Effect of locally increased melted layer thickness on the mechanical properties of laser sintered tool steel parts

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Abstract. Additive technologies have several advantages over conventional manufacturing, such as the freedom of geometry of the products and internal structures. There are also some limitations and problems, deriving from stopping the process during the production. By restarting the process, the building often continues with a thicker starting layer due to the deposition of two or more layers. The effect of skipped melting of layers is investigated in this paper. Maraging steel powder (MS1) was used in direct metal laser sintering (DMLS) process to produce samples with increased thickness of melted layers. The layer thickness was increased in 20 μm steps up to 160 μm with 0.5 mm offset between the increased thickness layers. Porosity caused by the uneven melting was measured by optical microscope, mechanical tests were carried out to quantify the effect of skipped layers and fractured surfaces were observed under SEM. We have found that the yield strength and tensile strength are not affected if the layer thickness is slightly increased locally in the laser sintered part, while even a small increase in porosity greatly reduces the total elongation of the specimen. The decrease of impact energy due to the porosities shows similar correlation with the decrease of percentage elongation at break. However, the Charpy impact test is much more sensitive to layer skipping, the lack of melted layers lowers the impact strength significantly.

1. Introduction

Additive technologies make it possible to produce almost any geometry of products and internal structures. This manufacturing freedom is also used in the design of injection molding dies. Curved cooling lines that can follow the geometry of the part (conformal cooling) produces better quality product with shorter cycle times than traditional tools with straight drilling [1][2].

The final part quality is influenced by various factors: the powder material, exposure parameters such as laser power, scan speed, layer thickness and exposure-strategies, as well as the inert gas flow and temperatures in the process chamber [3]. Problems occurring during the process can result in job failure, create porosities or other defects. Due to the layer-wise nature of the process, these defects will not always be visible once the part production is completed. By introducing an on-line process monitoring system, the part quality can be monitored during the build [4].

Especially when printing large pieces, the production process sometimes needs to be interrupted due to lens cleaning, build powder refilling, collision or other technical problems. When restarting the process, changing the temperature of the system or moving the table may result in a thicker starting layer thickness. Inadequate powder deposition settings, uneven heights of hybrid parts, or table movements...
due to collisions may cause the laser to melt more than the optimal amount of metal powder. The effect of printing parameters, especially the layer thickness on the quality of printed parts are discussed in several literature.

The influence of layer thickness with 304 steel in the range of 20-40 μm has shown that the ductility and tensile strength are independent of slice thickness [5]. Samples were fabricated with layer thickness of 30, 50 and 70 μm and laser scanning speed set at 70 and 90 mm/s, at layer thickness of 70 μm porosity increases and cracks started to form which decreased strength and ductility [6].

During the manufacturing of molds by laser sintering, production parameters are not changed, the parts are produced with uniform layer thickness. It has been found that the available literature does not deal with the problem often encountered in practice when parts of a workpiece have an increased build thickness. During printing the part is under periodic reheating, the top layer and a couple of layers below that are remelted [7].

In our experiment, we made specimens from 1.2709 metal powders with DMLS technology. In the specified cross section of the specimens, the construction layer thickness was changed in the range of 20-160 μm and the effect of the increased layer thickness on the porosity and mechanical properties of the test specimens were investigated.

2. Experimental

2.1. Sample manufacturing

For the experiments „MaragingSteel MS1” steel powder – a regular material of the injection moulds having conformal cooling channels – was used to prepare samples by direct metal laser sintering. EOSINT M270 (200W) equipment was used by applying EOS MS1_Surface 1.0 parameter setting and 20 μm layer thickness.

We printed rectangular prism test pieces to quantify the porosity by skipping layers. Increased thickness of melted layers was created; the thickness was increased in 20 μm steps with a 0.5 mm offset between the increased thickness layers. Cylindrical Ø8 mm tensile test bars and 10x10 mm Charpy impact specimens with V notch were made with different layer thickness in the middle layer of the specimens. The samples were numbered 1 to 8, the test layer thickness corresponded to the multiplication of the number of the sample and the original layer thickness. (For the specimen No. 7 the average thickness of the specimen to be melted in the middle is 7×20 μm = 140 μm.)

