Influence of the direction of selective laser sintering on machinability of parts from 316L steel

V P Alexeev, A V Balyakin and A I Khaimovich

Samara University, 34, Moskovskoye Shosse, Samara, 443086, Russia

Email: alexeev_v.p@mail.ru

Abstract. This work presents the results of research of the impact of layer-by-layer growing of workpieces made of 316L steel on their machinability. The results of determination of residual stresses and measurement of hardness of the workpieces grown have been demonstrated. A series of experimental studies has been performed in order to determine the cutting force which occurs in the process of machining. The microstructure of the workpieces grown has been examined. It has been shown that the workpieces machined using Selective Laser Melting technology have the microstructure which is a totality of ‘microwelded seams’, which have a significant influence on the behavior of deformation processes in case of machining. The studies have shown that in case of lateral milling of the horizontally grown workpiece, the codirectional microwelded borders prevent any significant deformation of the misalignment which increases the cutting force by up to 10% as compared with milling of the vertically grown workpiece.

1. Introduction

The development of new technologies for fast manufacture of goods and products is the most promising area in modern machine building. One of the methods which enable the reduction of the manufacture time of parts and components is the technology of Selective Laser Melting (SLM) of a powdered material based on a three-dimensional model [1]. Selective laser melting opens up new possibilities in the manufacture of superlight metallic structures of irregular shapes and reduces the time of manufacture, while also enabling one to avoid manufacture of labor-intensive tooling (cast or extruded), which is normally expensive, and is undoubtedly interesting for the development and test deployment of the manufacturing process for new products [2].

Austenitic stainless steels (ASSS) are widely used due to their high resistance to corrosion and oxidizing. However, these materials are considered to be hard-to-machine as they feature high mechanical- and microstructure responsivity to deformation and deformation speed. 316L steel has been extensively used in medicine due to its high corrosion resistance and biocompatibility.

There have been studies [7, 8] of the conditions for formation of the microstructure and evaluation of properties of grown workpieces. There are also several works on the formation of materials and products with the use of the methods of layer-by-layer laser melting [3-8], however, until now, a number of issues relating to subsequent machining of parts made using SLM technology have not been properly studied, particularly the issue of mechanical treatment. The purpose of this work is to research the impact of layer-by-layer growing of workpieces made of 316L steel on their machinability.
2. Materials and Methods
The method of investigation of the influence of the direction of layer-by-layer laser growing of workpieces on their machinability includes the following steps: acquisition of workpieces with different direction of growing out of 316L material using SLM method with SLM 280HL machine and studying their microstructure; studying the condition of the surface layer by hardness measurement and determination of residual stresses in the subsurface layer of the grown workpieces; set up and carrying out of in-situ tests for determination of the cutting force.

Workpieces with dimensions (H×W×D) 6×24×40 mm (Figure 1) were prepared for the study of the impact of layer-by-layer growing. They were grown out of the powdered metal of 316L stainless steel using the SLM 280HL machine. The average size of the particles is 15…60 µm. For powder melting within the machine an IR fiber laser with the wavelength of 1075 nm and peak power of 400 Wt working in the continuous regime is used. So as to prevent powder particles from oxidizing and inflammation during the process of monolayers formation, the chamber is filled with noble gas, while the oxygen content does not exceed 0.2 %. The chemical composition of the powder is shown in Table 1.

**Table 1.** The chemical composition ‘mass. %’ of 316L

| Grade   | C    | Si   | Mn | P    | S    | Cr   | Ni   | Mo   |
|---------|------|------|----|------|------|------|------|------|
| AISI 316 L | ≤0.030 | ≤0.75 | ≤2.0 | ≤0.045 | ≤0.030 | 16.0–18.0 | 10.0–14.0 | 2.0–3.0 |

Workpieces were placed on a growth platform horizontally (Figure 1 a) and vertically (Figure 1 b). When growing workpieces using the 316L stainless steel powder on the SLM 280HL machine, 1-mm thick supports were additionally grown across the perimeter of the lower surface. These supports served as a heat sink (Figure 1 c).

