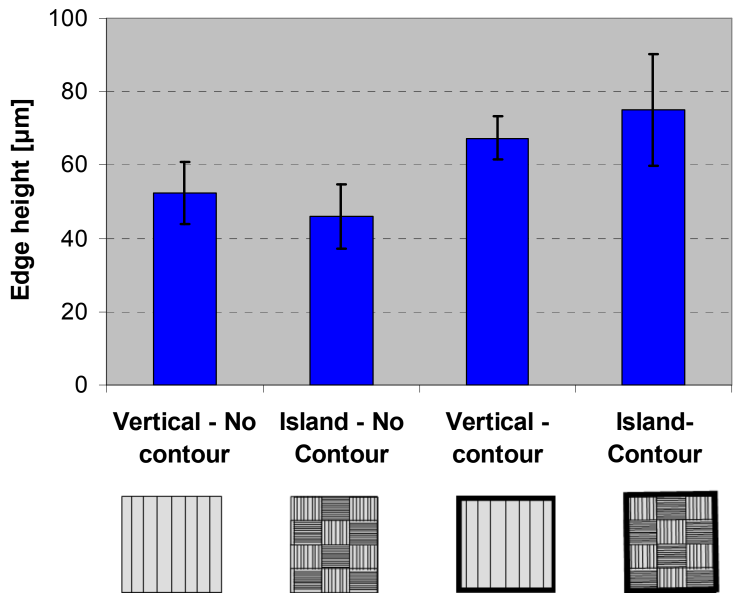


Figure 9: The influence of island scanning on the edge-effect problem

When too high edges are encountered, the general solution from the SLM equipment supplier is to alter the contour parameters. In order to verify this technique, the SLM parameters for filling were kept as nominal values (360 mm/s and 100 W) whereas different combinations of laser power and scan speed were applied to the contours in the second set of tests. Eight scan speeds starting from 250 mm/s to 700 mm/s together with three laser power values (105, 93 and 83 W) were examined. The results are presented in Figure 10. Close to the nominal scan speed, decreasing the laser power increases the edge heights. At high scan speeds, there seems to be a small reduction in the edge height with maximum laser power but the standard deviation is too high to assure reliable results. Thus, it is concluded that increasing the scan speed or decreasing the laser power of the contour section is not a feasible solution to the edge-effect problem encountered in the SLM process.

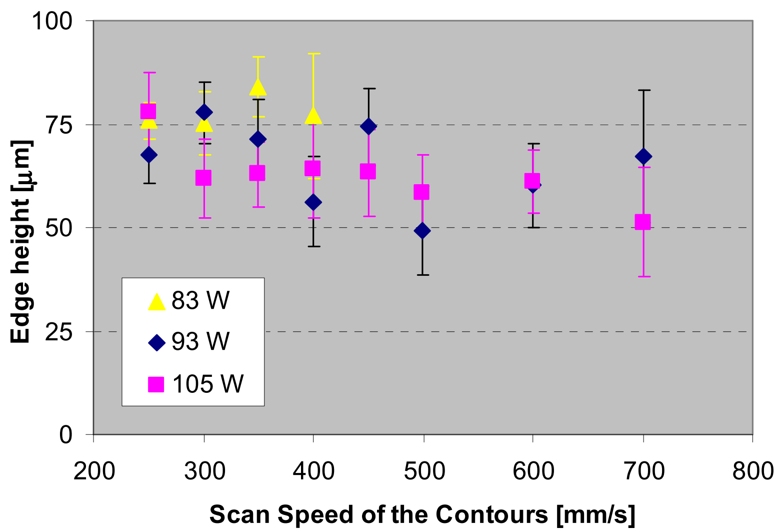


Figure 10: Different edge heights derived with various contour parameters at fixed filling parameters

4.5 Fill vector scanning patterns

This section is concerned with the effect of various filling vector scan patterns. Figure 11a reveals the edge height of 316L parts for four different cases which were produced with parameters of a scan speed of 300 mm/s and a laser power of 105 W both for filling and contours. The arrow shows the direction of measuring the edges height for all cases. The first scan strategy consists of all horizontal scan tracks whereas the scanned area is exposed to laser radiation twice in the second one (i.e. re-melting). The third column represents the results for the scan strategy where all hatch lines were scanned diagonally. The last one is the case with the first one rotated for 90°. The 3D height maps of the same parts are shown in Figure 11b where the surface texture is clearly seen. In terms of the edge-effect, the second strategy which includes melting of the powder followed by re-melting with a rotation of 90° for the fill lines, the edge height is higher than the others. This is in good agreement with the results obtained for re-melting of stainless steel and Ti6Al4V powders [14]. The other three cases give more or less the same results. Consequently, it seems that laser re-melting during SLM, used to improve density or surface quality, results in a more pronounced edge-effect. The 3D height maps of Figure 11b however, clearly demonstrates the lower surface roughness results obtained with laser re-melting.

