Open access • Journal Article • DOI:10.4028/WWW.SCIENTIFIC.NET/KEM.554-557.1828

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Published on: 02 May 2013 - Key Engineering Materials (Trans Tech Publications Ltd)

Topics: Residual stress, Selective laser melting and Hole drilling method

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Key Engineering Materials Vols. 554-557 (2013) pp 1828-1834
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doi:10.4028/www.scientific.net/KEM.554-557.1828

Investigation of residual stresses induced during the selective laser melting process

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Keywords: Selective laser melting, layer additional method, Residual stresses.

Abstract. The selective laser melting process (SLM), belonging to the family of additive manufacturing processes, can create complex geometry parts from a CAD file. Previously, only prototypes were created by SLM, but now this process is used to manufacture quickly and directly functional parts. For example, in the PEP (Centre Technique de la Plasturgie), this process is used to manufacture tooling parts or injection molds with cooling channels that can't be obtained by conventional routes. During the process, the laser beam generates violent heating and cooling cycles in the material inducing important thermal gradients in the consolidated part. The cyclic thermal expansions and contractions exceeding the maximum elastic strain of the material induce heterogeneous plastic strains and generate internal stresses the level of which can reaches the yield stress of the material and cracks may appear during the process. This paper deals with the measurement and analysis of residual stresses during the selective laser melting of a simple part in maraging steel. The objective of this study is the analysis of experimental results to validate the numerical model previously presented in [1]. A new method is proposed to evaluate the residual stresses induced during the SLM process, a rosette is fixed on the bottom face of the support. The residual stresses in the created part are calculated from strain and temperature variations when the fused layer is consolidating during the cooling between two layers. Process parameters like the powder thickness or the cooling time between successive layers are studied in this paper.

Introduction

The SLM process is an additive process used to create metal parts with complexes shapes from CAD data. The basic concept of SLM is similar to that of selective laser sintering (SLS). A moving laser beam is used to melt selectively powdered metal into successive cross-sections of a three dimensional part. Parts are manufactured on a mobile table moving upward by steps equal to the thickness of the layer (see Fig. 1). Additional powder is laid down on the top of each solidified layer and with the cooling it solidifies to form finally a solid material. For example, this method is used in the polymer processing industry to manufacture tooling parts or moulds designed with internal channels for conformal cooling which could not be obtained by conventional milling and drilling [2]. Parts obtained by SLM are dense and can be directly functional.

During the manufacturing, the interaction between the laser and the powder induces significant thermal gradients in the part thanks to high heating and cooling rates associated with cycling. These thermal effects generate important plastic strains, thereby, residual stresses. The consequences are the reduction of fatigue life of the part or the initiation of cracks. This paper deals with the understanding of the residual stresses generation and the measurement during SLM process.

Some authors have investigated the residual stresses generated in SLM parts using different experimental measurement methods such as the incremental hole drilling method in [3], the layer removal method see in [4] and [5] or the non-destructive method, by neutron diffraction in [6]. The layer removal method is of a particular interest in our case, strains gauges are bounded to the opposite face of the milling of successive layers to evaluate the residual stresses. The strain measurements are used to evaluate the internal stresses by mechanical balance formula. In the case of SLM, the measurement of the strain is proposed to take place during the melting process of successive powder layers. Three different specimens have been tested with different process parameters as the layer thickness and the cooling time between successive layers.