**Figure 1.** Workpieces synthesized from the powdered metal of 316L stainless steel on the growth platform: a – horizontal placement of the workpiece; b – vertical placement of the workpiece; c, d – method of placement of the workpieces with additional supports and without supports.

Contraction of the workpieces due to temperature stresses (Figure 1 d) was observed during the growth process in case there is no additional heat sink via the supports grown.

3. Measurement of Rockwell hardness of the grown workpieces
In order to determine the impact of the direction of the growth on hardness, the metals and alloys were tested for hardness in accordance with Rockwell method using the TK-2M hardness gage. Indenters with a steel ball of 1.588 mm in diameter were used under the load of 100 kgf. The hardness value was determined as an arithmetic average of three measurements in 6 points which were evenly distributed across the surface. The results of the hardness measurements are shown in Table 2.
Table 2 shows that hardness of the workpieces is identical within the limits of imprecision.

### 4. Determination of residual stresses in the core of the rectangular section

Determination of the residual stresses was performed using the automated system 'ASB-1' using the method of measuring deflection of the thin workpieces with preliminarily etched out surface layers which were cut out of the workpieces grown. The distribution of residual stresses in the workpiece grown vertically is shown in Figure 2a, and the distribution of residual stresses in the workpiece grown horizontally is shown in Figure 2b.

![Figure 2. Distribution of residual stresses workpiece grown a – vertically, b – horizontally.](image)

Chemical milling of the workpieces was carried out in the electrolyte: 1.7 l of orthophosphoric acid (density is 1.56 g/cm³); 0.3l of sulpharic acid (density is 1.84 g/cm³); 100g of chromium anhydrite. The speed of chemical milling was 1.15 µm/min. In Figure 2a,b it is shown that the maximum value of residual stresses in the vertically grown workpieces is by 431MPa less than that in the workpiece grown horizontally. However, the minimum value of the residual stresses is by 69 MPa greater for the vertically grown workpiece, than that for the workpiece grown horizontally. Furthermore, the depth of formation of residual stresses in the workpiece grown horizontally is by 10 µm greater. This may be explained by a different area of heat removal and the direction of the microwelded seam in the process of growing, as the chemical milling of the workpieces was carried out along the 40 mm side, and the microwelded seam will be either horizontal or vertical for each workpiece correspondently.

The graphs show that the depth of formation of residual stresses in the workpiece grown horizontally is greater than that in the workpiece grown vertically. This may be explained by the different conditions of heat removal from the workpieces in the process of growing them and the time of their exposure to laser irradiation. Heat removal and formation of thermal stresses should influence the differences in microstructure of the workpieces grown. This was the aim of the following study of microstructure.

### Table 2. Results of the measurement of hardness of the workpieces made of 316L stainless steel.

| Workpieces                      | Point # | Rockwell Hardness Number |
|---------------------------------|---------|--------------------------|
| Vertically grown workpiece      | 1       | 92                       |
|                                 | 2       | 89                       |
|                                 | 3       | 91                       |
|                                 | 4       | 88                       |
|                                 | 5       | 92                       |
|                                 | 6       | 87                       |
| Horizontally grown workpiece   | 1       | 91                       |
|                                 | 2       | 91                       |
|                                 | 3       | 87.5                     |
|                                 | 4       | 88.5                     |
|                                 | 5       | 92                       |
|                                 | 6       | 92                       |

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5. Studies of the microstructure of the workpieces grown
The workpieces were etched using the following solution ‘vol. %’: HCl – 22; HNO₃ – 15; HF – 41; H₂O – 22. The microstructure was examined using the ‘TESCAN VEGA’ scanning electronic microscope. The microstructure of the workpieces (Figure 3) is a mixture of layers: the light gray grains of the hard solution are based on chrome; the gray areas – ferrite, and the dark areas – austenite.

![Figure 3. The microstructure of the workpieces grown: a, b – horizontally; c, d – vertically; ↑ – direction of the layer-by-layer workpiece growing process.](image)

In Figure 3, one can clearly see the borders of the section of the border type ‘microwelded seams’ (hereinafter – Microwelded Seams Borders). These layer-type borders which are in the perpendicular direction towards the melting are significantly different than the borders of conventional grains in terms of crystallography.

