Residual Stress Measurement Measured by Different Type of Method on the 3D Print-thermal Spray

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Abstract: The development of 3D print-thermal spray systems, resistant against wear and corrosion is the main objective of an extensive research project handled in our institute. Additive technologies have potential to produce light and complex-shaped components. However, required service life and reliability under different load modes has to be ensured. Components surface needs to be protected against wear and corrosion. Such combination enables to exploit advantages of 3D printing with benefits provided by thermal spraying. One of the goals of the project is to determine the effect of residual stresses on the quality of the thermal coating and at the same time to optimize the application of the coating in terms of the level of residual stresses. First, the spray optimization was carried out on standard steel. The goal of presented research was to compare residual stresses in thermal coatings for different coating materials and process conditions. To be able to choose the optimum measurement procedure, several measurements method were compared. Both semi-destructive hole-drilling and groove grinding methods and non-destructive X-ray diffraction were used.

Keywords: Residual stresses; Hole-drilling method; X-ray diffraction; 3D print-thermal spray; Additive technologies; Thermal spraying technology

1 Introduction

3D-printing is often the technology of choice for manufacturing intricate-shaped parts with cooling channels and a light-weight structures. However, one of the disadvantages is lower strength when subjected to dynamic and cyclic loading, others are the presence of residual stresses, higher surface roughness and poor wear resistance.

Thermal spraying technology is a modern technology that offers the protection of the substrate surface from external influences, such as wear, corrosion, high temperature, oxidation or thermal shock. As well as 3D printing technology, the results are highly dependent on the process parameter settings. The microstructure of the coatings, the adhesion to the substrate and the development of the residual stresses are strongly influenced by the material used, the deposition technology and the process parameters.

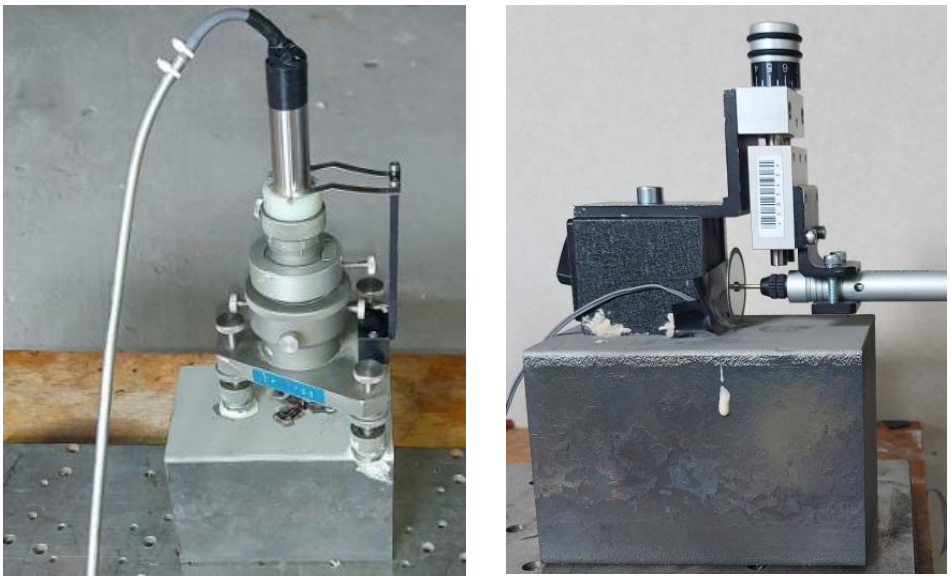
The 3D printed-thermally spray systems will be analyzed to study their mutual influence on adhesion strength and residual stress development in a more advanced stage of the project. The coatings will be deposited from powders and the spray parameter optimization will be done regarding coatings microstructure, phase composition and residual stress development from commercially available powders, WC- and CrC-based hard metals with variable amount of composition of matrix and new powder composition. Optimization of the spray parameters for coatings microstructure, phase composition and residual stress development will also be performed. Heat treatment will be used for further residual stress elimination.

At the beginning of the project, MS1 tool steel and following types of thermal sprays Amperit 588, Amperit 543 (42WC 42“CrC“- 16Ni) and WOKA 7502 (37WC-43“CrC“-18NiCo) were used. Thickness of the thermal spray layer was 0.5 mm. Main goal was to introduce compressive stresses into the surface layer.

2 Measurement of residual stresses with semi-destructive methods

The combination of 3D printing and thermal spray technology has not been studied yet, neither the residual stress of the layer, 3D printed material, nor the system.