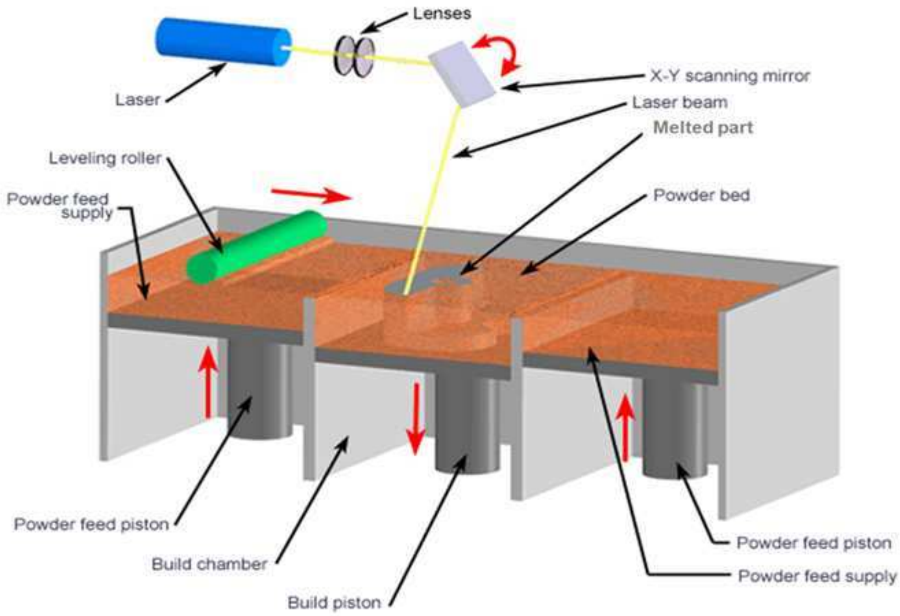

Fig. 1 Schematic illustration of the SLM process

Description of the experimental system

A machine EOS M270 was used for the experiments. The system is composed of a Yb : laser fiber with a power of 200 W. The laser beam diameter is 100 µm. The powder layer thickness can be set at 20 or 40 µm. The scan direction of the laser beam is rotated by 67° after the completion of each solidified layer. The atmosphere of the manufacturing chamber is oxidation free by use of nitrogen during the process. The part material is a maraging steel, the chemical composition of which is indicated in the Table 1 below. The powder size is an average diameter about 35 µm.

Table 1 Material composition of maraging steel

Elements	Fe	Ni	Co	Mo	Ti	Al	Cr	C	Mn, Si	P,S
[wt%]	64,6-69,35	17-19	8,5-9,5	4,5-5,2	0,6-0,8	0,05-0,15	0,5	0,03	< 0,1	< 0,01

The table shape support is design to allow the bonding of transducers with their wires for the data processing (in Fig. 2). The square support is 5 mm thick and 100 mm long. The thickness of the support is chosen in order to obtain significant strains and provide a thermal mass avoiding temperature higher than 260°C during the powder melting phase in the surrounding of the strain gauge rosette to prevent its debonding. A type K thermocouple is also bounded close to the strains gauges in order to record the temperature evolution for the thermal strain compensation calculus. The strains gauges and thermocouple are positioned at the center of support bottom.

