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RESIDUAL STRESS ON AISI 300 SINTERED MATERIALS – EFFECT OF THICKNESS

ZAOSTALI NAPONI U AISI 300 SINTEROVANIM MATERIJALIMA – UTICAJ DEBLJINE

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- hole drilling method (HDM)

Ključne reči
- selektivno topljenje laserom (SLM)
- zaostali naponi
- metoda bušenja rupa

Abstract

Selective Laser Melting (SLM) is one of the most interesting technologies in the rapid prototyping processes because it allows to build complex 3D metal parts. Moreover, full density can be reached and mechanical properties are similar to those obtained with conventional manufacturing processes. However, the most important drawback is related to the thermal transient encountered during solidification which generates highly variable residual thermal stresses in SLM parts. Parameters such as laser power, scanning strategy and velocity should be optimized also in order to allow full melting of the powders used in the process and minimize residual stresses that are strictly dependent on the manufacturing process and cannot be completely avoided. Geometry of parts should be optimized in order to keep residual stresses and distortions low. The aim of this paper is to investigate on residual stress distribution in SLM rectangular plates built by means of a new scanning strategy, implemented by dividing the fused zone in very small square sectors. The strain gauge hole drilling method is used to measure residual stress profiles in a set of test samples manufactured from the AISI Maraging 300 steel and characterized by different thickness. An analysis is performed in order to investigate the effect of thickness, position on the building platform and of distance from the surface of the specimens coming from the same process parameters on maximum and minimum principal residual stresses. The experimental results show that the melting/solidification mechanism generates highly variable thermal residual stresses in the SLM parts used in this study.

Izvod

Selektivno topljenje laserom (SLM) je jedna od najinteresantnijih tehnologija kod brzih procesa izrade prototipa, jer dozvoljava izradu složenih 3D metalnih delova. Osim toga, postiže se dovoljna gustina snage, a mehaničke osobine su slične onima koje se postižu konvencionalnim procesima izrade. Međutim, najvažniji nedostatak se ogleda u prenosu toplote pri očvršćavanju, koji izaziva veoma promenljive zaostale termičke napone u SLM delovima. Parametri kao što su snaga lasera, strategija skeniranja i brzina se takođe moraju optimizirati radi postizanja potpunog topljenja praha, koji se upotrebljavaju u postupku, i radi smanjenja zaostalih napona koji isključivo zavise od procesa proizvodnje i ne mogu se u potpunosti izbeći. Radi smanjenja zaostalih napona i izobličavanja delova, i geometrija delova se mora optimizovati. Cilj ovog rada je istraživanje raspodele zaostalih napona u SLM pravougaonim pločama izrađenim novom strategijom skeniranja, koja je uvodi podelu zone topljenja na vrlo male kvadratne površine. Metoda bušenja rupa sa mernim trakama se koristi za određivanje profila zaostalih napona na seriji ispitnih uzoraka, izrađenih od AISI Maraging 300 čelika sa različitim debljinama. Izvedena je analiza radi istraživanja uticaja debljine, položaja na konstrukciji, i rastojanja od površine uzoraka, sa istovetnim parametrima procesa, na maksimalne i minimalne glavne zaostale napone. Eksperimentalni rezultati pokazuju da mehanizam topljenja/očvršćavanja stvara velike promenljive termičke napone u SLM delovima, koji su obrađeni u ovom radu.

INTRODUCTION

Recent developments in Rapid Manufacturing, e.g. the application of modern fiber laser beam sources, enable the additive layer manufacturing (ALM) to substitute conventional manufacturing processes, /1/. Selective laser sintering (SLS) and selective laser melting (SLM) are two production technologies offering great advantages and opportunities compared to traditional material removal techniques: system flexibility, feasible part complexity and ability to process multiple metal powders (e.g. aluminium alloys, hot forming tool steel or titanium base alloys). Thus, variable classes of functional parts for almost all industrial sectors are can be realized. Representative examples are biocompatible implants, mould inserts or components for the automotive and aerospace industry, /1/ (Fig. 1).

