Residual stress analysis of ceramic coating by non-contact methods

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Abstract. A method for residual stress analysis of ceramic coatings by applying a laser for quasi non-destructive material removal and measuring the 3D deformation around the machined area by means of high-resolution digital holography is described. The residual stresses are retrieved by combination of the measured 3D deformations, the profile of the machined area, the coating thickness and the elastic materials parameters. Experimental results together with discussion of the difficulties, work in progress and potential of the method are presented.

Introduction

Ceramic coatings are commonly used to improve the wear or heat resistance of many technical components, but due to their application process, e.g. plasma or high velocity oxygen fuel spraying, rather high residual stresses can build up within the coating and underneath. The reason for that are differences in the coatings and substrates expansion coefficients, inhomogeneous distributed temperature during the process and the quenching of splats [1]. The hole drilling technique can be used for the detection of residual stresses in coatings. This is a quasi-non-destructive method with the advantage of time/cost efficient application and possibility of in situ measurements, without neglecting a good depth resolution and quantitative accuracy [2-5]. The residual stresses are locally relieved due to the material removal, which leads to a deformation of the surface around the hole. These deformations, measured as relaxed strains through strain gauges rosettes, in combination with appropriate calibration data (separately determined by simulation for the layer composite), allows the quantitative determination of the residual stress depth profiles. The disadvantage of the strain gauges is that they can only be used on flat and relatively smooth surfaces, where the rosette is applied. Furthermore they measure only in-plane strains (2-dimensional). Since the distance between the hole-centre and the strain gauge is always relatively large, there are limitations both in terms of spatial resolution and practicality. The accuracy of the measurements depends as well on the asymmetries of the hole and the positioning of the strain gauge rosette.

We propose an approach to avoid the mechanical drilling operation and the application of strain gauges, where a pulsed laser is used for the object machining (ablation process) leading to 3D residual deformation by stress relaxation which are measured by an optical system based on digital holographic interferometry. For the validation of the method, test plates were prepared, where aluminium/titan oxide coatings are deposited by atmospheric plasma spraying technique on aluminium substrates.

Experimental setup

The experimental setup for residual stress analysis (Fig.1) can be divided into two parts one for the machining of the object and the other for the measurement of the resulting 3D deformations. The harmonic separator (HS), transmits the infrared light for the laser machining (wavelength: 1064 nm) and reflects the visible green light (wavelength: 532 nm), for the deformation measurement, allowing at the same time machining and deformation measurements. Laser pulses with a power density higher than 10^9 W/cm² are used for the ablation of material, in order to obtain such density the laser beams having pulse length of some nanosecond are focused by a lens on the sample surface. Complex structures are machined by using a spatial light modulator (SLM), where a given light distribution is produced by writing a phase/amplitude pattern (computer generated hologram) on the SLM. The release of residual stresses by the laser machining system produces 3D deformations that are measured by the system based on digital holography shown in the bottom part of Fig. 1. Light from a laser is divided into two beams by the beam splitter BS, one is coupled into a single mode optical fibre and serves as the reference beam and the other one is further divided into four beams illuminating the object sequentially from four different directions. The phase of the wavefront scattered by the object changes as a function of the deformation [6, 7], and by processing holograms recorded by different illumination it is possible to measure the 3D deformation around the machined surface.

Results

The SLM based system was used for machining structures with different shape and depth on the coated surface. Figure 2.a shows a milled horizontal bar obtained after 64000 laser pulses, the depth of the machined structure is 130 µm. Figures 2. b-g shows the wrapped phase and the corresponding 3D deformations produced by the milling. By incremental loading structures (bars, crosses, rings) having different depth are produced and the resulting 3D deformations are measured. The residual stresses at different depth of the coating are calculated from the deformations together with the profile (shape, depth) of the machined surface and the material parameters. The coating used for the investigations shown in Fig. 2 had a thickness of 70 µm, at this depth the residual stress was -250 MPa.

