Microstructure - Property Relationships and Cross-Property-Correlations of
Thermal Sprayed Ni-Alloy Coatings

Nikolaus Margadant, Stephan Siegmann, J. Patscheider
EMPA, Swiss Federal Laboratories for Materials Testing and Research, Thun, Switzerland

Thomas Keller, Werner Wagner
Paul Scherrer Institute, Villigen, Switzerland

Jan Ilavsky
University of Maryland at College Park, College Park, MD, USA

Jan Pisacka
Institute of Plasma Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

Gérard Barbezat
Sulzer Metco AG, Wohlen, Switzerland

Petr Fiala
Skoda Research, Plzen, Czech Republic

Abstract

Relationships between the properties of thermally sprayed nickel based alloys and their microstructure (density, porosity, oxide phase content) are investigated. Cross-property-correlation of physical properties such as electrical conductivity and elasticity were examined. The experimental results of the structures and properties of the different coatings are discussed with respect to their pore surface area obtained by small angle neutron scattering (SANS) measurements.

As wide as possible range of thermally sprayed microstructures of NiCr and NiCrAlY was produced by vacuum - and atmospheric plasma spraying, flame spraying, HVOF and water stabilized plasma spraying. Commercially available powders with process specific grain size distributions were used as feedstock materials resulting in a wide range of microstructures of the coatings depending on the spraying technique and, to much less extent, on the variation of the process parameters.

In this work the examination of the pore structure was carried out by optical microscopy on metallographic cross sections. Phase composition and distribution were investigated by hot gas extraction for oxygen and nitrogen determination and by Scanning Auger Microscopy on polished cross sections and fracture surfaces. The properties of the coatings were characterized by their wear (ASTM G75) behavior, reflecting application-oriented properties.

Significant and varying amount of anisotropy of the coating properties – electrical conductivity and elastic modulus – was found in the sprayed microstructures. This anisotropy could be directly linked to microstructure anisotropy as characterized by Small-Angle Neutron Scattering.

Introduction

Optimization of the coatings for particular application requires finding coatings with proper combination of properties. This usually means, that the microstructure of the deposits needs to be optimized – however, our current understanding of microstructure-properties relationships is limited. This requires use of more complex microstructure characterization tools, such as small-angle neutron scattering - and development of new methods to characterize coating properties.

One of the crucial factors influencing the thermal spray coating properties are the pores - the distribution of their sizes and anisotropy. However, the anisotropy of the coatings including aspect ratio of the pore diameters and their orientation and the (often bimodal) pore size distribution (ranging from a few nm up to several μm) renders the determination by conventional image processing on cross sections difficult. The measured values of structural parameters such as porosity volume, pore internal surface, pore aspect ratio, pore orientation etc. exhibit large experimental uncertainties and depend on the sample preparation, and the experiments with sufficient statistics are
very time-consuming. Therefore combination of microstructure characterization methods needs to be applied to obtain more complex and reliable microstructure image.

Furthermore, predictions of coating properties based on most used microstructural parameters (for example porosity volume) are mostly not quantitative or limited to narrow range of microstructures, such as microstructures produced by one spray technique. However, more general dependencies – relationships across microstructure produced by various thermal spray techniques – are unknown yet.

Another attempt to avoid or reduce the above mentioned experimental difficulties is to handle the structural features theoretically and to carry out the experimental verification by means of cross property correlation only. This would allow for instance to predict a property “A” by measuring other properties “B” and “C”, which are experimentally easily accessible. On the other hand statements about the microstructure could be made by measuring the anisotropy of certain properties.

This work attempts to identify range of properties which could be used to characterize microstructures of the thermally sprayed deposits over as wide range of microstructures as possible. These properties are documented on Ni-based alloy deposits and compared to results of small-angle neutron scattering.

**Experimental**

Commercially available NiCr (80% Ni, 20% Cr) and NiCrAlY feedstock materials were used. The size ranges were selected so they were appropriate for each spraying technique used. As substrates pieces of construction steel with the dimensions 25 x 25 x 5 mm were used for all samples.