Figure 1. Typical applications produced by SLM, /1/.
Slika 1. Tipična primena izrade postupkom SLM, /1/

The difference between SLS and SLM concerns the binding mechanism that occurs between the powder particles, /2/. In SLS, either a combination of a low melting binder and high melting structural material is used – called liquid phase sintering (LPS) or the powder particles are just partially molten. In case of LPS, a post treatment is generally necessary to enhance the mechanical properties and to increase the part's density. In SLM, the powder particles are fully molten.

Despite having extensive advantages compared to conventional manufacturing technologies (e.g. milling), SLM still comprehends several process deficiencies that impose some serious limitations to the practical use. As a result of the locally concentrated energy input, the temperature gradient mechanism (TGM) and the related plasticization lead to residual stresses and part deformations. On the one hand, the dimensional size and shape accuracy as well as the mechanical strength of parts is influenced thereby. On the other hand, residual stresses contribute to crack formation or disconnection of parts from the base plate, /1/ (Fig. 2).

In order to investigate the residual stresses, the origin of the stresses is explained first. Using the hole drilling method, residual stress profiles are then measured in a set of test samples having different thickness. Thus, the influence of the number of layers on the residual stress profile can be concluded.

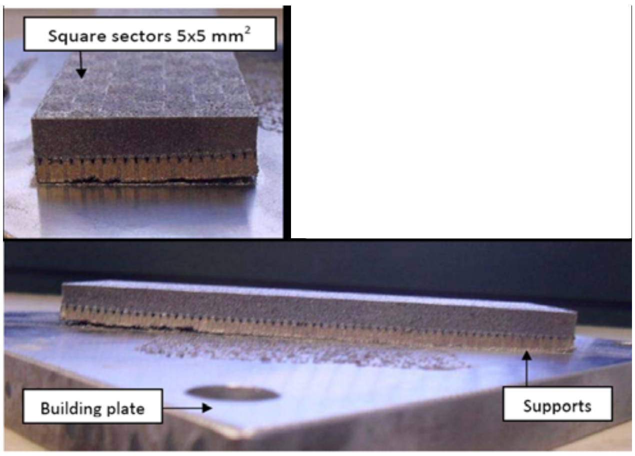

Figure 2. Distortion on SLM rectangular specimen.
Slika 2. Izobličenje pravougaonog SLM uzorka

MECHANISM OF RESIDUAL STRESS DEVELOPMENT

Each production process introduces some amount of residual stress, /2/. However, the amount of residual stress that is introduced varies a lot among different production processes. Laser based processes (laser welding, SLM, etc.) are known to introduce large amounts of residual stress, due to the large thermal gradients which are inherently present in the processes. In case of laser based processes, two mechanisms can be distinguished which cause residual stresses. The first mechanism introducing residual stress is called the temperature gradient mechanism (TGM). It results from the large thermal gradients that occur around the laser spot. Owing to the rapid heating of the upper surface by the laser beam and the rather slow heat conduction, a steep temperature gradient develops. The material strength simultaneously reduces due to the temperature rise. Since the expansion of the heated top layer is restricted by the underlying material, elastic compressive strains are induced. When the material's yield strength is reached, the top layer will be plastically compressed. A second mechanism that induces residual stresses is the cool-down phase of molten top layers (in SLM). The latter tend to shrink due to the thermal contraction. This deformation is again inhibited by the underlying material thus introducing tensile stress in the added top layer and compressive stress below.

