Structural properties of H13 tool steel parts produced with use of selective laser melting technology

J Šafka¹, M Ackermann¹ and L Voleský¹
¹ Technical University of Liberec, Institute for Nanomaterials, Advanced Technologies and Innovation, Studentská 2, Liberec, Czech Republic
E-mail: jiri.safka@tul.cz, michal.ackermann@tul.cz, lukas.volesky@tul.cz

Abstract. This paper deals with establishing of building parameters for 1.2344 (H13) tool steel processed using Selective Laser Melting (SLM) technology with layer thickness of 50 μm. In the first part of the work, testing matrix of models in the form of a cube with chamfered edge were built under various building parameters such as laser scanning speed and laser power. Resulting models were subjected to set of tests including measurement of surface roughness, inspection of inner structure with aid of Light Optical Microscopy and Scanning Electron Microscopy and evaluation of micro-hardness. These tests helped us to evaluate an influence of changes in building strategy to the properties of the resulting model. In the second part of the work, mechanical properties of the H13 steel were examined. For this purpose, the set of samples in the form of “dog bone” were printed under three different alignments towards the building plate and tested on universal testing machine. Mechanical testing of the samples should then reveal if the different orientation and thus different layering of the material somehow influence its mechanical properties. For this type of material, the producer provides the parameters for layer thickness of 30 μm only. Thus, our 50 μm building strategy brings shortening of the building time which is valuable especially for large models. Results of mechanical tests show slight variation in mechanical properties for various alignment of the sample.

1. Introduction
The 3D printers for processing of metal materials give an amazing possibility of sintering various types of metal powders [1, 2, 3]. The result is a metal piece which may involve the complex geometries of surfaces or the porous structures. Many “printed” parts are therefore impossible to be produced with conventional methods (machinging, metal casting, etc.) or it would demand complex and expensive approaches. Important factors in the processing (melting) of these materials are laser parameters, grain size of the powder, etc. [4, 5, 6]. Laser parameters directly affect the final quality and also the accuracy of the final part [7, 8]. In the case that different thickness of the layer is used, different laser parameters must be set. In this paper, the optimal parameters for the H13 tool steel with layer thickness of 50 μm are searched.

The sintering process was carried out on the SLM 280HL (SLM Solution GmbH) machine. This device, together with its software, allows the complete setting of individual laser parameters for a given layer. The thickness of the layers can be set from 20 to 100 μm. It is important to find the optimum ratio between the thickness of the layers, surface quality, internal structure quality and the time of production of the part. Due to the fact that supplier of the machine...
provided us with 30 µm parameters only, we wanted to develop parameters for frequently used 50 µm thick layer as well. This layer thickness is valuable especially in the case of large models because it dramatically reduces their building time.

2. Materials and methods

2.1. Laser parameters for H13 tool steel with layer thickness of 50 µm

Process of finding proper parameters for H13 tool steel with layer thickness of 50 µm was based on building several testing series of a cube model with chamfered edge (Figure 1 and 2). Each sample was then subjected to set of tests which goal was to evaluate quality of its inner structure and surface roughness. Namely, these tests were:

- Measurement of surface roughness
- Metallography and Light Optical Microscopy (LOM)
- Scanning electron microscopy (SEM)
- Measurement of the micro-(nano) hardness

On the basis of these results, we were able to find such settings of laser power and laser speed which produces a model with solid core structure and low porosity. Due to the fact that border layers of the model are treated in a different manner, we had to find laser parameters for this part as well. Main goal for this part of the model is to produce lowest possible surface roughness.

