Characterization of Internal Stresses in Hybrid Steel Structures Produced by Direct Metal Laser Sintering

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Abstract. In this study hybrid structure were produced by direct metal laser sintering of maraging steel (MS1) powder onto the surface of commercial mold steels. The over-sintering method should be analyzed to find the optimum pre- and post-heat treatment to minimize the internal stresses. The internal stress is directly proportional to the deformation if the solid thick part is reduced to thin plate like parts. Based on this recognition the deformation of the plates over-sintered with MS1 could be analyzed in order to explore the internal stresses and the effect of different pre- and post-heat treatments were examined.

Introduction

Direct Metal Laser Sintering is one of the most attractive additive manufacturing process, which can create a complex part geometry. The structure is built layer by layer using a focused laser beam for melting the metal powder. During the manufacturing the violent heating and cooling cycles inducing significant thermal gradients in the part. This thermal effect results important plastic strains and residual stress is generated in the part which can lead to the reduction of the fatigue life and formation of cracks in the part. Because of this phenomenon many papers are dealing with understanding and describing the residual stress generation. There are several destructive and non-destructive methods for examine the residual stresses.

In the scientific literature of layered manufacturing methods many researchers are dealing with the investigation of the stress formation during the processing. There are several papers which examine the role of laser beam patterns on the resulting stresses and warpage of the laser sintered specimen [1,2]. Kruth et al. investigated the effect of the temperature gradient mechanism and the different process parameters on the behavior of plate specimens. They concluded that the temperature change below the melting point will result in additional stresses in the newly deposited layer which tend to bend the part towards the laser. Part geometry and the scan strategy are affecting the time-varying processing temperatures which can cause internal stresses also [1]. They achieved an appreciable reduction in thermal deformations by appropriate scanning patterns and the beneficial effect of vaporization to restrain the balling effect was observed [1]. Pohl et al. [2] also found that the optimization of process conditions and material aspects results in a significant reduction of thermal stresses in case of plate-shaped specimens. Powder thickness and the cooling time between successive layers were studied by Van Belle et al.[3] and it was found that the residual stresses are decrease when the grain size increases from 20 μm to 40 μm.

Residual stresses generated during the rapid manufacturing process can be reduced also by thermal and mechanical treatments. Sanz et al.[4] examined the effect of different thermal and mechanical finishing treatments (shot peening and polishing) mainly on residual stresses and hardness. They found that shot peening, and final polishing improve and homogenize the surface residual state of the parts. Vrancken et al. [5] found that post-heat treatment reduced the stresses more than optimizing the parameters for the island-scanning strategy. Yadroitsava and Yadroitsaev [6] used X-ray diffraction technique and numerical simulation for investigation of the residual stress in DMLS samples made of stainless steel and Ti-alloy. They had the same conclusion as Vrancken et al, that during manufacturing, heat treatment is seen as the main way to reduce residual stresses in DMLS parts.

Residual stresses were measured by several methods in DMLS parts. By using strain gauge hole drilling method, Casavola et al. [7] pointed out that the residual stress decreased sharply with the distance from the top surface. In another study the effect of the scanning strategy was examined by neutron diffractometry [8].

DMLS technology is very expensive compared to the traditional cutting methods. If it is possible it is worth to combine the traditional technology and the laser sintering during processing. A cost-effective way of creating parts with special geometry is to produce hybrid structures by producing only the part of the structure having special geometry with laser sintering and the other part is made by traditional way. The hybrid part in that case made of two kind of steel having different physical and mechanical properties. During the process residual stresses generated which can determine the life cycle and the loading of the part.

In this paper hybrid metal structures were produced by over-sintering MS1 powder onto the top of different kind of commercial tool steel plates and the deformation of the resulted parts were measured to explore the internal stresses.

Experimental

Materials. For the over-sintering tests commercial molds steels, a precipitation hardening stainless steel ("S1") and "all-round" steel ("S2") materials were used as beam substrate and maraging steel powder (MS1 supplied by EOS) was applied for the laser sintering. The chemical composition of applied materials can be seen in Table 1.

Table 1. Chemical compositions of applied materials

Material	***C***	***Cr***	***Ni***	***Mn***	***Si***	***Al***	***Co***	***Mo***	***Ti***	***V***
Maraging steel powder	<0.03	<0.5	17-19	<0.1	<0.1	0.05-0.15	8.5-9.5	4.5-5.2	0.6-0.8	
Steel „S1“	0.03	12	9.2	0.3	0.3	1.6		1.4		
Steel „S2“	0.39	5.2		0.4	1.0			1.4		0.9

Direct Metal Laser Sintering. For the experiments EOS M270 DMLS equipment was used having Nd:YAG laser with 200W power, the powder layer thickness is 20 μm, using alternation beam scanning strategy in nitrogen atmosphere.