PREPARATION OF SPECIMENS

In the SLM process, physical models can be fabricated directly from CAD data in a layer-by-layer manner by using laser energy. The machine used to perform the experiments is located at the Politecnico di Bari. It uses a Nd:YAG laser source with a wavelength of 1.064 μm, a spot diameter of 200 μm and a maximum output power of 100 W in continuous mode. Operation in pulsed mode with a frequency between 0 and 65 kHz is also possible. By means of a stepper motor the build platform can be moved. Powder layers are deposited in one direction using a knife. The building chamber is filled with nitrogen to prevent oxidation of the parts. Since it is not possible to fully eliminate deformations that may lead to failures of the building process, parts were manufactured on top of a 15 mm thick substrate (base plate) bolted to the piston (Fig. 2). The layer thickness was set to 30 μm. The laser sintering strategy used in the preparation of specimen was random, in order

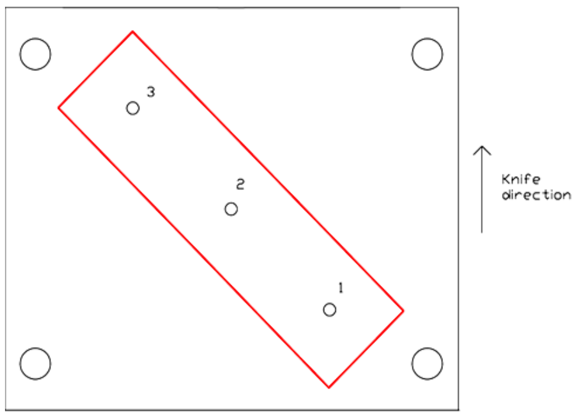

Figure 3. Geometry of SLM rectangular specimens (127 mm × 35 mm) with hole locations (1, 2, 3).
Slika 3. Geometrija SLM pravougaonih uzoraka (127 mm × 35 mm) sa položajima rupa (1, 2, 3)

not to "orient" mechanical properties in any specific directions, and optimized by dividing the part area in small square sectors of 5 × 5 mm^2, in order to produce parts with low residual stresses. Moreover, parts were built using supports of 5 mm height (Fig. 2) in order to facilitate the removal of parts from the building platform. Specimen geometry is reported in Fig. 3. The rectangular specimen is oblique on the building plates in order to facilitate the powder deposition by means of a knife. Positions 1, 2 and 3 indicate the locations of residual stress measurements.

The powder used for the study presents spherical particles of diameter up to 40 μm (Fig. 4) and has the composition of the AISI 18 Maraging 300 steel. It is a mixture consisting of 4.2% (wt.) Mo, 0.88% Ti, 65.9% Fe, 10.2% Co, 18.8% Ni and 0.02% C. AISI Maraging 300 steel is a very important material in the mould industry, with very high strength combined to high toughness. This material is typically used for complex tooling as well as for high performance industrial parts (i.e., in aerospace applications). The measured density of SLM parts is 8010 kg/m^3. Mechanical properties are as follows: tensile strength 1152 MPa, yield strength 985 MPa, Young modulus 166 GPa.