![Figure 1. CAD model of the sample.](image1)

![Figure 2. Printed testing series.](image2)

Settings of laser power and laser speed for both volume part of the model and its border part were defined in the range shown in Table 1.

| Table 1. Ranges of parameters for H13 tool steel testing series. |
|-------------|---------|---------|
|            | Laser power [W] | Laser speed [mm/s] |
| Outer shell | 50 – 150       | 340 – 540       |
| Volume      | 125 – 225      | 400 – 600       |

As it can be seen in Figure 2, size of the testing matrix was 6x6 elements. In this testing matrix, upper left element is characterized with lowest value of laser power and speed whereas lower right element is built under highest values from the range shown in Table 1. All the other matrix elements are built with linearly extrapolated parameters between the border values.
2.2. Tensile tests of the specimens
Second part of the work dealt with mechanical properties of the parts which were printed under our settings. For this purpose, another set of samples in the form of “dog bone” were printed (Figure 3).

![Figure 3. Tensile test specimen for evaluation of mechanical properties.](image)

Apart from standard mechanical values such as ultimate tensile strength $R_m$ of the material and its Young’s modulus of elasticity $E$ we were also interested if the different orientation of the model towards the building plate somehow influences mechanical properties of the material. Tensile test specimens were therefore printed in three different angles relatively to the building plate (Figure 4). Another interesting comparison of mechanical properties was done for the samples which were produced under our settings for 50 µm layer and the samples built with 30 µm layer thickness and settings provided by the manufacturer.

![Figure 4. Three different positions of the specimen relatively to the building plate.](image)

3. Results
3.1. Measurement of surface roughness
The surface roughness was measured to verify the quality of the border of the part and to measure the continuity of the individual layers. For the surface roughness measurement, the mechanical profilometer Bruser DeckTac XP with the roundness of the tip of 2 µm was used. On each of the 36 samples, the roughness was measured in three areas. Thanks to the results from roughness measurement it was possible to select several suitable samples for further analysis. Final measurement then consisted of evaluating real 3D surface topography of the last printed layer. In Figures 5 and 6 the 3D topography of the best and the worst surface of the printed samples is shown.
3.2. Metallography and Light Optical Microscopy (LOM)
Main goal of this work was evaluation of material porosity and thus the quality of material’s inner structure. Several devices were used for the sample preparation. Material cutting was done perpendicularly to sintered layers of the material on the precise metallographic saw Struers Secotom-50. After this process, the samples were immersed in conductive resin named PolyFast using the metallographic press Struers CitoPress-1. For subsequent grinding and polishing, the automatic metallographic polisher Struers Tegamin-25 was used. In order to accentuate the structure of the examined sample, etching was done by immersing the sample into Lorason solution for 15 s. Finally, scanning of structure was performed using a light optical microscope Carl Zeiss AXIO Imager M2 with an automatic shift in the mosaic mode with 100x magnification. In Figures 7 and 8 the resulting microstructure for a sample with minimum and maximum porosity, respectively, is shown.

3.3. Scanning electron microscopy (SEM)
With use of scanning electron microscope Carl Zeiss Ultra Plus, we were able to investigate whether volume and outer shell of the part are correctly connected. Together with visual analysis, chemical micro-analysis was done by scanning electron microscope. This analysis is used to evaluate differences in chemical composition of volume and shell part of the model. Typical results for most of the specimens are shown in Figures 9 and 10. In the Figure 9, the border between volume and shell part of the specimen is clearly visible. In comparison with volume area, shell part is characterized with finer structure which is caused by double processing of the skin layer. After the implementation of chemical analysis, the possibility of contamination
was eliminated as shown in Figure 10. Apart from standard alloying elements of H13 tool steel, there are no artificial elements present. On the other hand, there is a noticeable difference in the chemical composition of the layer and the substrate because the substrate contains larger amount of oxygen. This phenomenon is most probably caused by etching which causes corrosion of the material.