<table>
<thead>
<tr>
<th>Powder</th>
<th>Process</th>
<th>Parameter varied</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCr</td>
<td>FS</td>
<td>- (one condition only)</td>
</tr>
<tr>
<td></td>
<td>VPS</td>
<td>chamber pressure or plasma energy</td>
</tr>
<tr>
<td></td>
<td>HVOF</td>
<td>Kerosene flow rate</td>
</tr>
<tr>
<td></td>
<td>APS</td>
<td>spray distance or plasma current</td>
</tr>
<tr>
<td></td>
<td>WPS</td>
<td>- (one condition only)</td>
</tr>
<tr>
<td>NiCrAlY</td>
<td>FS</td>
<td>- (one condition only)</td>
</tr>
<tr>
<td></td>
<td>VPS</td>
<td>chamber pressure or plasma energy</td>
</tr>
<tr>
<td></td>
<td>APS</td>
<td>gas flow rate or gas composition</td>
</tr>
<tr>
<td></td>
<td>WPS</td>
<td>spray distance</td>
</tr>
</tbody>
</table>

**Table 1: Spraying processes and varied spray parameters of NiCr and NiCrAlY powders**

After rounding the edges and grit blasting the substrates were coated by vacuum - and atmospheric plasma spraying (VPS, APS), flame spraying (FS), HVOF and water stabilized plasma spraying (WSP).

For each process at least one of the spraying parameters listed in Table 1 was varied to obtain as wide range of microstructures as reasonably possible with each technique. Therefore not all of the deposits produced by each technique are representative of “standard” deposits routinely manufactured. More likely the results should bound the “field” of microstructures available by this technique.

**Metallography and Microscopy**

Samples were cut by abrasive saw and mounted in cross section in a methyl metacrylate base resin. Samples were metallographically prepared; first ground with SiC papers, then diamond polished and finished with colloidal silica. Samples were observed by means of optical microscopy.

**Porosimetry**

In a first step the density of the coatings was determined by a layer removal method. The samples were cut into pieces of approx. 17 by 17 mm with sharp edged cut perpendicular to the substrate surface.

The specific density was established from measurements of weight loss and the loss of thickness of a sample (coating on the substrate) before and after grinding away a certain volume.

Several samples were mounted on a magnetic table and the coatings were first ground to obtain a perfect parallel and smooth surface. These sample were precision weighted and their thickness was measured. Then a layer of deposit was ground away. Samples were again precision weighted and thickness measured.

The area of the coating was determined by performing the same procedure as for the coating within its substrate. The substrate density was determined by Archimedes buoyancy method. From these area, the thickness and the weight loss of the removed layer the density of the coating was calculated.

For the calculation of the porosity a three phase model was assumed: a metallic phase, an oxide phase and pores. The metallic phase density was assumed to be equal to the powder density which was measured by helium pyknometry. The amount of oxygen was determined by means of hot gas extraction. The samples were heated up to approx. 2500°C and the oxygen was measured as CO₂ by infrared detection, the nitrogen content was quantified by conductivity measurement of the extracted N₂. The oxides were assumed to be mainly chromium oxide (as confirmed by the Auger measurements) with a density of 5.21 g/cm³ [1]. The pores were assigned density of zero. The porosity was calculated based on these powder, oxide and pore densities, the overall density and the oxide weight percentage. The oxides, with lower density than the bulk material, would significantly reduce the apparent porosity of the coating.
Wear Testing
NiCr and NiCrAlY samples were tested according to ASTM standard G75 [2]. The samples were cut to a size of approx. 12.7 by 25.4 mm, chamfered and tested in a slurry of alumina abrasive which was used dispersed in distilled water. The weight loss depending on the wear time respectively the sliding distance was determined. For the calculation of the wear rate the first two data points were not considered because the coating surface was not polished and a certain running-in period was required to achieve a steady state in evenness and roughness of the samples. From each process and parameter setting at least two samples were tested and the given values represent the average wear rate obtained by the weight loss versus sliding distance curve assuming a linear behavior.

Ultrasonic Testing
The sound velocity of NiCr coatings parallel and perpendicular to the substrate surface were determined by ultrasonic measurements on three different setups (Figure 1): pulse-echo mode, transmission mode and contact mode as required by sample properties.

Figure 1 shows schematically the experimental setup of the samples and the transducers for the ultrasonic measurements. The pulse-echo-mode parallel and perpendicular to the substrate surface and the transmission mode were applied on adherent and freestanding coatings.