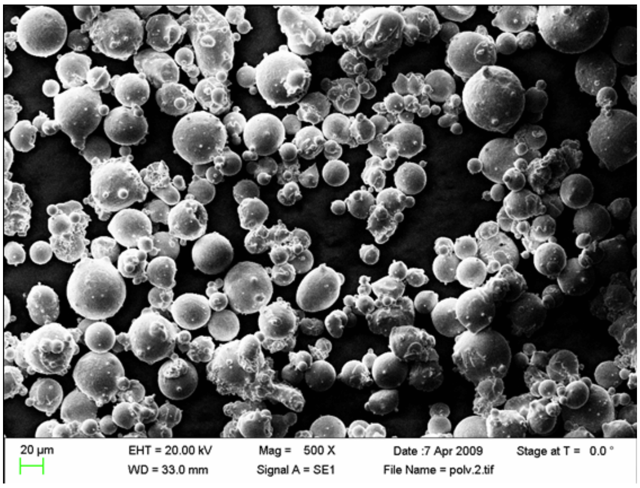

Figure 4. SEM micrograph of the powder.
Slika 4. Mikrografski snimak praha

MEASUREMENT OF RESIDUAL STRESS

The Hole Drilling Method (HDM) is the most widely used technique for residual stress measurement. The principle involves introduction of a small hole (1.8 mm diameter and up to about 1.0 mm depth) at the location where residual stress is measured. Due to drilling of the hole, residual stresses are relieved and the corresponding strains on the surface are measured using strain gauges bonded around the hole. From these measured strains, residual stresses are calculated using appropriate calibration constants derived for the particular type of rosette strain gauge used. The procedure for residual stress measurement using hole drilling is described in ASTM standards with designation E837-08. In most practical cases, the residual stresses are not uniform with depth. The incremental hole drilling method is an improvement of the basic hole drilling method, which involves carrying out the drilling in a series of small steps, which improves the versatility of the method and enables stress profiles and gradients to be measured. A high-speed air turbine and carbide cutters are used to drill the hole without introducing any further machining stresses and thereby modifying the existing stress system. The strain data at pre-determined depths are precisely acquired. Different stress calculation methods are used to arrive at the residual stress system from the measured strains. The major techniques in vogue are uniform stress, power series and integral methods. In any case, a meticulous measurement practice is crucial to obtaining good quality strain data and the application of the correct analysis method to the relieved strain data can provide accurate assessment of the residual stress field. In this case, in order to consider the variation of the residual stresses measured through thickness, the integral method is used. The accuracy of residual stress calculations from measured strain values obviously depend also on the level of accuracy at which the elastic modulus and Poisson's ratio are known. For this reason, E and ν values used in this work are obtained from tensile tests on the same material, /3/.

Distribution and magnitude of residual stresses generated in SLM-fabricated components depend on a number of factors. Material properties of the processed powder-like difference in heat conductivity between the loose powder bed and the solidified material, especially for zones at the corner of the part, process parameters like scanning strategy, laser power, layer thickness, energy distribution etc., and part geometry like area to be scanned, thickness of the build-up specimen etc., influence the appearance of thermal stresses in the part.

This paper aims to study the effect of two very important factors: (i) the thickness of the build-up specimen; (ii) the position on the building plate. Furthermore, the variation of residual stresses along the specimen thickness is an important aspect to investigate, both in the case of different location and different thickness. In order to reduce some of these factors, the dimensions of the building plate are much larger than the dimensions of the manufactured component which is rectangular with one dimension much larger than others. In addition, the scanning laser strategy is optimized by trying to have scan vectors always oriented along the normal to the part's elongation. These facts should allow to maximize the adhesion between layers thus ensuring a nearly full density which limits the magnitude of residual stresses, /4/.

Five SLM rectangular specimens are studied, as indicated in Table 1.

Table 1. Experimental plan.
Tabela 1. Plan eksperimenta

Plate	Thickness (mm)	Position
1	3	1, 2, 3
2	3	1, 2, 3
3	7	1, 2, 3
4	7	1, 2, 3
5	7	1, 2, 3

In all cases residual stresses measurements are executed by HDM at locations 1, 2 and 3 (Fig. 5).

Figure 5. Specimen with rosette strain gauges for the HDM.
Slika 5. Uzorak sa mernim rozetama za HDM

Figure 6 shows the drilling device utilized. Strain values are acquired with System 5000 by Micro Measurements. Strain gauge rosettes with three radial grids measure these strains (Fig. 5).

Figure 6. Measuring device for HDM (RS 200 Milling Guide by Micro Measurements).
Slika 6. Uređaj za merenje za HDM (RS 200 Micro Measurements)

EXPERIMENTAL RESULTS

In order to consider the variation of the residual stresses measured through the thickness, the Integral Method is used, /5/.

Residual stress are measured for several specimens of the two different classes of thickness, as reported in Table 1.

Two representative graphs are included in Figs. 7-8 that show the trend of calculated residual stresses in terms of maximal and minimal residual stress versus depth.

