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Experimental study of residual stresses in metal parts obtained by selective laser melting

C.E. Protasov[a], V.A. Safronov[a], D.V. Kotoban[a], A.V. Gusarov[a,b,*]

[a]*Moscow State University of Technology "STANKIN", Vadkovsky per. 3a, 127055 Moscow, Russia*
[b]*Institute of Photonic Technologies (LPT),Friedrich-Alexander-Universität Erlangen-Nürnberg, Konrad-Zuse-Str.3-5, 91052 Erlangen, Germany*

Abstract

High local temperature gradients occur at additive manufacturing by selective laser melting of powder. This gives rise to undesirable residual stresses, deformations, and cracks. To understand how to control the formation of the residual stresses, a reliable method is necessary for measuring their distribution in the fabricated part. It is proposed to cut the part into thin plates and to reconstruct the residual stresses from the measured deformation of the plates. This method is tested on beams with square cross-section built from stainless steel. The beams were cut by electrical discharge machining and chemically etched. The obtained stress profile in vertical transversal direction slightly increases from the top to the bottom of the beam. This dependency is confirmed by numerical modeling. The measured stress profile agrees with the known results by other authors.

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1. Introduction

Selective laser melting (SLM) is a layer-by-layer additive manufacturing technique where parts are built from powder. A thin powder layer is mechanically deposited on the growing surface and then selectively bound by a scanning laser beam. The powder and the underlying material are melted in the laser-interaction zone. The quality of the obtained material is comparable to that attained in metallurgical processes. An important and well-known drawback of SLM is the formation of high residual stresses and deformations, which may be responsible for

* Corresponding author. Tel.: +49-9131-85-23241 .
E-mail address: av.goussarov@gmail.com

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cracking and distortion of the built part. This problem is common for other laser technologies like welding because the laser beam heats a local zone to a high temperature while the rest of the part remains at the ambient temperature. Thus, a strong thermal shock is generated.

Gusarov et al. (2011,2013) showed that the conventional thermoelastic model is applicable to estimate residual stresses at SLM of several polymers and ceramics. In the framework of this model, the distribution of residual stresses is independent of the complicated transient temperature field in the part during the process. It depends on the shape of the zone where the temperature has attained the melting (softening) point where the thermal stresses are relaxed completely. The model is simple, so that the results are easy to analyze. For example, the residual stresses are proportional to the difference between the melting temperature and the ambient one. This is in line with the experimentally verified method of preheating, see Deckers et al. (2014).

Thermoplastic deformation of metal alloys is important under typical SLM conditions. In this case, the thermoelastic model may show qualitative tendencies, but rigorous calculation of the residual stresses requires a more complicated thermomechanical model. Thus, Brückner et al. (2007) and Zaeh and Branner (2010) used the model of elastoplastic flow combined with transient heat transfer. This numerical approach is time consuming because of two different scales in the problem, namely the size of the part and that of the laser-interaction zone. The existing numerical methods can estimate the distribution of residual stresses in metal parts. However, a deep parametric analysis is necessary for optimizing the process.

Various approaches to experimental measurement of residual stresses at SLM are being developed. Zaeh and Branner (2010) applied neutron diffraction and Yadroitsev and Yadroitsava (2015) used X-ray diffraction. In the diffraction methods, the sampling area is generally determined by the beam diameter while fine focusing may be difficult. Moreover, the penetration depth of the rays into the studied material cannot be changed. Thus, additional efforts are often necessary for positioning the sampling zone in depth. Therefore, the spatial resolution of the diffraction methods may be insufficient for small parts with nonuniform stress distribution.

Another group of experimental methods is based on deformation analysis at cutting the part. Wire electric discharge machining (EDM) is used because of its small influence zone. Zaeh and Branner (2010) studied deformation of SLM-fabricated t-shaped cantilever after cutting the supports. Mercelis and Kruth (2006) applied crack compliance method to measure transversal profile of residual stress in beams fabricated by SLM. In this method, strain is measured during transversal cutting of the beam by wire EDM. The obtained data require mathematical treatment to derive the stress profile.

The objective of this work is to test another deformation analysis-based method for measuring the residual stresses of SLM. Longitudinal cutting of the beam is applied. This may increase the sensitivity because of a high length-to-width ratio of the beam. The mathematical treatment becomes more straightforward.

2. Methods and materials

Consider a beam with arbitrary transversal profile of normal longitudinal stress $\sigma(z)$ shown in Fig 1a. Let the cross-section of the beam in plane (YZ) be rectangular and the stress do not depend on Y-coordinate. Figure 1b shows a thin layer cut from the beam between transversal coordinates $z - h/2$ and $z + h/2$. The cutting changes the force balance. Therefore, the layer can elongate/contract and bend. If the beam is uniform along axis X, the relative longitudinal deformation is independent of x and determined by relative deformation ε_0 of the middle plane $z = z_0$ and curvature radius R as follows:

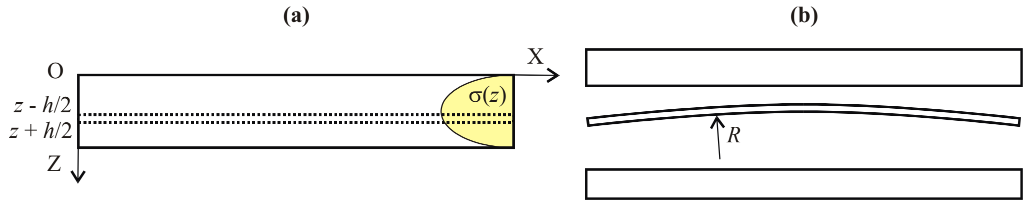

Fig. 1. Beam with residual stresses: (a) as fabricated; (b) after cutting a thin longitudinal layer.