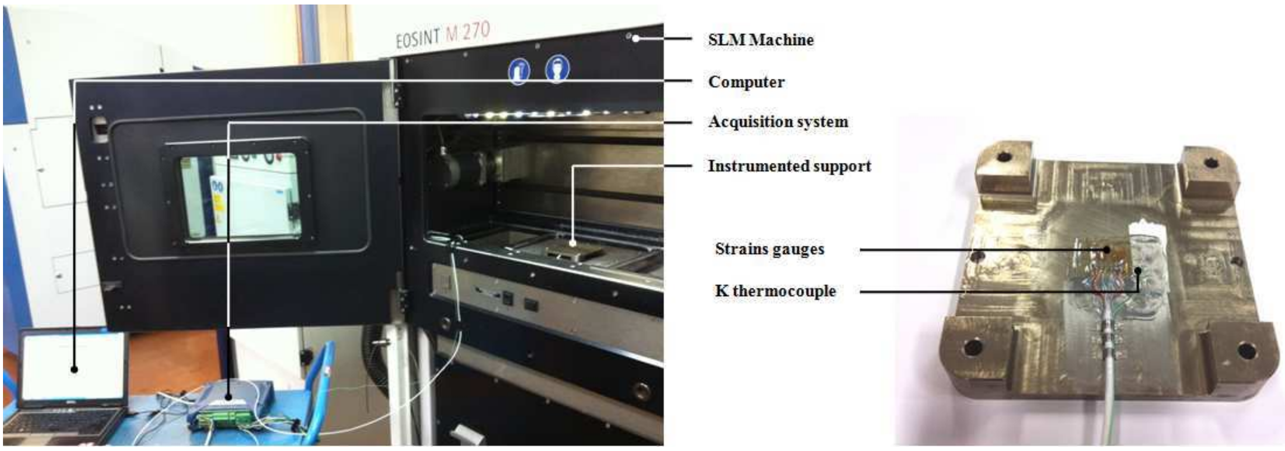

Fig. 2 Experimental system and instrumented support

The manufactured part by SLM is a square parallelepiped, 10 mm high (corresponding to 250 layers 40 µm thick) and 50 mm large. The instrumented support is clamped by bolts on the plate link to the moving bed of the machine and the transducer wires are connected to a FRONTDAQ data acquisition device. Three instrumented supports are studied for seek of the study of the influence of the layer thickness and cooling time between successive layers. The experimental conditions are indicated in the Table 2.

Table 2 : Experimental data

	Layer thickness	**Cooling time between layers**	**Manufacturing height**
Support 1	40 [µm]	8 [s]	10 [mm]
Support 2	20 [µm]	34 [s]	5 [mm]
Support 3	40 [µm]	34 [s]	10 [mm]

The well-known theory of the removal layer method is used [7] and modified to determine the residual stresses in the part and support during the layer addition with the measured strains. When a layer is added, a variation of the residual stress corresponding to elastic bending is calculated in the support and the created part with the mechanical balance. This theory assumes that the residual stress in the layer is proportional to the Young's modulus E, the Poisson ratio ν, the variation of measured strain $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ and the dimensionnal parameters. It is worthwhile to notice that in the powder grains and the first cooling instants, the material is so soft that plasticity takes place. This transient phenomenum is not considered in the calculus. The stress value in the n°i layer after cooling is calculated by adding the effects of the n-i following layers where n is the total number of layers without any consideration of plastic constitutive law in the equations (see Eq. 1 and 2).

$$\sigma_1(x_i^{'}, n) = \sigma_1(x_i^{'}, i) + \sum_{j=i+1}^{n} \Delta\sigma_1(x_i^{'}, j) \quad (1)$$

$$\sigma_2(x_i^{'}, n) = \sigma_2(x_i^{'}, i) + \sum_{j=i+1}^{n} \Delta\sigma_2(x_i^{'}, j) \quad (2)$$

Where $\sigma_1(x_i^{'},n)$ is the final residual stress of the layer n°i, $\sigma_1(x_i^{'},i)$ the stress created after the addition of the layer n°i and $\Delta\sigma_1(x_i^{'},j)$, the added stresses by the following melted layers. These formula based upon the self balance of the residual stress field do not take into account any possible external action induced by the clamping of the support. This strong assumption has to be check by a measure of possible bending effects.

Results analysis and discussions

The strains and temperature evolution have been recorded during the manufacturing process. The so called 45° degree rosettes with three strains gauges are used to determine the eigen strains and the eigen directions on the support surface once the laser beam moved in various direction during the melting phase of the powder. After the melting of each layer and some cooling time, the value of the strains and the temperature are recorded and processed by smoothing (see Fig. 3). The maximum and minimum eigen strains increase during the manufacturing process and reach 2000 µm/m when the temperature is quite constant at 82°C before the final cooling. The values of the two eigen strains are very similar, and this property can be linked to a biaxial stress state on the support surface.