In all case, compressive residual stress are observed near the free surface. Then they increase, and in case of 3 mm thick specimens they become tensile. In particular, in case of specimens 3 mm thick, principal residual stresses range from –400 to +50 MPa. In the case of specimens 7 mm thick, principal residual stresses range -250 to 0 MPa. This behaviour probably occurs because the very large number of laser passes required to complete 7 mm thick parts may be considered to be equivalent to a sort of thermal treatment which relaxes internal stresses. However, the stress magnitude does not exceed 50% of the yield stress of the analysed material (σ_y = 985 MPa). Therefore, the measured values of strain and the derived stress field are effective and totally realistic for the all depths.

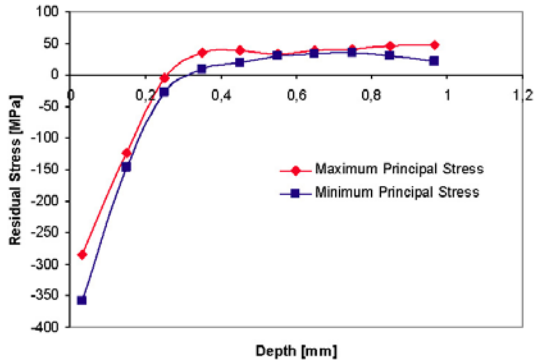

Figure 7. Residual principal stress on location 1 of plate 1 (3 mm).
Slika 7. Zaostali glavni napon na mestu 1 ploče 1 (3 mm)

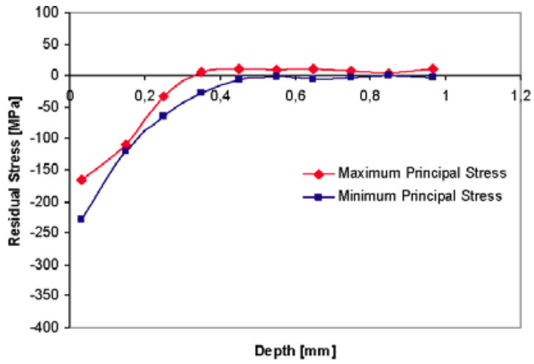

Figure 8. Residual principal stress on location 3 of plate 5 (7 mm).
Slika 8. Zaostali glavni napon na mestu 3 ploče 5 (7 mm)

Figures 9-13 show the trend of the calculated residual stresses in terms of Von Mises equivalent stress plotted versus the depth.

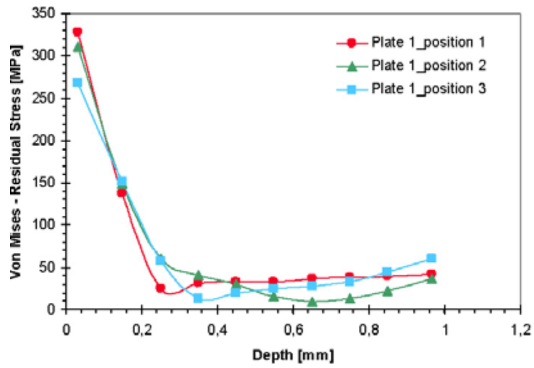

Figure 9. Residual stress values on rectangular plate 1 (3 mm).
Slika 9. Zaostali naponi u pravougaonoj ploči 1 (3 mm)

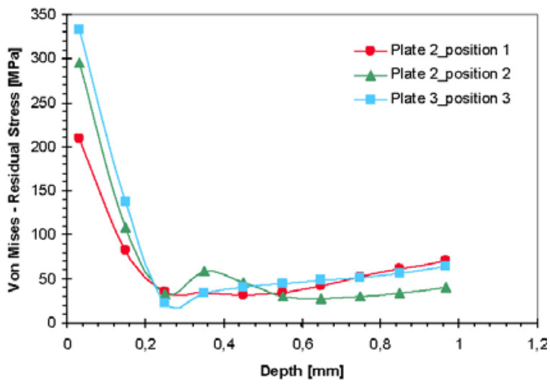

Figure 10. Residual stress values on rectangular plate 2 (3 mm).
Slika 10. Zaostali naponi u pravougaonoj ploči 2 (3 mm)