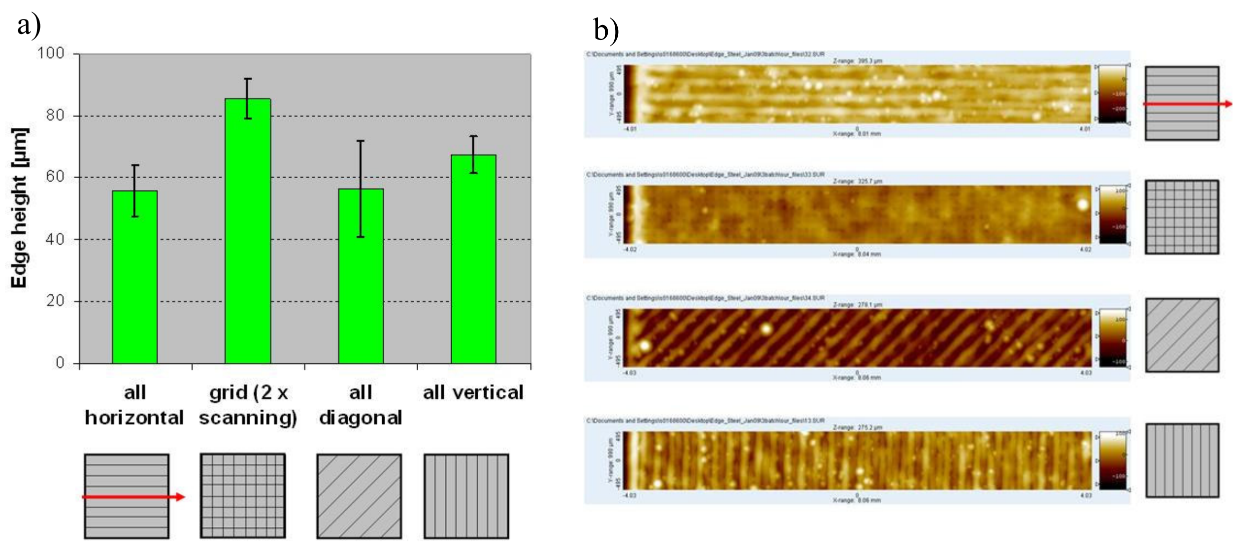


Figure 11: a) Influence of different scan strategies on the edge-effect problem, b) 3D height maps of the surfaces with different scan strategies

4.6 Shell and core effect

The last set of experiments conducted with 316 L was the separation of a part into two sections such as core and shell applying different set of parameters to each section. The thickness of the shell was chosen to be 0.4 mm. In each layer, the shell was first scanned and then the core was followed to be scanned on already solidified shell. In these tests, the core SLM parameters were kept constant (laser power 105 W and scan speed 300 mm/s), but different parameters were applied to the shells. A reference part was also built using the same settings (300 mm/s and 105 W) for contour and fill vectors. The results are presented in Figure 12.

Although the standard deviations of the edges derived in shell+core parts are higher than the reference part, the edge height decreases. Especially, when the three-dimensional profiles are observed, it can be concluded that there is no significant edge formation (~40 µm height) for shell+core parts whereas in the part which was scanned as one part with contour scanning, the edge is clearly distinguishable from the top of the surface. However, since low energy inputs are used in the shell, it is probable that the shell density would not be as high as the density in the core [15].