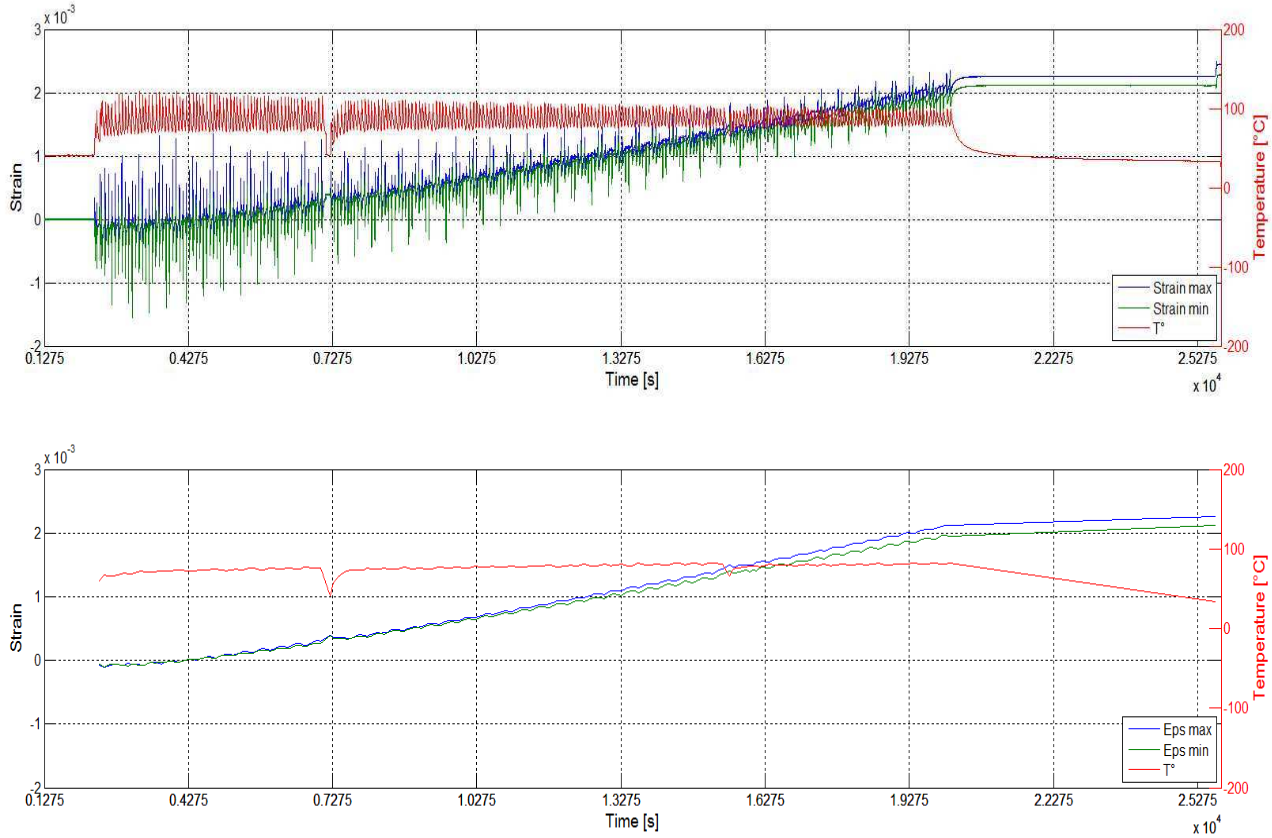

Fig. 3 Eigen strains and temperature evolution during SLM

Using the records of the strain magnitudes, a temperature correction, and equations (1) and (2), the found stress distributions in the melted layers and in the clamped support are presented at Fig. 4 for the three different cases described at Table 2. These results are the sum of the residual stresses and a bending of the clamped support. Of course, the discontinuity of the stress field at the interface of the support and the first melted layer does not fulfil the internal balance principle. This unrealistic approximation comes from two wrong assumptions : the stress distribution in the new layer is not uniform and the material in the vinicity of the melting is elastic-plastic with the temperature softening. Some plastic accomodation should be introduced in the calculus for the first layers. Linear stress are overestimated because the distribution cannot be linear in the vicinity of the first layer as the support material is softened by conduction through the powder.