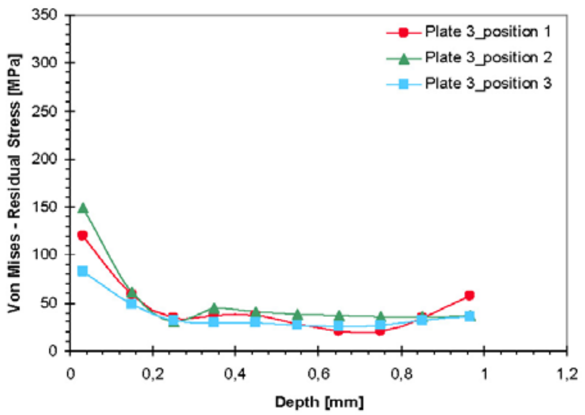

Figure 11. Residual stress values on rectangular plate 3 (7 mm).
Slika 11. Zaostali naponi u pravougaonoj ploči 3 (7 mm)

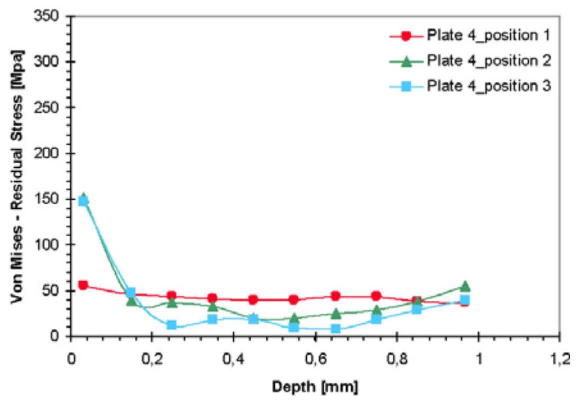

Figure 12. Residual stress values on rectangular plate 4 (7 mm).
Slika 12. Zaostali naponi u pravougaonoj ploči 4 (7 mm)

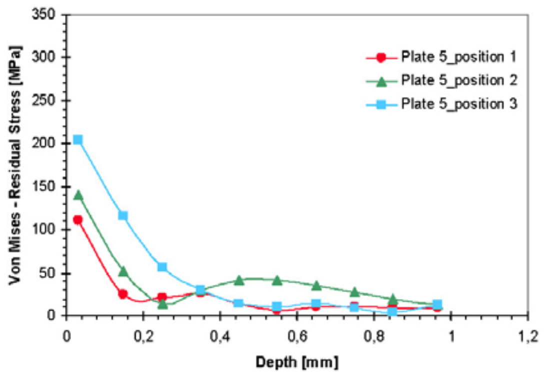

Figure 13. Residual stress values on rectangular plate 5 (7 mm).
Slika 13. Zaostali naponi u pravougaonoj ploči 5 (7 mm)

As previously said, measurements are executed on 5 rectangular plates of the same manufacturing process but different thickness. Residual stresses are variable inside the tested components. For all considered specimens and regardless of the hole location on the rectangular shape, residual stress value decreases sharply as we move far from the free surface.

Tables 2 and 3 report, for both thickness groups, the average values of residual stresses measured at two depths: respectively 0.15 and 0.85 mm from the specimen free surface. It appears that the inner layers (i.e. those 1.5 mm from the free surface) that were submitted to a larger number of laser passes than the outer layers (i.e. those 0.15 mm from the free surface in the vicinity of the zones heated by the laser beam in the last stage of the SLM process) were somehow thermally relieved. It should be reminded that the specimens tested in this research are realised using a very stiff building plate to prevent warping. The percentage of reduction of residual stress from the surface (0.15 mm) to the inner part (0.85 mm) ranges from 49 to 77% in the case of specimens 3 mm thick and from 35 to 56% in the case of specimens 7 mm thick. It should be noted that the depths analysed for the reduction (0.85 mm) correspond to a different fraction of each specimen thickness considered in the experiments: 28% for 3 mm thick specimens and 12% for 7 mm thick specimens.