Specimen design. The conventional mold-insert-like parts are chunky solid blocks, which tends to crack due to internal stresses. To evaluate the internal stress level, a conventional geometry cannot be used as the internal stress measurements are complex and imprecise. For testing the internal stress level in over-sintering method a simple geometry was designed, which doesn't tends to cracking, but could deform due to the internal stresses. For this reason a plate like geometry (110 mm x 20 mm x 3.5 mm) was designed to have a low moment of inertia (stiffness) in a building directions, thus the internal stress which builds up at the sintering stage could deform the part. This deformation is directly proportional to the internal stresses and definitely easier to measure.

Blocks have been placed – over-sintered – with same overall thickness onto the plates. MaragingSteel (MS1) has been used for building with 20 μm layers. At once 6 samples can be over-sintered with a special fixture (Fig. 1). These fixtures have been used for the sintering process and in some cases for the heat treatment as well.

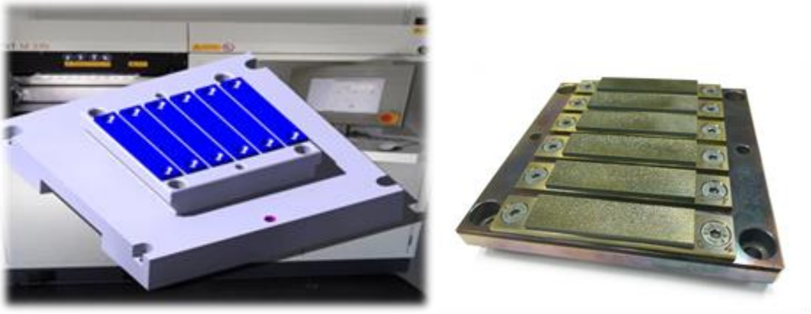

Fig. 1.
Specimens and arrangement for over-sintering: blue: plate which is fixed onto the build plate (left), and the finished samples (right)

Deformation measurement. The deformation has been measured on the surface as the sample parts warped due to the internal stresses upon the different heat treatments. Based on this fact, the deformation shows the level of the internal stresses. The deformation has been characterized with the reciprocal of the radius of curvature "R" (Fig. 2.), which measured on the centerline of the upper surface of the sample plate.

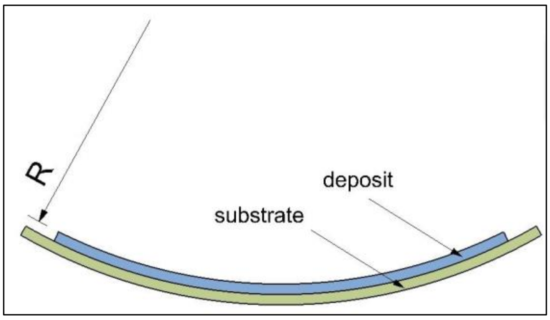

Fig. 2.
Deformation of the over-sintered samples and characterization of the deflection

The deformations have been measured with GOM ATOS digital optical system and have been evaluated with GOM Inspect software. The GOM measurements have been verified with Taylor Hobson – Talysurf CLI2000 scanning surface topography instrument.

Heat treatment. Two kind of heat treatment methods ("A" as age hardening and "Q" as quenching with high temperature heating) were applied in the different stages of the experiments. Age hardening is for MS1 and the S1 materials and quenching is for S2 steel. Their parameters can be seen in Table 2.

Table 2. Heat treatment parameters

Method	sign	Temperature [°C]	duration [h]	atmosphere
Age-hardening	A	530	2	air
Quenching + 2x Tempering	Q	1050 + 530 and 480	0.5 + 2 and 2	inert gas

Hardness test. The heat treatments were controlled with Vickers (HV30) hardness measurements by KB75 type equipment according to the specifications of standard MSZ EN ISO 6507-1, than the hardness were conversed to HRC hardness.

Research Plan. The base steel materials (S1 and S2) were applied as received or after heat treatment for over sintering. The heat treatments of hybrid systems after laser sintering were carried out with leaving or detaching from build plate. The deformations were measured in different stages of the manufacturing (Fig. 3).

