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The Influence of Processing Parameters on the Mechanical Properties of SLM Parts

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Abstract

Selective Laser Melting (SLM) is a method of additive manufacturing (AM), which builds metal parts in a layer by layer procedure based on a CAD template. The cross section of the CAD part is melted into the respective layer. The melting of metal powder by an energy beam and successful mastering of the whole manufacturing procedure requires complex management, because multitudes of variables enter the SLM process. These variables are laser power, scan speed, thickness of layer, overlap rate and building direction. This article summarizes their impact on tensile properties and structure of printing materials. An important finding of the investigation follows. The SLM built steel samples usually have better tensile properties than those conventionally manufactured providing the additive manufacturing is properly managed.

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Keywords: Rapid prototyping; Additive Manufacturing; 3D printing; SLM; SLS

1. Introduction

Rapid prototyping is a synonym for the rapid production of parts from a variety of materials. As the title implies, this technology was initially intended for the production of prototypes. Currently, the preferred expression is additive manufacturing. This term is used because the production method is widely used to make parts, which are not prototypes. Demonstration of the use of the AM technology in practice was published in the article [10] by N. O. Balc et al., which show the application of this technology in practice. This technology is also used to repair

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defective metal parts. The theory behind these repairs can be found in [9], with the difference that the polished part is not fixed to the nozzle laser, but is placed in the AM device. There are different technologies which fall within this production category, but this article is focused on production systems whose working processes are based on the SLM method. This method additively builds parts from metal by selectively melting powder and enables the automatic production of plastic parts without the need for tools. This category includes technologies from companies such as LENS, EOS (DMLS), Arcam (EBM), SLM, etc., which use a laser or electron energy beam to melt the metal powder.

AM parts are characterized by their mechanical properties which are affected by the settings of the process parameters. These relationships are the focus of articles by D. Gu et al. who studied in the article [3] the change of integrity of materials produced with different combination of process parameters. The two parameters (laser power and scan speed) were tested on stainless steel 316L. The same author in article [2] described how the same two parameters affected the structure of materials from steel 316L. K.Guan et al. [5] comprehensively summarized dependencies of parameters for other metal material, namely for steel 304. Another study by C. P. Paul et al., article [4], investigated the behavior of Inconel 625 with changing of process parameters. These articles however dealt only with one type of material. The purpose of this paper is to fill in the void. The aim of this paper is to briefly summarize the current insights in this field of research.

2. Mechanical Properties

In general different production technologies produce parts with varying characteristics. It is expected that laser built parts will be different from parts made of the same material but manufactured by a different method. The outcome of the survey is that AM metal parts often have much finer grains than molded or cast structures. Generally, this is attributed to very fast solidification of laser heated material. This happens due to the rapid conduction of heat from the molten zone into the surrounding metal. These high speeds of cooling can lead to the formation of unbalanced crystal phases. For example, see the structure in Figure 1, which shows a metallographic sample of EOS Cobalt Chrome MP1, which was built on the EOSINT M270 system using standard parameters. At the highest resolution of 5000x it is possible to see that the grains are approximately 0.3 to 0.6 µm in size. [1]

When the part is being created layer-by-layer the individual lines of material are gradually melted and recrystallized. Therefore, it would be expected that the resulting structure of AM in all cases will be fine-grained and similar to the structure in Figure 1. However the example of the laser built Ti6Al4V component does not show any such fine-grained structure. For AM methods the dendrite crystals are usually oriented vertically to the applied layer and the crystals have at least the height of the thickness of one layer. The Ti6A14V structure also had crystals oriented this way, which were much thicker than the thickness of one layer. This phenomenon is explained by the fact that the laser energy was so large that it once again remolded the bottom layer of the manufactured unit, which eliminated visible borders and enabled crystal growth through several layers due to repeated re-crystallization. [1]