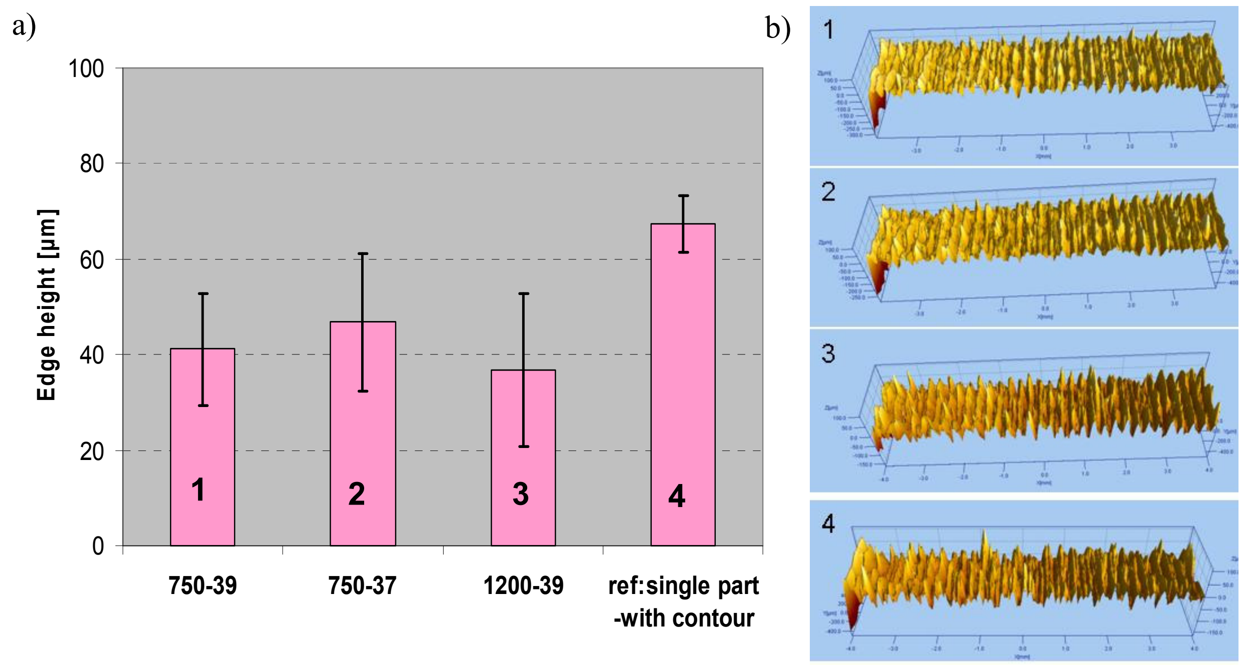


Figure 12: a) Shell and core part results b) 3D profiles of the core+shell parts

4.7 Ramping laser power profile

One important derivation of the tests with the LM machine was how the edge effect could be improved by using a ramp profile for the laser power in one scan vector. As the laser beam approaches the free edge, the laser power is gradually decreased, and this resulted in almost no edge as shown in Figure 13. The starting power was selected as 40 W which is around the nominal power for Ti6Al4V alloy and then as the laser moved to the core of the part, it was increased to 80 W which was very high and resulted in very porous structure as seen in the figure due to evaporation or key hole-effect taking place during the process. Normally, with the default parameters, it is possible to reach up to 99.5% relative density on that equipment with this material. However, when the edges are investigated, it is clear that the ramp profile for the power solves the problem but the starting and threshold laser powers should be optimized for part density.

4.8 Post-fill scan strategy

The goal of this strategy was to compensate the edge-effect by filling up the valleys that were formed by the edges during the SLM processing. The test specimens from Ti6Al4V were produced at the material's nominal parameters. The contour of the parts was scanned before the core with the same processing parameters used for fill vectors. The distance between the contour vectors and fill vectors was chosen to be 45 µm and 75 µm respectively. Upon completion of part scanning, either one or three extra powder layer(s) were deposited and scanned (with no contour) without lowering the building platform.