As the K thermocouple and the rosette are not bonded at the same place but with a distance of 0.5 mm, the thermal correction of the measured total strain has to take into account the temperature gradient on the support surface. A thermal transient simulation has been performed and revealed an homogeneous temperature distribution in this area. So it has been considered that the thermocouple and gauge temperatures were equal. After the thermal strain correction, the recorded strain results were smoothed before the calculus of the stress distribution.

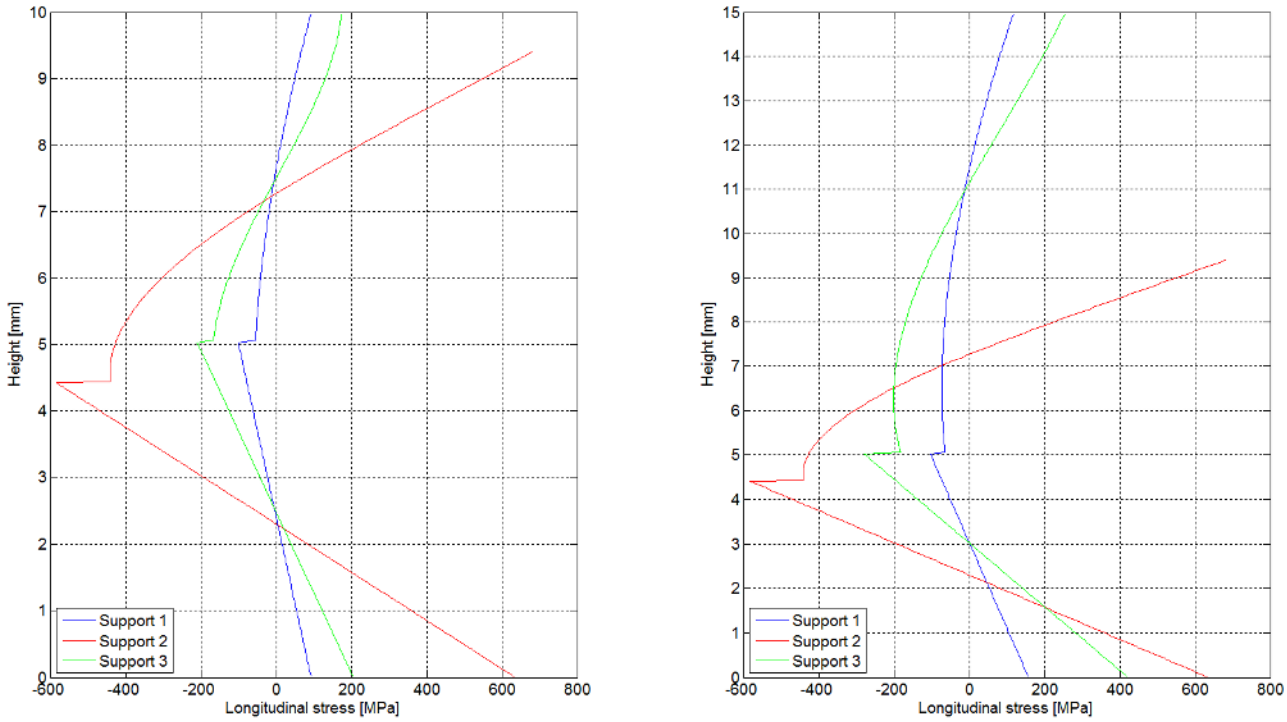

Fig. 4 Eigen stresses in the part for a manufacturing height of 5 mm (left) and 10 mm (right)

At Fig. 4, the eigen stress distributions in the melted layers and the three supports are presented as a function of the part thickness at the end of the process and for the half and the final thickness for support 1 and 3. For the three cases, residual stresses on the free surface of the melted layers are tensile ones. The internal stress increase to the interface between the support and the melted part until to the last solidified layer. The experiment for the 20 µm powder grain and long cooling time (Support 2) but with a final thickness of 5 mm leads to the highest level of internal stress close to 700 MPa, whereas the experiment for the 40 µm powder grain and the 10 mm final thickness predicts only 200 MPa (Support 3).