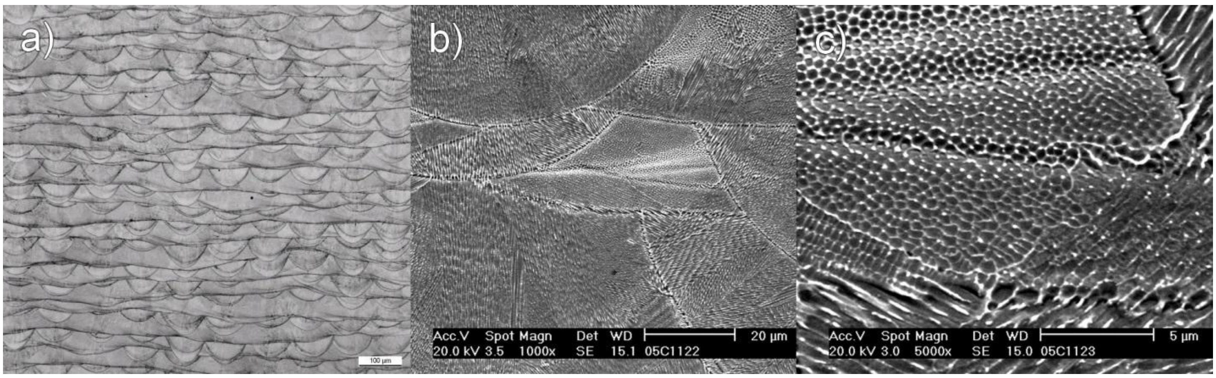

Fig. 1. EOS CobaltChrome- MP1; a) 10x enlarged; b) 1000x SEM; c) 5000x SEM. [1].

From these findings we can deduce that the structure and properties of the material depend on the selected parameters of the production and attributes of the melted powder.

This observation was followed by further investigation of the effect of the procedural parameters on the initial properties of AM products.

3. The influence of laser power and scanning speed on the structure of the material [2]

The amount of liquid phase in the melted components depends on the melting temperature, which is further influenced by the energy transferred to the powder. The main parameters that affect the mentioned energy are the laser power and the scanning speed. Different combinations, demonstrated on the stainless steel 316L with a layer thickness of 20 µm, were mentioned in an article by D. Gu and Y. Shen. [2] These combinations were considered in order to determine the influence of different ray performances and scanning speeds. The powder melting track on one layer proceeds along a simple linear raster as shown in Figure 2. The following cases summarize the observations made from the examined dependencies. Each individual case produces a similar melting mechanism:

I. No melting: The delivered energy beam was insufficient to melt the powder and so a large amount of powder remained in its initial state after the production.
II. Partial melting: Medium beam performance in combination with a low scanning speed (<0.06 m/s) formed a liquid phase on the particles' surface. This phase will bake together the unmelted cores of particles into coarsened balls with about the diameter of the beam after crystallization. This surface shows the first type of balling phenomenon. [3]
III. Melting with the balling phenomenon: At a high laser output and a high scanning speed (≥0.06 m / s) the shapes made by the melting track, as seen on the surface, were long, thin cylindrical lines, which later split up into rows of coarse beads. This was a result of the reduction of surface tension.
IV. Complete melting: The laser energy was so great that permanent tracks of molten metal material were created. The tracks formed continuous lines of fully melted compact solid surface.

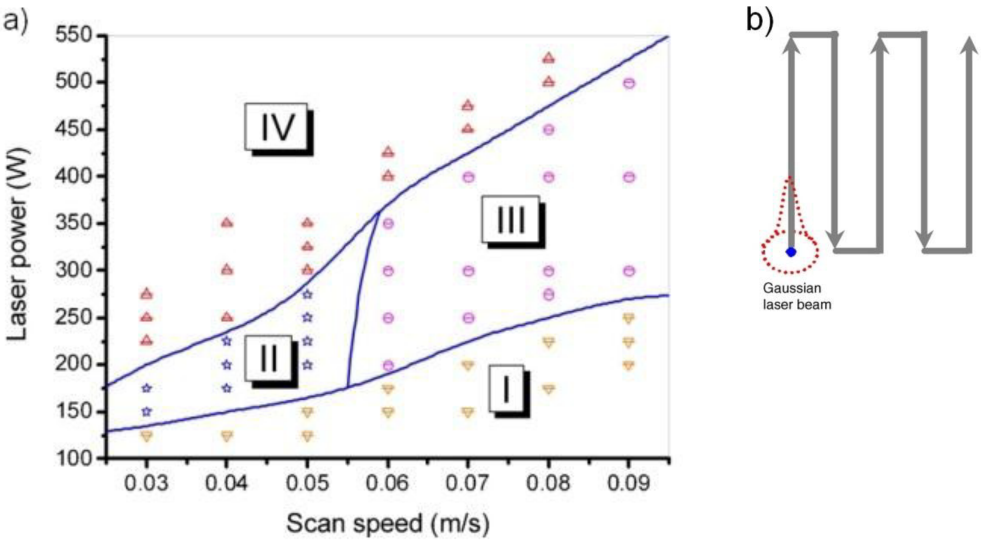

Fig. 2. a) Dependency of the structure on the procedural parameters; b) Procedure of the powder laser scanning. [2]