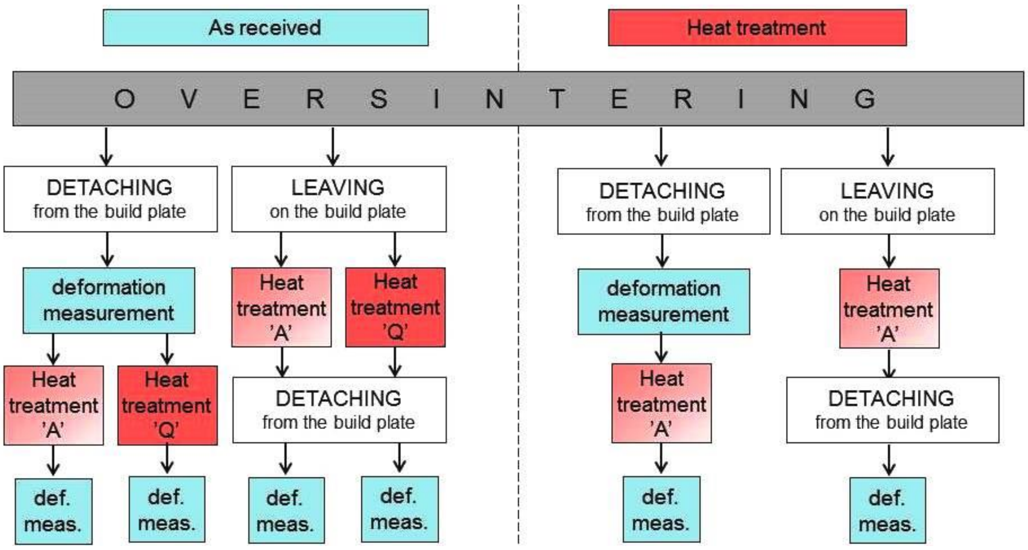

Fig. 3.
Measurement plan for both S1 and S2 materials

Results

Deformation of MS1 plate. As a preliminary measurement, mild plates were over-sintered with six different thicknesses (0.25, 0.5, 1, 1.75, 2.75, 4 mm) from MS1 material than deformation has been measured. It was proved with the high-resolution contact measurements (Talysurf CLI2000) that the optical measurement system (GOM scanner) is precise enough for the evaluations. Typical GOM scans end the results of the different measurement methods are presented on Fig. 4.

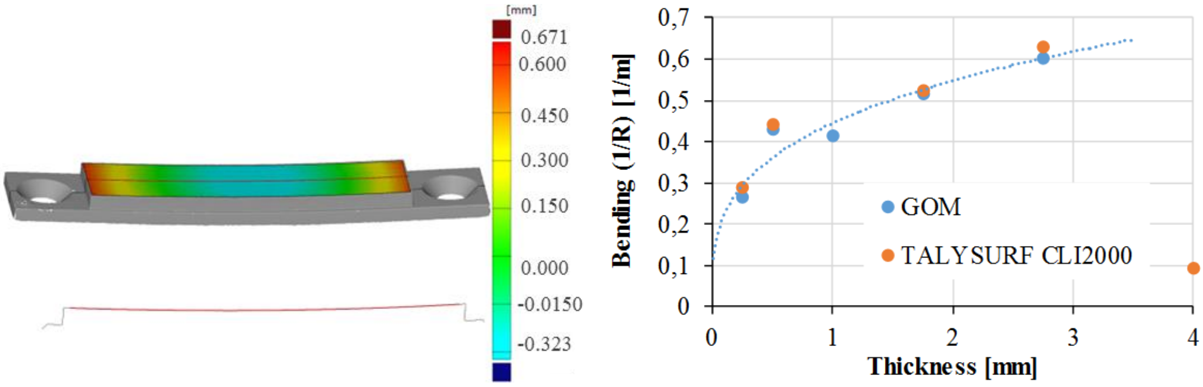

Fig. 4.
Typical GOM scan of a sample plate (left top) and the cross section of that (left bottom); Deformation of MS1 plates as a function of the thickness, measured with GOM and Talysurf systems

As it can be seen, the deformation was increased with the thicknesses up to a certain level than the over-sintered part detached from the base plate due to the internal stresses. In these measurements the 4 mm thickness over-sintered layer was detached and the cracks from the side can be seen (Fig. 5). For the measurements a stable sample must be sintered to avoid cracking. If cracks are popping up, unstable measurements will appear.