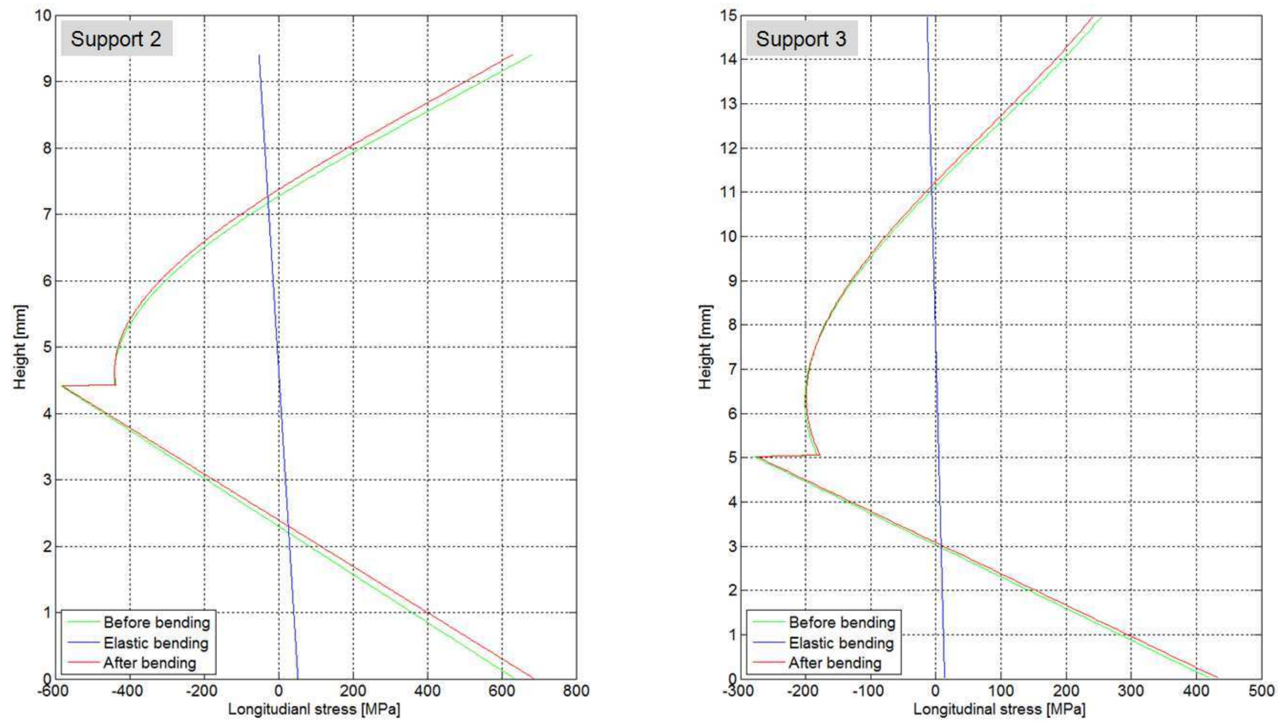

Fig. 5 Eigen stresses before and after bending effects

These values are calculated for a clamped support supposed to introduced no bending, the actual bending of the plate has to be introduced for the estimation of the residual stress in the part unclamped. As the record of the strain gauges where completed only after the loosening of the bolts clamping the support, the strain variation allows the calculus of the bending moment in the support. For Support 3, the maximum bending stress was found equal to 13 MPa whence for Support 2 the level is higher at 52 MPa (see Fig.5). So, the assumptions of negligible bending effects seems to be right for the application of the removing layer method formula for Support 3. Considering the elastic behaviour of the material, the calculus of the residual stress distribution at the end of the process leads also to a correct estimation of the stress levels. But the intermediate results are not reliable as the method used cannot properly evaluate bending effects for each layer.