Figure 2 graphically plots procedural parameters for the above mentioned structure types. Laser power and scanning speed values are rendered on the axes. Morphological structures of the surfaces of individual cases are indicated in Figure 3. When the laser power is at 300 W and scanning speeds are at 0.05 m/s a fully consistent melted surface was formed (Fig. 3.a) typical for case 4. However, when increasing the scanning speed to 0.08 m/s while keeping the laser power constant, a typical structure for case 3 is formed. This structure consisted of coarse individual agglomerates of a spherical shape (Fig. 3.b), which are characteristic for the phenomenon called "balling" of the first kind. This was the first time the phenomenon began to emerge in this group's production settings. With the reduction in laser performance to 250 W and scanning speed to 0.05 m/s the sample showed a porous structure with open pores at the surface (Fig. 3.c). In addition the melted surface consisted of very long longitudinal structures on a grid matrix and did not have the form of spherical agglomerates. The beam energy was in fact great enough that individual agglomerates were attached with strong bonds ("bridges") to each other. Therefore, the structure of the sample showed no brittleness, which is characteristic for materials exhibiting balling. This case is illustrated in Figure 2 as the range of contact for cases 2 and 4. [2]

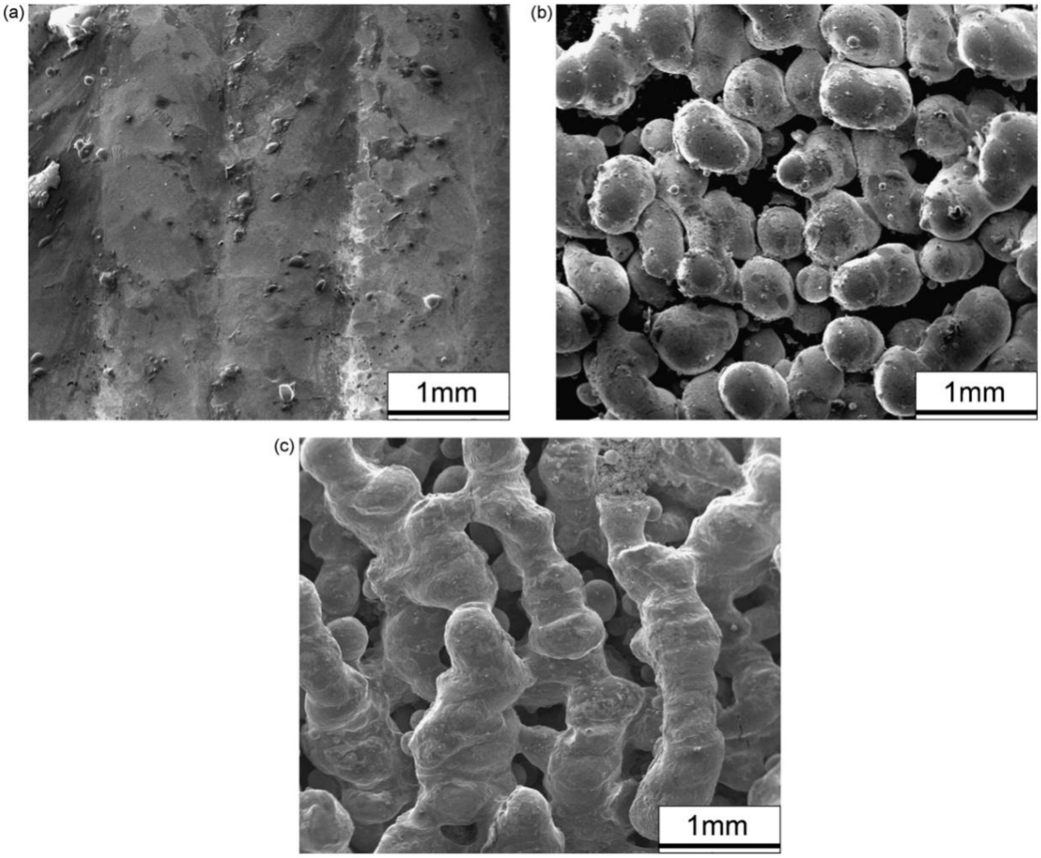

Fig. 3. The structure of molten samples; a) full consistent surface; b) surface with balling phenomenon; c) porous structure. [2]

