RESIDUAL STRESS MEASUREMENTS IN THERMALLY SPRAYED METALLIC COATINGS

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1. ABSTRACT

The performance of thermally sprayed coatings is significantly influenced by residual stresses [1]. In the present research project five different spraying techniques (Vacuum, Atmospheric and Water Stabilised Plasma Spray, Flame Spray and Wire Arc Spray) were applied to manufacture metallic NiCrAlY deposits of diverse types of microstructures. Residual stress measurements were performed by the technique of neutron diffraction at the strain scanner D1A at the Institute Laue-Langevin in Grenoble / France and by bending measurements using laser profilometry [2]. The recently designed set-up at D1A allowed to employ two radially focusing collimators, defining a gauge volume of 0.65x1x10 mm³ [3]. Strain profiles in the substrate and in the deposit of about 1 mm thickness were obtained up to 50/°/g113° near the interface. Estimated average stress values deduced from the neutron strain profile agree with results from bending measurements.

2. INTRODUCTION

A wide range of microstructure as well as spray technique dependent substrate and impact particle temperatures are known to vary significantly residual stress states within thermally sprayed coatings. Deposition thicknesses are often limited by a lack of adhesion due to build up of residual stresses. Knowing macroscopic average stress values as well as stress profiles - especially in the interface region - could help to better optimise the spraying parameters.

To characterise the microstructure of the deposits, one technique employed is small angle neutron scattering. By this method the total specific surface area as well as mean dimensions of the pores and stress induced cracks are determined. It is expected that well characterised void systems allow to relate residual stress states within the deposits to the crack network. Here we focus on the residual stress measurements recently performed at the instrument D1A.

3. EXPERIMENTAL

A commercially available NiCrAlY powder (Ni 67%, Cr 22%, Al 10%, Y 1%) was used as feedstock material and construction steel as substrate material. After cutting the substrates, they were heat treated to relax any stresses. To increase the adhesion, the substrates were grit blasted before the spraying process, as it is usually the case. The sizes of the substrates were 100x25x4.6 mm³. Thicknesses of the coatings varied between 0.95 mm and 1.25 mm. All samples investigated were sprayed by optimised spray parameters.

Through thickness strain measurements were performed at the instrument D1A. The reflections Ni {111} in the deposit and Fe {110} in the substrate were chosen at a wavelength of 2.994 Angstroem to yield 2/°/g113° values near 90° for optimum spatial resolution. The configuration at the strain scanner D1A allows horizontal as well as vertical scans with high lateral resolution of 1 mm. The advantage of vertical scanning is the not existing surface error. When vertically scanning, a long path of the neutrons through the sample material made measurements in the highly absorbing deposits not achievable in a reasonable time. When performing a horizontal scan, strain values from a partially filled gauge volume near a surface have to be corrected for the surface error. However, due to a horizontal movement of the collimator in the primary beam, the artificial peak shift could significantly be reduced to only the geometrical shift at a maximum value of \( \Delta d/d [10^{-6}] = 400 \). The data shown are corrected by an experimental surface error obtained from scanning a stress free powder sample through the gauge volume. The set-up for horizontal sample scans in transmission and reflection mode for strain measurements in the surface plane and perpendicular to it is shown in Figure 1. The sample position with respect to the neutron beam was obtained from the amplitudes of the Bragg peaks of the scan. From this position and the size of the gauge volume, the centre of mass of the scattering material was calculated. Peak
positions were converted into strain values implicitly employing the Bragg law by
\[ \varepsilon = \frac{d_{hl} - d_{hl,0}}{d_{hl,0}} \Delta \theta \cot \theta_k \]  
(1)
where \(d_{hl,0}\) is a stress free reference value obtained from an annealed feedstock powder and eroded free standing samples. The samples were mounted on a translation table and scanned through the gauge volume in steps of minimal 0.1 mm.

To determine macroscopic average stress values, bending measurements were performed by applying laser profilometry. An UBM laser profilometer was used with a resolution of 30 data points per millimetres on the not coated side of the substrate. For each sample analysed three subsequent scans along the extended direction were made: One scan after cutting and annealing, one after grit blasting and a final scan after spraying. An average strain value is obtained by Stoney’s equation for thin coatings:
\[ \sigma_{\text{Deposit}} = \frac{\kappa E_{\text{Subst}} H_{\text{Subst}}^2}{6h_{\text{Deposit}} (1 - \nu_{\text{Subst}})} \]  
(2)
where \(\kappa\) is the curvature parameter obtained by the inverse radius of a circle fitted to the bending data. The curvature is assumed to be introduced by the thermal spray process only. The resulting \(\sigma_{\text{Deposit}}\) is the calculated constant in-plane stress value in the coating. In the case of the here discussed atmospheric plasma sprayed coating the following values were applied: Thickness of substrate and coating: \(H_{\text{Subst}} = 4.6\) mm and \(h_{\text{Deposit}} = 0.95\) mm and elastic modulus and Poisson ratio of the substrate \(E_{\text{Subst}} = 209\) GPa and \(\nu_{\text{Subst}} = 0.33\) [1].