Tables 2-3 summarize also the effect of position on the building plate: the comparison between values of residual stresses measured for specimens of the same location on the build plate indicated that residual stresses corresponding to positions 1 and 2 seem to be lower than in the other case. It could be explained by remembering that location 2 is at the centre of the plate, where the laser beam is perfectly perpendicular to the powder bed and therefore produces the best configuration of the molten/re-solidified zone.

Locations 1 and 3 have slopes with respect to the laser beam, so the scanning strategy does not make it possible to line up the laser orthogonally to the layer surface and the density of energy in a different location could not be uniformly distributed. Moreover the powder storage is on the right of the powder platform and the knife moves from right to left for covering the powder bed. So, because of the geometry of the deposition system, the position 1 is the position where the distribution of powder is more accurate while position 3 is the more underdog. For this reason, residual stress is maximal at position 3.

Table 2. Von Mises residual stress on rectangular plates 1, 2 (thickness 3 mm).
Tabela 2. Von Mises zaostali napon u pravougaonim pločama 1, 2 (debljine 3 mm)

Specimen	Residual stress (MPa) Depth 0.15 (mm)			Residual stress (MPa) Depth 0.85 (mm)			Reduction (%)		
	Position			Position			Position		
Plate thickness 3 mm	1	2	3	1	2	3	1	2	3
1	137	149	151	40	23	44	71	85	71
2	82	108	137	61	34	56	26	68	59
Mean	110	129	144	50	28	50	49	77	65
St. Dev.	39	28	10	15	8	8	32	12	8

Table 3. Von Mises residual stress on plates 3, 4, 5 (thickness 7 mm).
Tabela 3. Von Mises zaostali napon u pločama 3, 4, 5 (debljine 7 mm)

Specimen	Residual stress (MPa) Depth 0.15 (mm)			Residual stress (MPa) Depth 0.85 (mm)			Reduction (%)		
	Position			Position			Position		
Plate thickness 7 mm	1	2	3	1	2	3	1	2	3
3	59	61	48	35	36	32	41	41	34
4	46	39	48	38	39	29	17	2	39
5	25	52	116	10	20	4	61	62	97
Mean	43	51	71	27	31	22	40	35	56
St. Dev.	17	11	39	16	10	15	22	31	35

CONCLUSION

Selective laser melting (SLM) is a technological process, which utilizes a laser beam to generate the energy for melting the powder and building parts of complicated geometry. However, this procedure may have some inherent drawbacks such as warping, cracking and residual stresses. The last melted layer generally shrinks during cooling while the layer underneath, already solidified constrains it and prevents further shrinking. Since this mechanism occurs for each layer at each step of the SLM process, residual stresses may develop inside the manufactured component. The whole phenomenon is very complicated and depends also on thermo-physical properties of the material (thermal expansion coefficient, thermal conductivity, density, etc).

This paper studies the magnitude of residual stresses developed in SLM fabricated components of rectangular shape with different thickness. Residual stresses are measured by means of the hole drilling method in three different locations on building plates (1, 2 and 3) and then the variation of residual stresses along the specimen thickness is also investigated.

Experimental results are processed with Integral Method. Results of experimental tests provided the following indications: (i) principal residual stresses near free surface (i.e., at 0.15 mm depth) are compressive and in absolute terms higher than their counterpart measured at 0.85 mm. In other words stress magnitude decreases moving towards inner layers. (ii) For thick specimens (7 mm), residual stresses are small compared with thin specimens (3 mm) However, the stress magnitude does not exceed 50% of the yield stress of the analysed material (σ_y = 985 MPa). Therefore, the measured values of strain and the derived stress field are effective and totally realistic for all depths. (iii) The position on the building plate affects the magnitude of residual stress: position 3 corresponds to the highest stress values.

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