![Figure 9. SEM picture of shell/volume connection](image1.jpg)

![Figure 10. Result of micro-chemical analysis of shell/volume part](image2.jpg)

3.4. Measurement of the micro-(nano) hardness
This last test is another way to compare difference between properties of skin and volume part of the sample. In this case, the indentation test was performed with use of CSM Instruments Nano-Hardness device. In cross-section of the metallographic cut, four indentation tests were done into the both layer and the substrate material. Results of the tests are shown in Table 2.

| test ID          | 1  | 2  | 3  | 4  | Average |
|------------------|----|----|----|----|---------|
| Outer shell hardness [HV] | 745 | 738 | 747 | 748 | 745     |
| Volume hardness [HV]     | 620 | 626 | 575 | 628 | 612     |

3.5. Mechanical tests of H13 tool steel samples
After completion of the building process, the samples were cleaned and tested on the universal testing machine TIRA with the force sensor with force range of 100 kN. Each sample was clamped into specially shaped jaws and prestressed to a value of 1 kN. At the end of prestressing part, the mechanical extensometer with initial length of \( l_0 = 30 \text{ mm} \) between the pins was attached to the sample. Concerning setup, tests were done under position control with loading rate of 5 mm/min until rupture of the specimen occurred (Figure 11). In the post-processing part of the tensile tests, the resulting channels of force and elongation from the extensometer were converted to the values of engineering stress and strain with respect to dimensions of the sample. Final tensile test diagrams were then used for comparison of all the desired samples.

Figure 12 shows tensile test diagrams of the samples which were built with the 50 \( \mu \text{m} \) building strategy and under different angle relatively to building plate. As apparent from the figure, at least two samples were tested for each angle. One can note that the samples built under angle of
30° relatively to building plate shows highest values of ultimate tensile strength. Second set of tensile test diagrams (Figure 13), show comparison of the data for samples built under constant angle of 90° and with use of 50 µm and the original 30 µm building strategy. This graph clearly shows that no major change in mechanical properties is present for the samples built with our parameters for 50 µm layer and the samples built with original strategy for 30 µm layer.

**Figure 11.** Tensile test of the H13 tool steel specimen.

**Figure 12.** Tensile tests of the samples built under different angles relatively to building plate.

**Figure 13.** Comparison of results for samples printed with 50 µm and 30 µm layer thickness.
4. Discussion

First part of the work was aimed to find laser parameters for H13 tool steel powder and 50 µm thick layer. Several testing matrices of samples were printed and examined using variety of material tests. As it can be seen in Section 3, our most successful specimen has mean surface roughness of 24 µm and inner structure with minimum porosity. For comparison, Badrossamay et. al [9] reports average value of surface roughness to be 26.9 ± 3.1 µm for scanning parameters of 110 W laser power and 15 mm/s scanning speed. Further testing then showed that even though the machine is used for several powders, no contamination of the material with another alloying elements was found. Nano-indentation of the volume and skin part of the specimen also showed that there is a difference in hardness of these two parts. While skin part of the sample has average hardness of 745 HV (62 HRC), the hardness of the core is slightly lower – 612 HV (56 HRC). As it was mentioned before, this fact is most probably caused by multiple laser exposure of skin layer.

In the second part we tested mechanical properties of the samples which were printed with newly found parameters. Ultimate tensile strength of the samples varies between 1000 and 1200 MPa. Different orientation of the sample somewhat affected mechanical properties of the material. This effect can be caused by different layering of the material which leads to variation of mechanical properties in certain direction. Similar observation is described in the work of Holzweissig et al. [10]. The authors performed tensile test of the specimens which were printed perpendicular and parallel to the building direction. Reported ultimate tensile stress values for H13 tool steel varies between 1550 and 1650 MPa and 1150 and 1175 MPa, respectively.

5. Conclusions

Results which were proposed in this paper show that we reached our goal, i.e. successful development of the parameters for H13 tool steel powder and the layer thickness of 50 µm. With these settings, it will be possible to build large models in shorter time while preserving dense inner structure of the model and its appropriate mechanical properties. Mechanical testing of the samples also shown that there is a difference in mechanical properties of the samples which were build under different orientation versus the building plate of the machine. This phenomenon will be studied more in detail in our further work.

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