Table 1 contains the curvature data obtained for the APS sample by profilometry. Different signs of the curvature imply a bending of the sample in different directions. The compressive strain introduced by the grit blasting is overcompensated by tensile “quenching” stresses induced during the deposition. From equation (2) a macroscopic average stress in the coating of \(\sigma_{\text{Deposit}} = 221\) MPa is calculated.

### Table 1: Curvature data of the NiCrAlY APS coating obtained from profilometry

<table>
<thead>
<tr>
<th>curvature and annealing</th>
<th>after grit blasting</th>
<th>after spraying</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\kappa [1/m])</td>
<td>(\approx 0)</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

Figure 2 displays the in-plane strain, oriented parallel to the surface, as a function of depth into the coating as well as into the substrate for the Atmospheric Plasma Sprayed NiCrAlY sample. In the coating the strains are tensile and highest at the surface. This can be explained by the fact that the spray process generates tensile quenching stresses in the coating, and that on top no more layers under tensile strain are deposited which could introduce compressive strains in the deeper layers and partly compensate the tensile strains. The data point nearest to the interface is already in the compressive region. In the substrate compressive strain is found near the interface, whereas deeper inside, near the not coated surface, the stresses tend to be tensile. The compressive strain near the interface can be explained by the fact that the tensile stresses in the coating must be balanced by compressive strains inside the substrate.

Figure 1: Set-up employed for horizontal scans in transmission and reflection mode at the powder diffractometer D1A.

4. RESULTS
The strain profile in an Atmospheric Plasma Sprayed deposit and its substrate, determined by neutron strain scanning, is shown in Figure 2. Generally, the strain information obtained by the technique of strain scanning has to be regarded as an average over the region sampled by the gauge volume. This implies that near surfaces the spatial resolution is as high as the gauge volume has penetrated the sample. It is gradually reduced when the gauge volume is more and more filled with diffracting material. In the case of the deposit, the gauge volume even exceeds the deposit thickness and therefore the strain values from the middle of the deposit has to be interpreted accordingly by keeping in mind that all regions of the deposit contribute to this strain information.

Figure 2: Through thickness strain profile in an atmospheric plasma sprayed NiCrAlY deposit and its substrate.
Assuming a biaxial stress model with zero stress component perpendicular to the surface plane (as it is the case in thin coatings) and isotropy in the surface plane, the stress is obtained from the strain by the formula:

\[ \sigma_{\text{Deposit}} = \varepsilon E_{\text{Deposit}} (1 - \nu_{\text{Deposit}}) \]  

(3)

Taking the strain value in a depth of approximately half the thickness of the deposit, \( \varepsilon = 600 \text{E}-6 \), to be an average value of the whole deposit, one obtains, taking the Ni{111} values \( E_{\text{Deposit}} = 233 \text{ GPa} \) and \( \nu_{\text{Deposit}} = 0.29 \) obtained from the Eshelby Kroener model [1], the approximate average stress \( \sigma_{\text{Deposit}} = 196 \text{ MPa} \), which is quantitatively consistent with the value of the curvature measurements.

5. CONCLUSIONS AND PROSPECTS

For an Atmospheric Plasma Sprayed deposit a residual strain profile in the coating as well as in the substrate obtained by the neutron strain scanning is presented and compared with the bending results. As seen from figure 2, the technique of neutron scattering is able to resolve existing gradients - limited by the spatial resolution due to the size of the gauge volume. Quantitative agreement is found with the average macroscopic stress value obtained from curvature measurements within the assumptions made. Particularly stresses near surfaces i.e. at the interface between the substrate and the deposit can be determined, though the data have to be corrected for the surface error.

Measurements on samples manufactured by the remaining spraying techniques will be performed to analyse spray technique specific stress profiles and average stress values with the aim to relate the residual stresses to the microstructure and properties of the deposits. A strong influence between residual stresses and the void structure is expected due to microcracking, depending on the particular spraying technique.

6. ACKNOWLEDGEMENTS

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7. REFERENCES