![Figure 1: Scheme of ultrasonic measurements by pulse-echo perpendicular (A) and parallel (B) and by transmission mode perpendicular (C) and parallel (D) to the substrate surface.](image)

The values for the sound velocities were obtained as the average from two measurements. The values of the elastic modulus E, the shear modulus G and the Poisson ratio ν were then calculated straightforward from the sound velocities and the density data according to formulas given below [3]

\[
\mu = \frac{1}{2} - \left( \frac{c_T}{c_L} \right)^2
\]

\[
G = \rho c_T^2
\]

\[
E = 2G(1 + \mu)
\]

If possible the elastic constants in both directions were determined by measuring run time of pulse-echo from the LL-peak (longitudinal-longitudinal) wave and the run time of the echo of the LT-peak (longitudinal-transversal) by immersion technique.

For the pulse-echo measurements the coated samples of 25 x 25 mm were cut in pieces of approx. 18 x 18 mm, the upper surface of the coating was ground by SiC abrasive and parallel to one edge a thin slot was cut through the coating in the substrate in order to obtain an isolated coating strip of approx. 2 mm in thickness without delaminating it (Figure 1).

If the peak resulting from the substrate-coating interface could not be detected anymore because of the attenuation, the coatings were delaminated by wire-electro discharge machining to make a contact mode or transmission mode measurement possible without any influence from the substrate. A machine tool from Charmilles Technology was used with a wire of 250 µm in diameter and a feed rate of 3 mm per minute. Half of the wire cross section cut the substrate, the other half crossed the coating in order to obtain a maximum thickness of a freestanding coating without any interfacial zone.

A selected choice of NiCr coatings sprayed by different techniques under variation of the parameter settings (Table 2) was tested to obtain a wide range of elastic properties.

<table>
<thead>
<tr>
<th>Coating/ Orientation</th>
<th>Immersion technique</th>
<th>Contact mode</th>
<th>Pulse-Echo</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS ( \perp )</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>FS ( | )</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VPS ( | ) ( | )</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>APS ( | ) ( \perp )</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HVOF ( \perp )</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HVOF ( | )</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Experimental setup for ultrasonic measurements parallel (\( \| \)) and perpendicular (\( \perp \)) to the substrate surface.
For the immersion technique an ultrasonic scanner from Ultrasonic Sciences Ltd. was used with 20 MHz transducers from Harisonic Type I3-2004-R with 25 mm focus distance. In contact mode a Krautkrämer USIP 2 apparatus was used in combination with 10 MHz Harisonic transducers type HLI-CM1002 and 20 MHz transducers from Panametrics type V212BB.

Electric Conductivity Measurements
The electric conductivity was measured by a 4-electrode technique on thin sections of the samples. NiCr samples were cut to strips of a thickness of approx. 3 mm which were subsequently plane ground to a thickness of approx. 1 mm with parallel section plane on a magnetic table. The samples were subsequently embedded in resin and ground and polished to a final thickness of approximately 300 μm. The embedded samples were slit by a diamond filament saw with a wire diameter of 140 μm at a minimum thrust (Figure 2) in order to produce electrically insulated strips. The strips for the measurements perpendicular to the substrate surface had a width of approx. 300 μm, whereas the coating strip for the measurements parallel to the substrate surface had a width slightly below the coating thickness.

The potential difference under direct-current was measured by a digital wave prober from Karl Suss company with a Keithley 2002 multimeter. The sharp tungsten electrodes were positioned under an optical microscope and mechanically pressed in the sample surface. All electrodes were aligned in one line. The outer two electrodes were current-bearing while the inner two electrodes in between were used for the voltage tap over the electrode distance d.

One voltage electrode was shifted stepwise across the surface and the specific resistance was calculated from the slope of the curve obtained of overall resistance R versus the electrode distance d assuming a behavior according to Ohms law within the coating material. A current of 7.183 mA was applied and the measured resistivity was the average of 10 cycles. The precise thickness of the strip was determined after the measurements on its cross sections.

![Figure 2: Scheme of the samples for the electric conductivity measurements a) perpendicular and b) parallel to the substrate surface.](image)

In the case of the measurements perpendicular to the substrate surface one of the current electrodes was placed within the substrate and the other in the coating (Figure 3). One of the voltage electrode was placed on top of the coating, the other voltage electrode was shifted across the substrate in the coating.

For the conductivity measurements parallel to the substrate surface all electrodes were located on the electrically insulated strip of coating.

![Figure 3: Arrangement of the electrodes for conductivity measurements on an insulated strip in the direction perpendicular to the substrate surface.](image)

Results

Microscopy
In Figure 4 to Figure 8 the ground and mechanically polished cross sections of NiCr coatings are shown including the coating – substrate interface. For each coating process and coating material only one example is given which represents the deposit manufactured with spraying parameters close to the standard settings. All the images of the NiCr coatings have the same magnification factor to render the structure more comparable. All micrographs show coatings in the as sprayed state without any additional pre or post treatment.