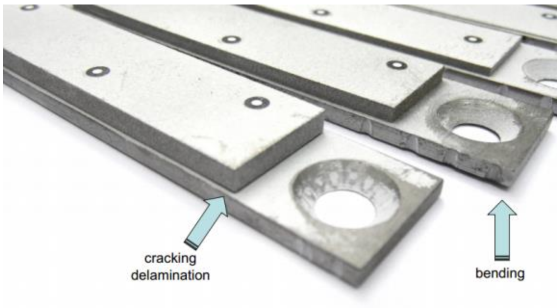

Fig. 5.
Deformation and delamination on the samples

Hardness (HRC). The Rockwell C type hardness values of the heat treated steel materials can be seen in Table 2.

Table 2. HRC type hardness of the applied steels after heat treatments

Method	**Material**	**Temperature** [°C]	**duration [h]**	**Hardness (HRC)**
A: Age-hardening	MS1 sintered	530	2	55-56
A: Age-hardening	S1 raw	530	2	53
A: Age-hardening	S2 raw	530	2	~10
Q: Hardening + 2x Tempering	MS1 sintered	1050+ / 530 and 480	0.5 / 2 and 2	53-56
Q: Hardening + 2x Tempering	S2 raw	1050+ / 530 and 480	0.5 / 2 and 2	58
A: Age-hardening	S1 age-hardened	530	2	51
A: Age-hardening	S2 hardened+ tempered	530	2	57

Deformation. The plan (Fig. 3) was carried out in case of both steels (S1 and S2) and the deformations were measured before and after the heat treatments. It can be seen that the best result can be achieved with those samples which are sintered onto the plate without heat treatment followed by the age-hardening on 530°C, 2 hours at air (Fig. 6). All measurements were done with 3 samples. The maximum standard deviation was under 0.03 1/m, while the relative standard deviation was 18.7% and the average standard deviation was 6.3%.

Fig. 6.
Deformations of the samples 1/R (1/m) for S1 material (left) and S2 material (right)

Summary

In this research paper hybrid structures was produced by using commercial tool steels having different chemical compositions. Maraging steel powder was over-sintered on the top of the steel plates by DMLS technology. Heat treatment was used in the different steps of the manufacturing and the residual stresses generated during the processing was described by deformation measurements,

It was proved that the over-sintering method could be evaluated with the deformation measurements. As the deformations clearly characterize the internal stresses, this method can help to find the best pre heat treatment and heat treatment for the over-sintering. In case of both steels the lowest deformation was measured when no heat treatment was applied before the laser sintering and the hybrid structure was leaving on the base plate during the lower temperature heat treatment (age hardening).

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References

[1] J.P. Kruth, L. Froyen, J. Van Vaerenbergh, P. Mercelis, M. Rombouts, B. Lauwers, Selective laser melting of iron-based powder, Journal of Materials Processing Technology, Volume 149, Issues 1–3 (2004) 616-622

[2] H. Pohl, A. Simchi, M. Issa, H. C. Dias, Thermal stresses in Direct Metal Laser Sintering, Solid Freeform Fabrication Proceedings, 2001 The University of Texas at Austin, ISSN 1053-2153, (2001) 366-372

[3] L. Van Belle, G. Vansteenkiste, J-C. Boyer, Investigation of residual stresses induced during the selective laser melting process, Key Engineering Materials 554-557 (2013) 1828-2834

[4] C. Sanz, V. Garcia Navas, O. Gonzalo, G. Vansteenkiste, Study of surface integrity of rapid manufacturing parts after different thermal and finishing treatments, Procedia Engineering, Volume 19 (2011) 294-299

[5] B. Vrancken, R. Wauthle, J.-P. Kruth, J. Van Humbeeck, Study of the influence of material properties on residual stress in selective laser melting, Proceedings of Solid Freeform Fabrication Symposium (2013) 393-407

[6] I. Yadroitsava, I. Yadroitsev, Residual stress in metal specimens produced by direct metal laser sintering, Proceedings of Solid Freeform Fabrication Symposium (2015) 614-625

[7] C. Casavola, S. L. Campanelli, C. Pappalettere, Preliminary investigation on distribution of residual stress generated by the selective laser melting process, The Journal of Strain Analysis for Engineering Design, Volume 44, Number 1 (2009) 93-104

[8] M. F. Zaeh, G. Branner, Investigations on residual stresses and deformations in selective laser melting, Production Engineering - Research and Development, Volume 4 (2010) 35–45