2.2. Test methods

Tests for determining mechanical properties were carried out, tensile tests according to ISO 6892-1 B method on an INSTRON 5582 testing machine and Charpy V-notched impact tests according to ISO 148-1 standard at room temperature.

Porosity of the increased layer thicknesses were measured on micrographs. The sample was ground and polished. Panorama image was taken with a Zeiss Axioimager M1 microscope. We determined the amount of pores on the microscopic image with an in-house developed software for quantitative analysis. The surface morphology studies were conducted using a HITACHI 3400 scanning electron microscope (SEM).

3. Results

3.1. Porosity

A cross-section perpendicular to the construction direction of the test specimen was analysed after polishing. The microscopic investigation for porosity analysis was carried out by scanning the entire surface of the part and panorama image was created. The porosity was determined by an in-house-developed software. To quantify the degree of porosity, we marked areas with the same size around the skipped layers. The resulted porosity is the proportion of porosity measured on the reference surface to the size of the reference surface (Figure 1).
The region with the higher layer thickness, No. 6-8 has clearly visible lines of pores. While looking at the layers with lower layer thickness, No. 5 and below, the pores are difficult to see on the microscope image.

![Figure 1. Panorama image of the polished cross section of the laser sintered part containing skipped layers with different thicknesses (20-160 µm) with the porosity measurements of the layers. The image of the rough outer surface was overlaid on the micrograph.](image1)

Analysing the porosity values, it can be concluded that skipping 1-2 layers does not cause measurable increase in porosity on the tool surface. However, in the case of Nr. 6, by skipping more layers and melting 120 µm thickness of powder, the porosity has multiplied. Moreover, by increasing the number of skipped layers, porosity increases exponentially. In the area of layer with higher thickness, it can be clearly seen that large-scale structures are created instead of prior uniform melting. The material structure is non-continuous; the input heat energy cannot melt the metal powder and in the area of scanning boundaries, significant porosity remains (Figure 2).

![Figure 2. (a) Microstructure and location of the pores in specimen Nr. 7 (140 µm), (b) calculated porosity values on the cross section (b)](image2)

3.2. Mechanical properties
Tensile test measurements were carried out at room temperature using a non-contact video extensometer to measure strain. In our study, three specimens for each modified layer thickness were tested and from the load-extension curve the Yield strength, Ultimate tensile strength and percentage elongation after fracture ($A_{40}$) and percentage non-proportional elongation at maximum force ($A_{g}$) were determined. The resulted strength values and the test curves are given in Figure 3.
Figure 3. (a) load-extension curves of DMLS specimens with modified layer thicknesses (20-160 µm) and (b) calculated yield strength and ultimate tensile strength values.

Based on the results it can be established that the yield strength and tensile strength are not affected if the layer thickness is slightly increased locally in the laser sintered part. A significant decrease in the yield strength and tensile strength values was found in case of No. 8 specimen, in which a 160 µm layer was melted in one step. By comparing the test curves, it can be established that all specimens having different skipped layer thickness show the same load-extension values up to the failure as those made by constant layer thickness (20 µm). It can be stated that at static load, the maximal 5.5% local porosity created in the specimen does not affect the elastic deformation ability of the specimen.

The elongation values determined during the test as a function of the porosity can be seen in Figure 4. There is a well-defined correlation between the porosity and elongation values, the elongation decreases by increasing the porosity. Even a small increase in porosity greatly reduces the total elongation of the specimen. This can be explained by the smaller cross-section of the porous part, and higher local stresses generated around the porosity acts as starting points of failure. Linear relationship was found between the percentage non-proportional elongation at maximum force and the porosity. The more porosity in the material the shorter the uniform deformation is (Figure 4.b).

Figure 4. (a) percentage elongation at break and (b) percentage non-proportional elongation at maximum force as a function of porosity

Based on the strength and elongation values it can be stated that the specimens with 40 µm and 60 µm local layer thickness and the specimen built with 20 µm constant layer thickness showed no significant difference under static loading.