![Diagram](image)
In Figure 9 to Figure 12 the analogous cross sections of the NiCrAlY coatings are shown all at the same but lower magnification than the NiCr coatings.
Porosity and Wear
Table 3 presents the values of the density, the oxygen content, the calculated porosity and the wear rate of the NiCr coatings and in Table 4 and Figure 13 the corresponding values of the NiCrAlY coatings are given. The oxygen content of the NiCrAlY deposits is under investigation at this time, but preliminary results show, that it is low (below 1 wt%) for all measured samples. For the NiCr coatings the relative accuracy of the weight percentage of oxygen is in the range of ±3 % (FS) up to ±13 % (VPS). The error of the density is estimated to be below 1 %.

<table>
<thead>
<tr>
<th>Process</th>
<th>Parameter</th>
<th>Density [g/cm³]</th>
<th>Oxygen-Content [wt.-%]</th>
<th>Porosity [%]</th>
<th>Wear Rate [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS</td>
<td>a</td>
<td>7.079</td>
<td>4.66</td>
<td>7.0</td>
<td>0.1254</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>6.774</td>
<td>5.66</td>
<td>9.5</td>
<td>0.1135</td>
</tr>
<tr>
<td>VPS</td>
<td>a</td>
<td>7.732</td>
<td>0.24</td>
<td>6.1</td>
<td>0.2127</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>7.890</td>
<td>0.24</td>
<td>4.1</td>
<td>0.2184</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>7.625</td>
<td>0.27</td>
<td>7.3</td>
<td>0.2061</td>
</tr>
<tr>
<td>HVOF</td>
<td>a</td>
<td>7.804</td>
<td>0.26</td>
<td>5.2</td>
<td>0.1730</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>7.985</td>
<td>0.25</td>
<td>3.0</td>
<td>0.1968</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>8.068</td>
<td>0.29</td>
<td>1.9</td>
<td>0.1462</td>
</tr>
<tr>
<td>APS</td>
<td>a</td>
<td>7.364</td>
<td>2.98</td>
<td>6.0</td>
<td>0.1524</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>7.356</td>
<td>2.99</td>
<td>6.1</td>
<td>0.1665</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>7.347</td>
<td>2.57</td>
<td>6.9</td>
<td>0.1490</td>
</tr>
<tr>
<td>WPS</td>
<td>a</td>
<td>6.767</td>
<td>6.26</td>
<td>8.6</td>
<td>0.0731</td>
</tr>
</tbody>
</table>

Table 3: Density, oxygen content, porosity and wear rate of NiCr 80/20 coatings.

According to the helium pyknometry the average density of the NiCr powder was 8.2674 g/cm³.
Figure 13: Wear rate of NiCrAlY coatings produced by different spraying techniques with 3 different spraying parameters (except flame spraying FS).

The density of the NiCrAlY powder was 7,254 g/cm³ for the grain size < 38 μm and 7,247 g/cm³ for the grain size –106 +53 μm. The density of the substrate determined by the Archimedes buoyancy method was 7,868 g/cm³.

The weight was measured by an accuracy of ± 0.005 mg for density and wear rate measurements. The linear behavior of the slope in the wear curve is reflected in a correlation coefficient of 0.98 or better.

The variation in wear rate of two similar samples is in the range of ±2% up to ±12% depending on the spraying technique.

<table>
<thead>
<tr>
<th>Process</th>
<th>Parameter</th>
<th>Density [g/cm³]</th>
<th>Porosity [%]</th>
<th>Wear Rate [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS</td>
<td>a</td>
<td>6.404</td>
<td>11.4</td>
<td>0.0768</td>
</tr>
<tr>
<td>VPS</td>
<td>a</td>
<td>6.875</td>
<td>3.9</td>
<td>0.0950</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>6.889</td>
<td>4.6</td>
<td>0.0886</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>6.914</td>
<td>4.1</td>
<td>0.1073</td>
</tr>
<tr>
<td>APS</td>
<td>a</td>
<td>6.625</td>
<td>8.1</td>
<td>0.1222</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>6.494</td>
<td>9.9</td>
<td>0.1295</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>6.619</td>
<td>8.4</td>
<td>0.1366</td>
</tr>
<tr>
<td>WPS</td>
<td>a</td>
<td>6.368</td>
<td>11.9</td>
<td>0.0580</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>6.451</td>
<td>10.9</td>
<td>0.0711</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>6.566</td>
<td>9.3</td>
<td>0.0736</td>
</tr>
</tbody>
</table>

Table 4: Density, porosity and wear rate of NiCrAlY coatings.