There are no traces of recrystallizing and growth of grains in the workpieces grown. The volume of all the grains is determined by the particle size of initial powder. Let us denote the value of the unit of the surface energy of the microwelded seam with \( \sigma_{\text{surf}} \) and inscribe the average grain in the spheroid with semi-axes \( a, b \) \( (a \leq b) \) (Figure 3a), equal to the grain volume \( V \), then the boundary energy \( U_{\text{surf}} \) of the total area \( S_{\text{surf}} \) can be described as follows:

\[
U_{\text{surf}} = S_{\text{surf}} \sigma_{\text{surf}} = 2\pi a^2 \left( 1 + \frac{e^2}{\sqrt{e^2 - 1}} \arcsin \left( \frac{\sqrt{e^2 - 1}}{e} \right) \right) \sigma_{\text{surf}}
\]

Relation \( e = b \cdot a^{-1} \) characterizes the form of the spheroid and determines the boundary surface energy. Therefore, taking into consideration that the boundary belongs to two neighbor grains, the boundary energy per the unit of grain volume will be determined as follows:

\[
u_{\text{surf}} = \frac{U_{\text{surf}}}{2V} = \frac{3}{4b} \left( 1 + \frac{e^2}{\sqrt{e^2 - 1}} \arcsin \left( \frac{\sqrt{e^2 - 1}}{e} \right) \right) \sigma_{\text{surf}}
\]

The greater is \( e \) in (2), the greater is the specific energy of the boundary \( u_{\text{surf}} \). The minimum value of \( u_{\text{surf}} \) is for the grain, the form of which is similar to a sphere \( (e \to 1) \).

The boundary specific energy of spherical shape grain of equal volume will be expressed as:

\[
u_{\text{sphere}} = \frac{3\sigma_{\text{surf}}}{2r}, \quad r = b / e^{2/3}
\]

See Table 3 for the comparison values of boundary specific energy for the workpieces with different direction of growing.
Table 3. Connection between the boundary specific energy and direction of workpiece growing

| Workpieces grown | $b$ (µm) | $e = b / a$ | $u_{\text{surf}} / \sigma_{\text{surf}}$ (µm$^{-1}$) | $u_{\text{spher}} / \sigma_{\text{spher}}$ (µm$^{-1}$) | $u_{\text{surf}} / u_{\text{spher}}$ (%) |
|------------------|---------|-------------|---------------------------------|---------------------------------|-------------------------------|
| Vertically       | 49      | 3.55        | 0.089                           | 0.072                           | 19                            |
| Horizontally     | 50      | 3.76        | 0.091                           | 0.072                           | 20                            |

According to Table 3, boundary specific energy of the grown workpieces is commensurable and does not exceed 20% of the specific energy of the grain spherical shape of the equal volume. Crystallization of the melted alloy begins with the seal border, due to which the seam border is significantly different from the grain material in terms of the chemical composition (surface segregation). High energy of the borders makes them a preferred place for nucleation and allocation of the second phase [11]. Second phase segregation is carried out at the boundaries (figure 3) corresponding to the direction of $b$-axis of the spheroid. Study [7] pointed out the influence of the ‘microwelded seam’ type borders on the mesostructural age hardening of 316L alloy.

6. Setting up and conducting of full-scale tests to determine the cutting force

In order to determine the cutting force, we used the methodology of previous experimental research [9]. The cutting instrument used was an end-cutting carbide mill [10], with 12 mm diameters, and the number of teeth is 4. The workbench for the experiments included the ‘ALZMETALLBAZ 15 CNC’ production center equipped with a Kistler dynamometric table which served to register changes in the components of cutting force $F_x$, $F_y$, $F_z$ in real time. For this test, the cutting speed varied from 60 – 100 m/min, and a transfer to a tooth from 0.05 mm - 0.2 mm/tooth, lateral removal $t = 0.1$ mm – 1 mm. The surface of each workpiece was preliminarily machined so as to ensure that roughness of all the workpieces had the same $Ra 1.25$. Table 4 shows the results of measurement of the cutting force when machining in the following modes: $S = 0.2$ mm/tooth, $t = 1$ mm.