Distorsions measure and results

The deformed geometry of three supports has been recorded with a ROMER measuring system on the top surface of the support. A 2D spline of the MatLab software was used for the interpolations of the recorded point coordinates, see the corresponding deformed surfaces at Fig. 6 above, the Support 2 with a final layer thickness of 5 mm is more bended as it is less stiff, a vertical residual deflection of 0.9 mm is found when Support 3 with a final layer thickness of 10 mm as a deflection amplitude of 0.6 mm. For Support 1 melted from 40 µm powder grain and a low cooling time, the deflection is very weak with its maximum amplitude equal to 0.2 mm. This case is very peculiar because this support was badly clamped with only one bolt tighten on the machine bench and shows of course that the deformed configuration and the internal stresses are very sensitive to the actual boundary conditions.

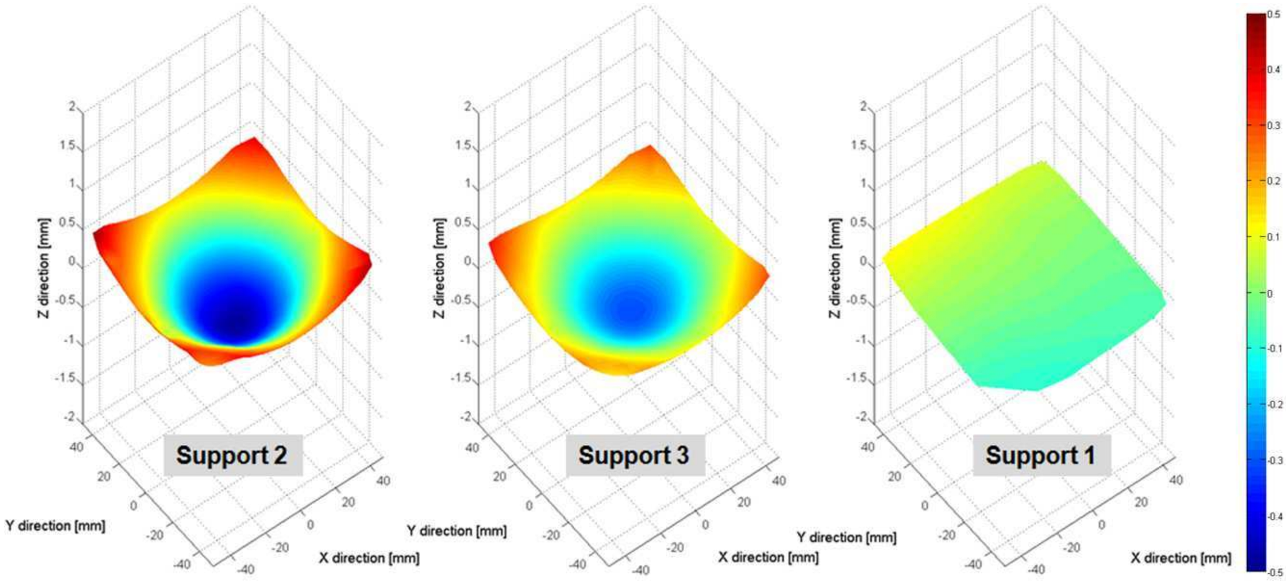

Fig. 6 Distorsion of supports surface

Conclusions

Experimental investigations of residual stresses with strain gauges during the SLM process coupled to a modified removal layer method gives estimation of the maximum residual stress on the last melted layer laid down on a support. The residual stresses are found to be extremely large with a final layer thickness of 5 mm a grain size of 20 µm and a long cooling time (Support 2) and their magnitudes decrease when the final thickness and the grain size 40 µm (Support 3) increase. The deformations of the supports are important for the same experimental parameters as the internal stresses produce severe bending of the thin part. The bending effects are very sensitive to the actual boundary conditions, clamping producing bending stress level of equal to 8% of the residual stress magnitude in the worst case. The records of the experimental strains and of the deformed geometry of the three supports will be later used for a comparison with a numerical simulation of the three experiments. The aim of this comparison will be a validation of some assumptions introduced in a thermo-mechanical analysis of the SLM process under development.

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