Ultrasonic Measurements
Various ultrasonic techniques were needed for measurements of the different samples and different orientations. This was caused by significant variations of the coating properties and shows high variability of the thermally sprayed microstructures.

If the signal of the transversal wave was to weak to be detected, a Poisson ratio of 0.265 was assumed to calculate the elastic constants.

Currently available results show, that wide range of microstructures manufactured in this project resulted in wide range of measured properties found by ultrasonic measurements.

Elastic moduly measured in direction perpendicular to the substrate surface varied for the different spraying techniques between about 30 and 150 GPa, shear moduly in the same direction varied between 13 and 60 GPa.

Elastic moduly measured in direction parallel with the substrate surface varied between 60 and 170 GPa, shear moduly in the same direction varied between 24 and 67 GPa.

The discussion of the absolute values of the measured moduly is beyond the scope of this paper, however, the anisotropy of the elastic moduly and its relationships to other properties and microstructure characterization are presented. The anisotropy of the measured elastic moduly is presented, together with other data in Table 5.

Electric Conductivity
An example of typical data from measurement the resistivity versus electrode distance of one of the samples perpendicular to the substrate surface is shown in Figure 14. The curve reflects both, the conductivity of the substrate and the conductivity of the coating itself.

![Figure 14: Resistivity measurements perpendicular to the substrate surface for an APS NiCrAlY sample.](image)

In Figure 15 the corresponding resistivity of the coating versus electrode distance parallel to the substrate surface is plotted.
Figure 15: Resistivity measurement within a NiCrAlY coating parallel to the substrate surface.

The specific resistivity values were calculated by the linear slope of the curve shown in Figure 14 and Figure 15 the width and the thickness of the coating strip and by the electrode distance d. The precision of the resistance measurements by the multimeter is around ± 0.5 μΩ. The error due to the fluctuation in sample cross sectional area and by the inhomogeneity of the electric field is estimated to be at least ± 10 %.

The values for both directions (parallel and perpendicular to the substrate surface), were divided to obtain their anisotropy ratio listed in Table 5. These values are complemented by the surface area anisotropy ratio expressed as aspect ratio of the ellipsoid fitted on the apparent porod surface area distribution measured by means of small angle neutron scattering (SANS) on samples from the same batch of sample material [4], [5].

\[
\begin{array}{cccc}
\rho_{\parallel} & \rho_{\perp} \\
0.9 & 1.1 & 1.2 & 1.1 \\
3.1 & 1.4 & 2.0 & 1.4 \\
3.8 & 1.4 & 2.0 & 1.9 \\
8.6 & & & 2.6 \\
\end{array}
\]

Table 5: Comparison of microstructure anisotropy of NiCr coatings (expressed as SANS surface area anisotropy) and anisotropy of the electrical resistivity, anisotropy of the ultrasound waves speed and anisotropy of the elastic modulus calculated from ultrasonic measurements.

Discussion

The presented results show wide variability of the microstructures which can be obtained by various thermal spray techniques. Micrographs in Figure 7 to Figure 12 show that each of the microstructures seems to be dominated by different microstructural features – apart from common lamellar structure.

For the NiCr material the coatings manufactured by FS and WSP indicate large amount of oxides, confirmed by measurements of oxygen content (Table 3). Other techniques (VPS, HVOF) seem to exhibit much “cleaner” microstructure concerning oxides and large voids. The variation of oxygen in this material measured by hot gas extraction (Table 3) is significant – range is about 0.24 wt.-% to about 6.3 wt.-%.

Such variation should have large influence on the mechanical properties of the deposits. The overall variation of mechanical properties (wear) is about 3 times with the lowest wear loss having the samples with the highest oxide content. However, the data in [4] indicate that there is a complex relationship with the measured microstructure characteristics. Therefore the current work attempts to complement the data with more detailed results on the NiCr deposits and with data on NiCrAIY deposits.

The NiCr coating microstructure anisotropy was characterized by small-angle neutron scattering. The results of the absolute specific surface area measurements was presented in [4]. However, more detailed analysis of the results of these SANS measurements allow now to characterize the microstructure anisotropy by the anisotropy of the apparent Porod surface area distribution [5]. These values are included in Table 5. Generally isotropic microstructure would exhibit the SANS surface area anisotropy value of 1, highly anisotropic microstructure would exhibit values far from 1, lower or larger
than 1 depending on which void system is dominating the surfaces in the microstructure.