4. Impact of the hatch angle

The hatch angle θ is defined as the angle between laser scanning directions on consecutive layers as shown in Figure 4. For example, a hatch angle of 90 ° means that after the deposition of melted rows in four layers, the orientation of the next melted row will be the same as the rows of the first layer. Anisotropy of mechanical properties is difficult to remove. This happens when an unsuitable hatch angle is selected. The hatch angle parameter affects the performance of the manufactured parts. But this statement is not yet completely resolved. For example C.P. Paul et al. [4] point out that in a sample of melted Inconel 625 tensile properties of the material were not influenced by the hatch angle. However Kai Guan et al. [5] also discussed this issue in their work. Samples of stainless steel material 304 were investigated. These samples were built using the same manufacturing properties: (laser power 200 W, scanning speed 0.25 m/s, layer thickness 20 µm, overlap rate 40%, building direction 0°). The difference in individual samples was in the hatch angle used 90°, 105°, 120°, 135°, 150°. [5]

Figure 5 shows after how many layers, expressed as interval number *N*, the direction of the melting line will match the direction of the line in the initial layer depending on the examined hatch angle.

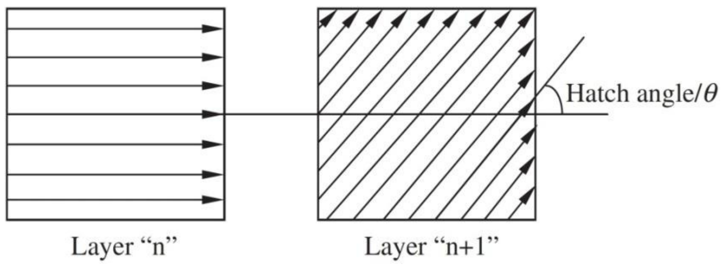

Fig. 4. Rotations in lines in neighbouring planes. [5]

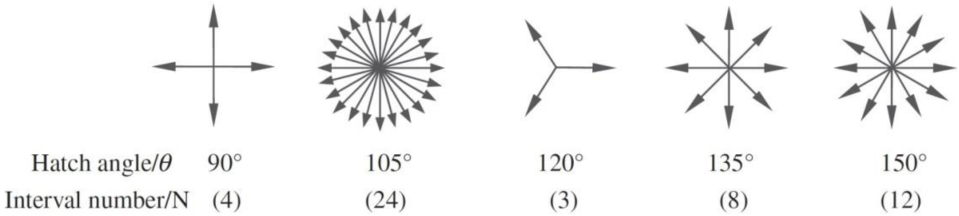

Fig. 5. The diagram of intervals under different hatch angles. [5]

Tensile properties of investigated samples are shown in Table 1. From this we can deduce that the samples produced by a hatch angle of 105 ° have the most satisfactory mechanical properties in many applications. Otherwise, all samples of SLM have higher values $\sigma_{0.2}$ / UTS than the ANSI standard. A link between the number of layers and the mechanical properties was found. With the growth of the interval number *N*, the mechanical properties improve, and the anisotropic behaviour of the mechanical properties decreases. This dependency was also confirmed by ENSZ et al. [7]. They introduced a kind of randomness of the scanning angle into the LENS manufacturing process technology and the integrity of the connection of sample layers was improved. Thus, a higher interval number increases the probability of defect removal and reduces anisotropy. [5]

Table 1.Tensile properties of SLM samples depending on the hatch angle. [5]

Hatch angle (°)	σ0.2 (MPa)	UTS (MPa)	EL (%)	σ0.2/UTS
90	530-551	696-713	32.4-43.6	0.77
105	566-570	714-717	40.6-42.8	0.79
120	540-545	682-685	36.5-37.9	0.79
135	541-556	691-693	36.6-38.4	0.79
150	534-555	698-703	39.6-40.4	0.78

5. Influence of building direction on mechanical properties of test sample

The building direction is defined as an acute angle between the longitudinal axis of a given sample and the vertical axis. How this variable affects the properties of the manufactured product is covered in the article by W. Shifeng et al. [8] The starting material used for these experiments was stainless steel 316L, and the melting parameters were set as follows: fiber laser power 180W, scanning speed 900 mm/s, powder layer thickness 20 µm, scanning sparing 0.06 mm. Four vertical and horizontal samples were setup at different angles as shown in Figure 6. [8]