Therefore, theoretical calculation of residual stress in the layers were performed at the beginning. Determination of the residual stresses was measured using three methods, two of them were performed by Research and Testing Institute Pilsen, namely semi-destructive hole-drilling method [1] and groove-grinding method and the last one X-ray diffraction, which was performed by Department of Solid State Engineering, in Prague. Both devices for semi-destructive measurement of residual stresses are presented in Fig. 1.



(a) (b)

Fig. 1 Measuring devices which were used for measurement of residual stresses: (a) hole-drilling method, (b) groove-grinding method.

In a first step, the residual stresses were measured on the opposite side of a 5 mm thick thin plate. Here, two strain gauges LWK-06-W250D-350 in the longitudinal and transversal direction and Pt-thermal resistance sensor were fixed to the bottom side using spot welder, see Fig. 2. The layer was deposited on the front side. The goal was to measure the residual stresses through the change of the curvature. However, the sensitivity of such a measurement was very low, only approx. 12% of residual stresses of the layer were detected on the bottom. On the other hand, the strain gauges withstood a relatively high temperature without destruction.

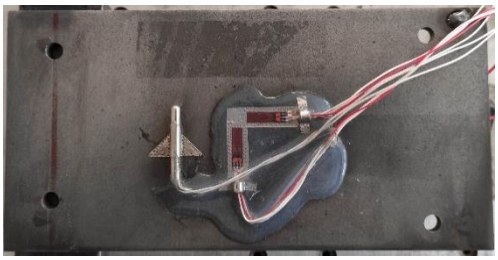


Fig. 2 Plate with the strain gauges and Pt-thermal sensor.

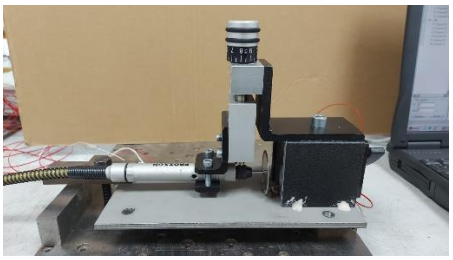


Fig. 3 Groove grinding method on the plate of 5mm thickness.

The groove-grinding method was used at the beginning of the investigations on a 5 mm thick plate, see Fig. 3 and the results in Fig. 4. The HBM 0,6/120LY11 strain gauge was used for the measurement and the groove was performed 2 mm from the center of the grid of strain gauge, a diamond wheel with a diameter of 38 mm was used as a tool. Depth of the groove was 2 mm and the step of grooving was 0.05 mm. Grinding was used to achieve the base material, where stress relaxation could be observed.

Based on FEM calculations, the size of the steel cube for applying the layer was optimized to minimize the bending stresses. The result was the cuboid with dimensions of 100×100×150 mm, with which further tests were performed.

In the first step, the residual stresses were measured in the CrC-NiCr layer by the groove-grinding method on the optimized cuboid, see Fig. 1b). The goal was to compare residual stresses in the layer of the 5 mm plate and the layer on the cuboid. For both material thicknesses the depth courses of residual stresses were comparable, see Fig. 4.

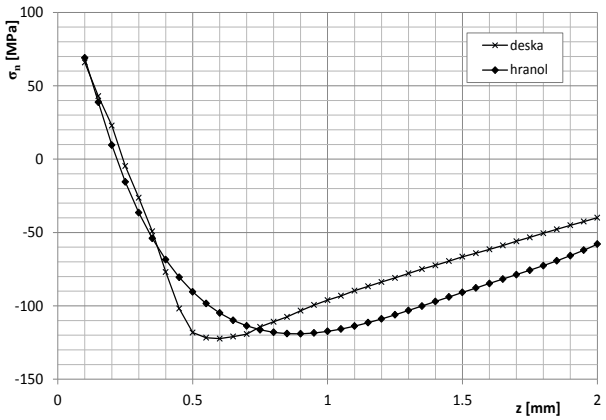


Fig. 4 Comparison of the depth courses of residual stresses measured on the plate – "deska" and on the cuboid – "hranol".

Next step was the comparison of different types of Amperit 543 (42WC42"CrC" 16Ni) and WOKA 7502 layers. Residual stress measurement was performed by hole-drilling method using Vishay RS-200 device with air turbine with the speed of over 200 000 rpm. A TML FRS-2-11 strain gauge rosette and a SINT D2/1 diamond cutter (⌀ 1.6 mm) were used. An 8-chanell HBM SPIDER8 amplifier and Catman Professional software were applied for the data acquisition. Evaluation of residual stresses was performed by the SINT EVAIL7.2 software from SINT and also using user developed software in spreadsheet.

Three specimens with different coating parameters were prepared using Amperit 543 and WOKA 7502, corresponding to the main optimalization, see Table 1.