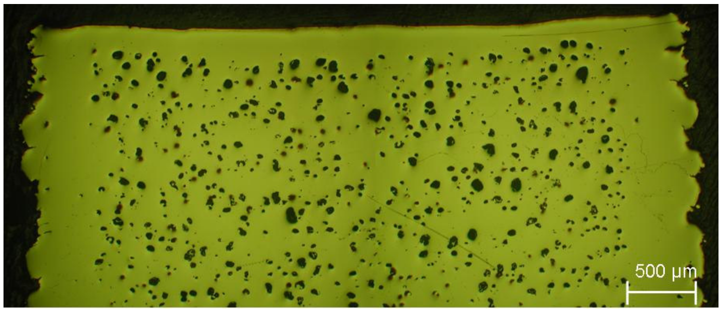


Figure 13: Result of ramp power profile

Figure 14 is concerned with the post-fill strategy. Part (a) represents the measured edge heights for 45 µm and 75 µm fill contour distances respectively. These findings suggest that the post-fill strategy gives the lowest edge height when a distance of 75 µm between the contour and fill vectors, and three extra powder layers are selected. Part (b) shows the three dimensional map as well as the average profile of the mentioned setting. The heights of the edges of the part made by this strategy are about 35 µm. Since the edge height of a part made by standard scanning strategy is about 70 µm, this strategy gives a reduction of the edge-effect by 50%.

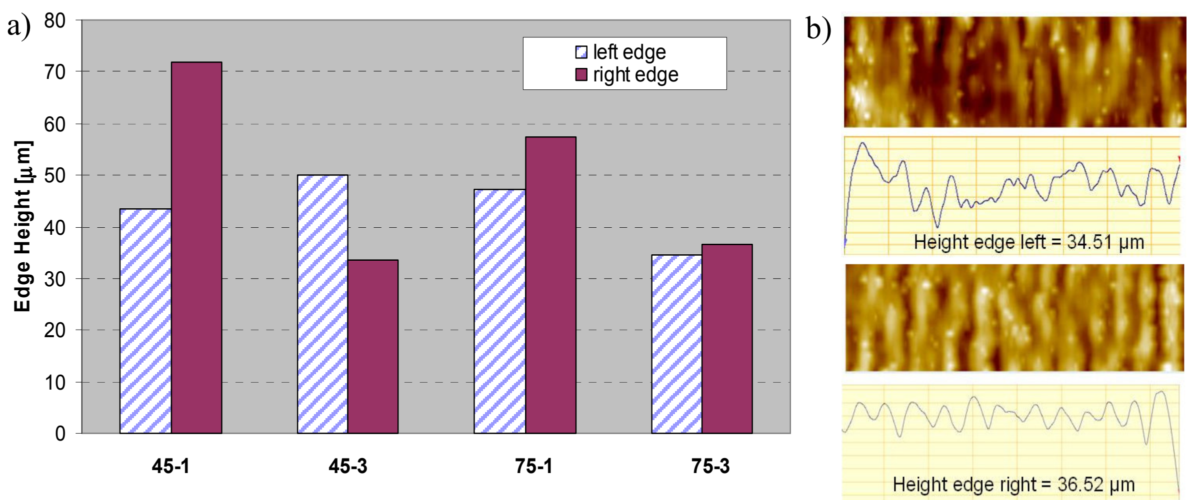


Figure 14: a) Measured height of the left and right edge for parts made with post-fill scan strategies, b) 3D map and average profile of produced part having the lowest height of the edges

5. CONCLUSIONS

This paper has studied the edge-effect problem as one of deleterious phenomenon encountered during SLM. It has demonstrated the main physical mechanisms that influence the elevated ridges within the SLM part’s top surfaces. This incident is likely associated with the melt flow, and affected by material properties as well as processing parameters.

Experimental studies on the SLM of stainless steel and titanium powders have shown that, whilst it is not possible, at this stage, to eliminate the formation of elevated edges completely, the flatness of the top surface can be improved greatly by applying appropriate process parameters as well as adapted scanning strategies.

It is found that contour scanning enlarges the edge-effect, but, on the other hand, the part's dimensional accuracy implies the borders of part to be scanned first. Dividing the part into the shell and the core sections with an overlap between them, not only may reduce the edge heights, but also improve the part quality as contour scanning does. The part's density homogeneity, however, has also to be considered.

Applying the middle-fill scan strategy, where the first line scan of each layer is positioned at the middle of the part, shows that the ridges from the part borders are displaced to the middle of the part. The high height ridges from the top surface almost disappear when the random-fill scan strategy is used. In the latter technique, the first scan line's position is changed in a random order for each layer being scanned. This technique, however, does not imply contour scanning, which is necessary to achieve good dimensional accuracy. The post-fill scan strategy can be used together with contour scanning in order to reduce the edge-effect. A reduction of 50% in edge height is obtained when an appropriate distance between the contour vectors and fill vectors is chosen during SLM process, and without lowering the building platform, three further extra powder layers are deposited and scanned upon completion of the part.

6. ACKNOWLEDGEMENTS

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