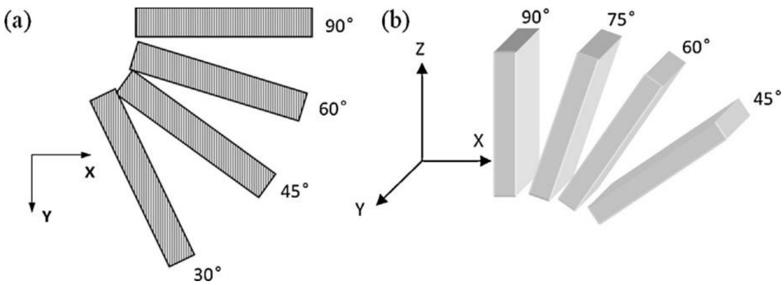

Fig. 6.Manufacturingstrategy of the tensile samples: a) horizontal; b) vertical. [8]

After material testing the average values of strength in horizontal and vertical directions were calculated for samples in horizontal and vertical positions. The average value for horizontal positions was 624 MPa and for vertical 669 MPa. The vertical samples were 6.8% stronger. The average elongation of vertical samples was greater by 68.5% compared to horizontal samples (49.6% vertical, 15.6% horizontal). These results suggest that the mechanical properties of the SLM parts built along the vertical direction were higher than those built in the horizontal direction. This indicates anisotropic behaviour of mechanical properties. The sample built in the direction of 0° (the longitudinal axis is parallel with the x-axis) showed the worst elongation and the lowest strength. Another sample built along a 45° angle had the best combination of strength and ductility, while the sample built at 60° had maximum elongation. [8]

Significant anisotropy was demonstrated in measurements of steel 304 samples published in an article by Kai Guan et al. [5] Samples were built in the directions of 0°, 45°, 90° and succumbed a tensile test. Conditions under which they were built were as follows: fiber laser power 200W, scanning speed 250 mm/s, layer thickness 20 µm, scanning angle 90°, overlap rate 40%. Figure 7 shows plotted correlations among mechanical properties of the samples. Horizontally built samples showed better ductility. Vertically built samples showed an optimal combination of strength and ductility. The sample built at a 45° angle had the worst mechanical properties of all tested parameters. [5]

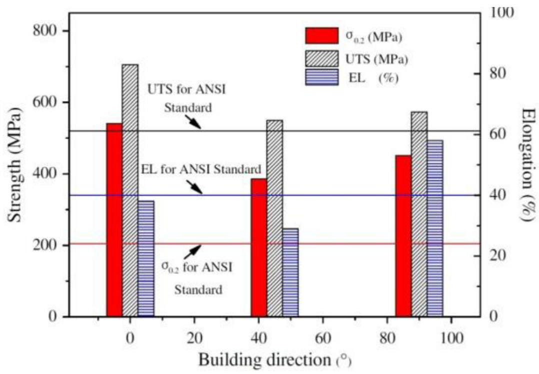

Fig. 7. Tensile properties of SLM specimens at varying building directions. [5]

These differences between samples during the tensile tests are explained by the orientation of the elongated structural grains. This grain orientation depends on the conditions during the solidification phase. Generally these grains grow in a direction from the cooler side to the warmer side (the upper surface is exposed to the laser beam while the bottom surface rests on a solidified metal substrate). The elongated grains are oriented in the direction of the thermal gradient as shown in Figure 8. The melting lines lie in a plane parallel with the building platform of the 3D printers. Therefore, samples built with a different building direction had differently oriented elongated grains and the tensile properties of these samples were different. [8]

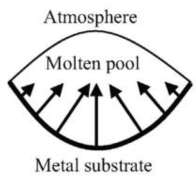

Fig. 8. Diagram of the solidification of melted pool during SLM process. [8]

Both measurements demonstrated that the tensile properties of SLM samples were influenced by the direction of the welding of adjacent layers. This direction is also affected by the orientation of the elongated grains of the microstructure of the material. This explains why we observed varying properties of samples during tensile stress projection along the main axis. [5]

A study of flat and cylindrical samples conducted by the EOS company (DMLS) proved to be inconclusive. The outcome of this study pointed rather to the fact that the effect of orientation correlates more with the type of material used rather than with the geometry of the sample. Table 2 shows the outcome of measurements of the comparison between samples manufactured in vertical and horizontal positions. Table 2 demonstrates that the item MS1 shows somewhat better properties for the horizontally manufactured sample than for the vertically manufactured sample. Item Ti64 in this case has a higher yield strength and elongation in the vertical direction, although the differences are relatively small. [6]

Table 2. Comparison of mechanical properties of horizontal and vertical DMLS samples.