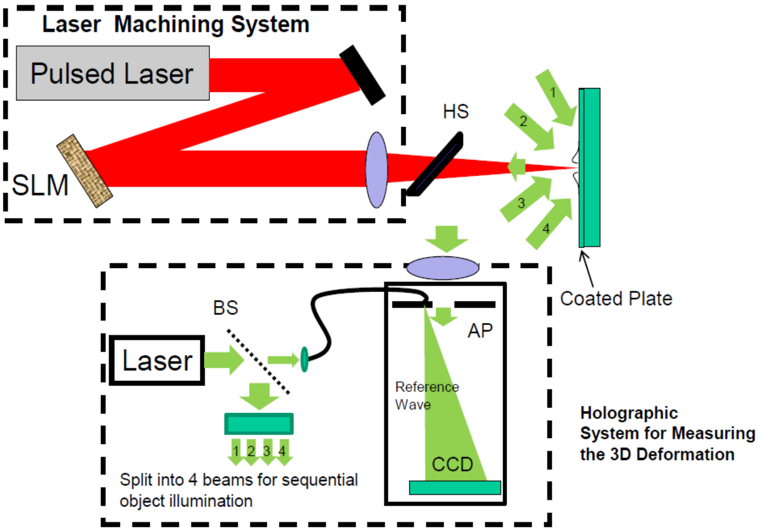

Fig. 1. Setup for laser machining and measurement of the 3D object deformation by digital holography. SLM: Spatial Light Modulator, HS: harmonic separator; BS: Beam splitter; AP: Aperture.

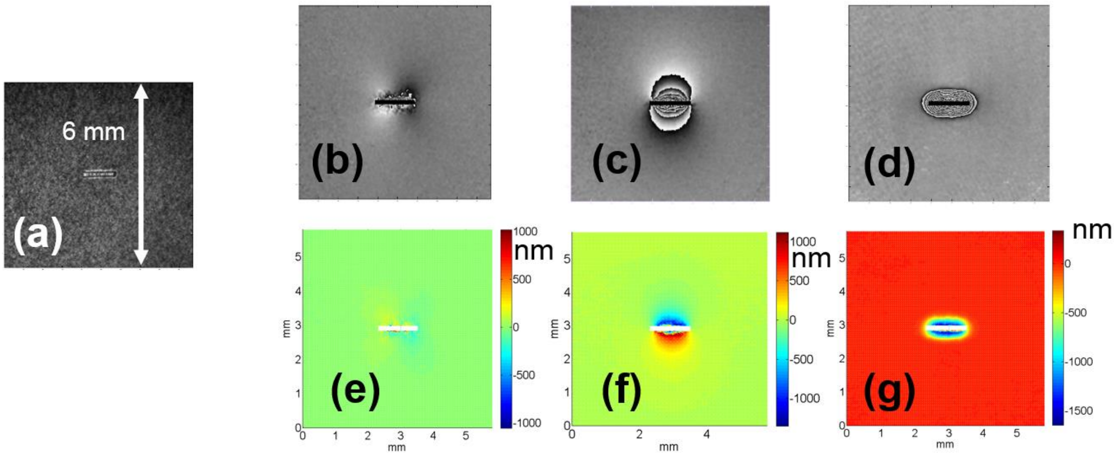

Fig. 2: Image of the bar shaped machined structure after 64000 laser pulses (a). Phase modulo 2π (wrapped phases) and calculated displacements along the x (b, e), y (c, f) and z (d, g).

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References

[1] M. Wenzelburger, D. López, R. Gadow, "*Methods and application of residual stress analysis on thermally sprayed coatings and layer composites*", Surface and Coatings Technology, 201 (5), 1995-2001, 2006.

[2] 4 G. S. Schajer, M. B. Prime, "*Use of Inverse Solutions for Residual Stress Measurements*", J. Eng. Mater. Technol., 125(3), pp. 375-382, 2006

[3] G. S. Schajer, T. J. Rickert, "*Incremental Computation Technique for Residual Stress Calculations Using the Integral Method*", Experimental Mechanics, Vol.51, No.7, pp.1217-1222, 2011.

[4] G. S. Schajer, C. Abraham, "*Residual Stress Measurements in Finite-Thickness Materials by Hole-Drilling*", Experimental Mechanics (2014) 54:1515–1522.

[5] G. S. Schajer, P. S. Whitehead, "*Hole drilling and ring coring*" Chapter 2 in" Practical residual stress measurement methods", Schajer, G.S. (ed), Wiley, Chichester, UK.

[6] S. Seebacher, W. Osten, T. Baumbach, W. Jüptner, "*The determination of material parameters of microcomponents using digital holography*", Optics and Laser in Engineering, 36, 103-126, 2001.

[7] G. Pedrini, W. Osten, and M. E. Gusev, "*High-speed digital holographic interferometry for vibration measurement*", Appl. Opt. 45, 3456-3462, 2006.