Table 1. Deposition parameters.

Sample				Layer param.	
Ser. 1 #	**Material**	**Ser. 2 #**	**Material**	**Φ**	**Press. [Pa]**
1	Amperit 543	1	WOKA	0,66	6,8
2	Amperit 543	2	WOKA	0,75	7,8
3	Amperit 543	3	WOKA	0,85	8,5

Sample No. 3 was measured both with hole-drilling and X-ray diffraction.

3 Measurement of residual stresses using X-ray diffraction

The X-ray diffraction measurements were performed using the X´Pert Pro MPD diffractometer in Bragg-Brentano geometry. Evaluation was focused for two major phases in the layer, namely WC and Cr_3C_2, and for the base material. The {*111*} diffraction lines of WC phase, {*361*} of Cr_3C_2 phase and {*211*} of α-Fe phase were analyzed using chromium radiation. The residual stresses values were calculated from lattice deformations determined on the basis of experimental dependencies of $2\theta(\sin^2\psi)$ assuming a biaxial state of residual stress (θ is the diffraction angle, ψ the angle between the sample surface and the diffracting lattice planes) [2].

In order to determine the depth courses of macroscopic residual stresses, gradual electrolytic removal of the surface layers of the material was chosen using electrolytic polishing realized using the PROTO Electro polisher with A2 electrolyte. The thickness of the removed layer was measured using a digital micrometer.

Based on the results of strain analysis, it can be said that majority WC phase shows homogeneous tensile residual stresses (RS) at the surface, whereas RS values of minority Cr_3C_2 phase shows moderate compressive values. The depth courses of the RS of both analyzed phases have a decreasing trend. RS are tensile in the case of the WC phase and compressive in the case of Cr_3C_2. At depths greater than 0.5 mm, residual stresses were determined for MS1 tool steel as the major phase. Only compressive residual stresses of about 130 MPa were described (see Fig. 4).

4 Evaluated residual stresses

Evaluated results are presented in Fig. 5. Residual stresses in the Amperit 543 layer which have decreasing trend from tensile residual stresses to the compressive for each sample. A very high residual stress gradient was found at the interface between the layer and the base material, and rapid relaxation accompanied by an audible crack was observed when the hole was drilled. This behavior was able to observe only in the Amperit 543 layer.

The evaluated residual stresses in this paper are the mean values of the measured stresses in the principal directions (the both stresses in the principal directions are nearly the same). This is described as a hydrostatic stress state with zero shear stresses.

It is evident that samples using Amperit 543 have higher tensile residual stresses than the others. Samples with WOKA 7502 have compressive residual stresses.

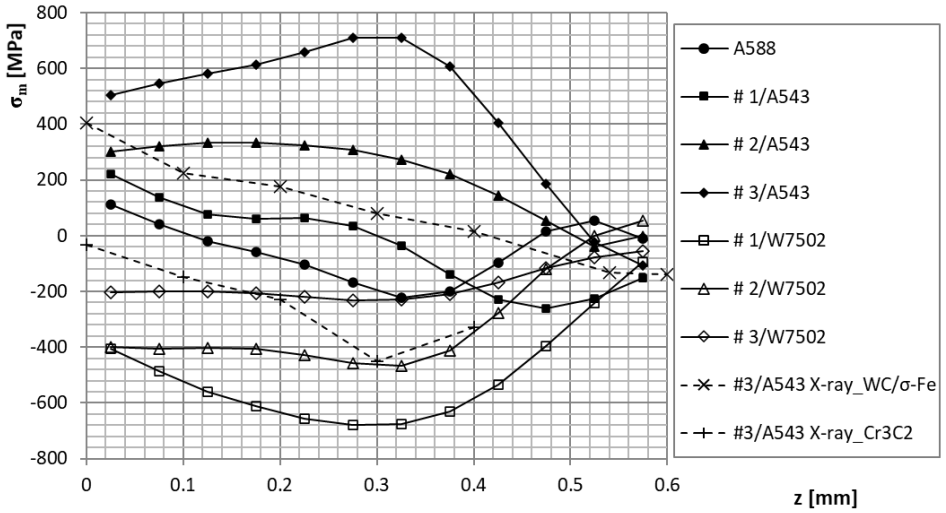


Fig. 5 Comparison of the mean component of depth courses of the residual stresses measurement including measurements by the X-ray diffraction.

Conclusion

The compressive residual stresses were proven after some optimization procedures in WOKA 7502 layer using hole-drilling method. The main goal was achieved, compressive residual stresses were obtained for all selected deposition parameters. Further, it was also found that X-ray diffraction and hole drilling method give approximately the same values of macroscopic residual stresses.

Acknowledgements

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