		EOS MaragingSteel MS1		*EOS Titanium Ti64*	
		horizontal	vertical	horizontal	vertical
Young's modulus	(GPa)	172	160	112	111
Yield strength	(MPa)	1085	1076	1043	1088
UTS	(MPa)	1188	1140	1248	1201
Elongation	(%)	13,3	10,0	8,5	10,6

6. Other parameters

From the survey it was concluded that other parameters such as layer thickness and overlap rate do not significantly affect the default properties of steel materials. Default parameters for these experiments were set as follows: Laser power 200 W, a scanning speed of 0.25 m / s, layer thickness 20 µm, hatch angle 90 °, building direction: 0 °. [5]

The measurement of ***the influence of layer thickness*** with 304 steel in the range of 20-40 µm showed that the ductility and tensile strength do not depend on the thickness. It was shown that the SLM samples have a higher value $\sigma_{0.2}$ / UTS than ANSI standard samples as can be seen from the values obtained in Table 3. [5]

Table 3. Mechanical properties of SLM samples for varying layer thickness. [5]

Layer thickness (µm)	$\sigma_{0.2}$ (MPa)	UTS (MPa)	EL (%)	$\sigma_{0.2}$/UTS
20	530-551	696-713	32.4-43.6	0.77
30	519-533	666-687	40.8-41.8	0.78
40	541-545	694-703	39.0-42.3	0.78
ANSI	≥205	≥520	≥40	0.39

The overlap rate is expressed as a percentage and indicates what amount of area is influenced by the repeated melting with the energy beam. The dependence of varying overlap on the resulting properties of the material were investigated on six samples which were produced with an overlap of 0%, 10%, 20%, 30%, 40% and 50%, while other parameters remained constant. The results are recorded in Table 4, from which it can be deduced that changes in the overlap rate do not have a significant influence on the mechanical properties of the SLM samples in this case. This is attributed to the set production parameters, since the incident energy was so great that even for 0% overlap good smelting conditions occurred. Compared to a standard ANSI sample SLM samples had much higher amounts of $\sigma_{0.2}$ / UTS, but lower elongation. [5]

Table 4. Tensile properties of SLMed samples for varying overlap rate. [5]

Overlap rate (%)	$\sigma_{0.2}$ (MPa)	UTS (MPa)	EL (%)	$\sigma_{0.2}$/UTS
0	531-541	682-704	40.1-43.6	0.77
10	525-561	685-690	36.0-38.0	0.79
20	547-556	682-697	38.0-39.2	0.80
30	525-569	666-713	35.8-38.0	0.80
40	530-551	696-713	32.4-43.6	0.77
50	519-561	651-700	31.2-37.2	0.80

7. Conclusion

It has been shown that SLM technology enables production of many different materials. It can produce high quality parts. However, based on this study, it is evident that process parameters influence the mechanical properties, and they vary depending on the kind of material used. For example, a change in power of the energy beam will be expressed differently in the mechanical properties of the melted material of steel 304 and titanium alloy.

In summary, samples of steel which were produced by AM with the proper parameters had better tensile test results than ANSI samples.

On the other hand, some process parameters may be designated as important for the default mechanical and physical properties of the product. The laser power settings and scanning speeds perhaps have the most significant effect on these properties. Their combination, providing other parameters are reasonably set, significantly affects the size of dendritic crystals and the general structure of the melted region including the surface. Different combinations of these two parameters will produce a whole range of properties of the output parts, ranging from a fully consistent surface, to a porous structure, to the balling defect of both kinds.

Different settings of the building direction confirm the evidence of anisotropy in tensile properties. Research results showed that tensile properties of samples built along the vertical axis were better than those made along the horizontal axis. The building direction may alter the tensile properties of the products, because this parameter specifies how elongated grains are oriented in the microstructure of the material. If the angle of the building direction is less than 45 °, significant deterioration in the mechanical and geometrical properties may appear as a result of the delamination of the layers. In this case it is recommended to add a supporting structure to improve these properties.

Based on a properly selected hatch angle the samples interval number of layers grows. Samples with the highest interval number of layers have excellent tensile properties, because of the isotropy microstructure. When the hatch angle is adjusted, the anisotropy of mechanical properties is modified.

The thickness of layer shows influence on surface roughness rather than on the tensile nature of samples. This parameter with overlap rate does not significantly participate in the formation of the mechanical properties of the material. But they may participate on the costs associated with the necessary production time for the AM product. [2] [5] [8]

Acknowledgements

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