Table 5 indicates, that for the NiCr coatings there is a direct relationship between the microstructure anisotropy and the cross properties of the coatings – the anisotropy of the electric conductivity and elastic modulus respectively. The nearly isotropic microstructure (first column in Table 5) shows also nearly isotropic electric conductivity and elastic modulus. Highly anisotropic microstructure (last column) shows also significant anisotropy of the electrical conductivity and elastic modulus. The sensitivity of these two measured properties of deposits to the microstructure anisotropy is different. This may be attributed to the fact that the difference of the elasticity of the metal and oxide phase is relatively small. The elastic modulus of a NiCr 80/20 is around $E=213$ GPa [6]. The E-modulus of chromium oxide in sputtered thin films shows values in the range of 100 GPa up to 325 GPa [7], while the bulk modulus of NiO is reported to be as high as 191 GPa [8]. In contrast, the specific electric resistance of NiCr 80/20 at $20^\circ C$ is 0.000112 $\Omega$cm [9], while the specific resistance of chromium oxide is in the range of $10^{-6}$ $\Omega$cm [10]. Figure 16 suggests that the electric conductivity is much more sensitive than the elasticity to the void system, secondary oxide phases and to the anisotropic structure of the coating in general.

Further evaluation of relationships between the microstructure characteristics and coating properties for this material is ongoing. The experimental methods refined in order to elucidate cross properties and anisotropy of thermally sprayed metallic coatings and to obtain a statistically relevant amount of data. In a further step the transferability of these data to theoretical models of transversely isotropic solids with nonspherical cavities as reported in [11], [12] will be examined.

NiCrAlY coatings were selected as further test material to extend systematically the range of microstructures. As mentioned above, the oxygen level in this material is generally lower for all of the samples. Therefore the properties of the deposits should be governed by the voids microstructure and not by presence of another oxide phase.

The currently available data on the NiCrAlY coatings are presented in the Figure 9 to Figure 12 where the optical microstructures are presented. Table 4 presents also density and porosity measurements obtained on the NiCrAlY deposits. The range of porosity values (about 4% to about 11.4%) is higher than the range of results obtained on NiCr deposits (4% to 9.5% without HVOF samples) – with lower overall oxide content. Note that at this time samples of NiCrAlY manufactured by HVOF system have not been tested so far. The SANS characterization of NiCrAlY deposits were utilized. These methods indicate presence of the significant anisotropy of the NiCr deposits electrical conductivity as well as the elastic modulus. This anisotropy seems to be directly related to the microstructure anisotropy, as characterized by small angle neutron scattering.

More complex evaluation should be possible on the samples of NiCrAlY, being now characterized in the project. These samples, due to their lower oxygen content, should exhibit simpler relationships between the microstructure and properties.

The relationship between the anisotropy of the electrical and mechanical properties indicates, that it may be possible to find cross correlation which would allow to measure one of the properties to estimate the second. The evaluation of these relationships are currently underway in this project and the complementary analytical methods are applied to the different coatings to obtain a statistically relevant set of data over the whole range of microstructures. These results should lead to a more general understanding between the microstructure, the properties and the cross property correlation of the coatings, so that it may be possible to model the microstructure – properties relationships and therefore enable engineering design of the microstructure for specific applications.

**Summary and Conclusion**

Several methods characterizing the electrical and mechanical properties of the thermally sprayed NiCr and NiCrAlY deposits were utilized. These methods indicate presence of the significant anisotropy of the NiCr deposits electrical conductivity as well as the elastic modulus. This anisotropy seems to be directly related to the microstructure anisotropy, as characterized by small angle neutron scattering.

**Acknowledgements**

Authors gratefully acknowledge the ultrasonic measurements from J. Neuenschwander and the resistivity measurements from R. Brönnimann, both from the EMPA Dübendorf, Switzerland. We would like to acknowledge partial support from Eureka / KTI grant agencies obtained under project Σ!1973 “Thermetcoat”.

**References**

2. ASTM G75, Standard Test Method for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number), ASTM, Philadelphia, PA 19111-5094, USA
5. T. Keller, W. Wagner, J. Illavsky, N.Margadant, S. Siegmann et. al., Microstructural Studies of Thermally