Table 4. Values of the cutting force when machining in modes $Sz = 0.05$ mm/tooth; $t = 1$ mm.

| Cutting form when processing the vertically grown workpiece, H | Cutting speed (m/min.) |
|---------------------------------------------------------------|------------------------|
|                                                               | 60                     | 80                     | 100                    |
| Cutting form when processing the horizontally grown workpiece, H | 108.45                 | 106.9                  | 105.7                  |
| Relative difference in the cutting force, %                   | 11.3                   | 7.9                    | 5.2                    |

7. Discussion of the Results of the Study

The formation of sheet-like phases of austenite in the grain located perpendicular to the border of the microwelded seam results in hardening of the material because partition distortions of the crystalline lattice, close to the borders of the layer, are the reason of the occurrence of volumetric residual stresses (residual stresses of the first kind). Due to the enhanced heat removal when growing the workpieces horizontally, versus the workpieces grown vertically, there is a difference in the kinetics of crystallization of the grain of the melted layer. The horizontally grown workpieces feature more intensive extraction of the second phase (Figures 3 a, b). This conclusion can also be indirectly validated by the results of measurement of residual stresses (Figures 2). Residual stresses in the horizontally grown workpieces near the surface at the depth of 10 µm reach relatively higher values as compared with those of the vertically grown workpieces – 750 MPa and 400 MPa, correspondingly. Thereafter, at the depth of 60 µm, the values of stresses level out up to 200 MPa. Microwelded borders have significant influence over the behavior of deformation processes as they are effective barriers for the movement of dislocations, which additionally contributes to age hardening of the material.

Another important result which requires discussion is the effect of hardening which can be observed when milling a horizontally grown workpiece. At the macro level, chip formation during
cutting is a process of consecutive deformations of dislocation at the time of application of compression stress. Accumulation of local deformations of dislocation results in micro-segmentation of chips, which means significant deformations of dislocation of the macrovolume – chip segments. In case of the lateral milling of a horizontally grown workpiece, the co-directional microwelded borders prevent any significant deformation of the dislocation, which, according to the test results (Table 4), increases the cutting force by up to 10% as compared with milling of a vertically grown workpiece. The comparative data analysis (Table 4) shows that as the cutting speed increases, the difference in the cutting force in case of lateral milling of the workpieces grown in different directions decreases. This fact can be explained by the thermal effect of plastic deformation. Due to increased localization of the temperature near the cutting edge as the speed of cutting increases, the movement of dislocations, which provide for the plastic deformation, overcomes the barrier formed by the microwelded seam. The softening action of the temperature has varying effects on the vertically- and horizontally grown workpieces. Whereas in case of the former, increased viscosity of the material along with the increased cutting speed result in the insignificant rise of the cutting force, in case of the latter it leads to its reduction due to the observed effect of the reduced action of the hardening effect of the microwelded seam as temperature increases.

8. Conclusion
1. The structure and physical and mechanical properties of workpieces made of 316L alloy were tested. These workpieces were manufactured using the technology of layer-by-layer laser melting. Because of more efficient heat removal during the process of horizontal growing of the workpieces as compared with the vertically grown workpieces, a difference was observed in the kinetics of crystallization of the grain of the melted layer, which influences its age hardening and the value of residual stresses. Residual stresses in the horizontally grown workpieces near the surface at the depth of 10 µm reach relatively higher values as compared with those of the vertically grown workpieces – 750 MPa and 400 MPa, correspondingly. Thereafter, at the depth of 60 µm the values of stresses level out up to 200 MPa.
2. It was demonstrated that the workpieces manufactured using SLM technology feature the microstructure which is a totality of ‘microwelded seams’ that have a significant influence on behavior of deformation processes during milling, as they are effective barriers for movement of the dislocations which additionally contributes to resistance of the material to the cutting force.
3. It was established that in case of lateral milling of a horizontally grown workpiece, the co-directional microwelded borders prevent any significant deformation of the dislocation, which, according to the test results, increases the cutting force by up to 10% as compared with milling of a vertically grown workpiece. As the cutting speed of horizontally grown workpieces increases, the hardening effect diminishes, which is stipulated by the stalling effect of the microwelded seam in terms of movement of the dislocations.

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