The V-notched Charpy test specimens of 10×10 mm cross section were tested at room temperature. The increased layer thickness was created in the centerline of the V-notch. Significant differences were found not only in the values of the impact energies but also in the quality of the fractured surface. Increasing porosity values showed less ductile behavior and this nature can be clearly seen on the
fractured surface, failure appears dull and rough to the naked eye, with clear amounts of gross plastic deformation (Figure 5). As it can be seen in Figure 5.b the energy absorbed by the specimens during fracture and the porosity shows similar correlation (exponential) as the percentage elongation at break (tensile test) and porosity. However, the Charpy test is much more sensitive to layer skipping and a minimal amount of layer thickness increase significantly lowers the impact energy of the material.

![Fractured surface of Charpy specimens No.1 and No.8](image)

**Figure 5.** (a) Fractured surface of Charpy specimens No.1 and No.8; (b) Effect of the porosity on the impact energy absorbed during Charpy test

The fractured surfaces of the broken Charpy impact test samples No.1 having uniform 20 µm layer thickness and No. 8 containing a 160 µm thick layer in the middle were analysed in details by scanning electron microscope to characterize the mode of fracture (Figure 6.).

![SEM image of fractured surface of Charpy specimens No.1 and No.8](image)

**Figure 6.** SEM image of fractured surface of Charpy specimens No.1 (a) and (c) and No.8 (b) and (d)
At lower magnification quite different topography can be observed in case of the lowest and highest melted layer thickness (Figure 6. a-b). In case of the specimen built with uniform layer thickness ductile fracture occurred by very fine dimples and micro-void nucleation and coalescence on the whole surface (Figure 6. c). Although, the fractured surface of the broken Charpy test specimen showed a brittle-like behaviour with no visible plastic deformation compared with the uniform layered sample, the SEM image shows that there are mostly ductile regions on the broken surface. However, the lack of fusion and visible cracks on the fracture surface function as stress concentrators. This is the main reason for the lower impact energies and gives ground to describe this kind of fracture as ductile (in those regions where the metal powder was totally melted) with local elements of brittle fracture.

Due to the high layer thickness and thus the inadequate melting several big holes can be discovered on the surface. Some powder particles in these areas were not melted and did not coalesce to the wall of the holes (signed with the arrows in Figure 6.d.).

4. Conclusions
Direct metal laser sintering has growing interest in tool manufacturing due to its several advantages over conventional technologies. However nearly the same mechanical properties can be achieved by proper heat treatment methods and the required surface quality can be achieved by post manufacturing with conventional technologies, there are also some limitations and problems in practical use. The sintering method often stops during the production and after restarting it often continues with a thicker starting layer due to the deposition two or more layers.

In our experiments, the effect of skip melting of layers during DMLS process was investigated by producing samples from maraging steel powder (MS1) with increased thickness of melted layers. The standard layer thickness was 20 μm, which was increased in steps up to 160 μm with 0.5 mm offset between the increased thickness layers. Porosity caused by the uneven melting has been inspected by optical microscope, and quantified by panorama microscopic images. Tensile and Charpy impact specimens containing a layer having different thickness in the middle were produced and tested to analyse the effect of skipped layers and the fractured surfaces were also observed under SEM.

It has been concluded that skipping one or two layers does not cause measurable increase in porosity, while skipping more layers and melting a 120 μm thick layer, the input heat energy cannot melt the metal powder and significant porosity remains. The porosity increased exponentially by increasing the melted layer thickness. The morphology was locally different in the area of the thicker melted layer; large-scale structures were created instead of prior uniform melting.

The yield strength and tensile strength were found not to be affected if the layer thickness is slightly increased locally in the laser-sintered part, while even a small increase in porosity greatly reduces the total elongation of the specimen. The decrease of impact energy due to the porosities shows similar correlation with the decrease of percentage elongation at break. However, the Charpy impact test is much more sensitive to layer skipping; the lack of melted layers lowers the impact strength significantly. Although the surface of the broken Charpy test specimen showed a brittle-like behaviour with no visible plastic deformation compared with the uniform layered sample, the SEM inspections indicate that there are mostly ductile regions on the broken surface between the porous parts of the surface.
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