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To cite this article: J Schubert and Z Česánek 2017 *J. Phys.: Conf. Ser.* **843** 012007

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Fracture evaluation of thermally sprayed coatings in dependence on cohesive strength

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Abstract. Measuring the cohesive strength of thermally sprayed coatings is relatively difficult matter, which can be accessed in many directions. This issue is nowadays solved by use of Scratch test method. This method is not completely sufficient for the cohesive strength testing because the coating is under load of combined stresses during the Scratch test. The reason to develop this method was need for exact measurement of tensile cohesion toughness of thermally sprayed coatings, which could provide results as close to a classic tensile test as possible. Another reason for development of this method was the impossibility of direct comparison with results obtained by other methods. Tested coatings were prepared using HP / HVOF (Stellite 6, NiCrBSi, CrC-NiCr and Hastelloy C-276). These coatings were selected as commonly used in commercial sector and also on because of rising customer demand for ability to provide such coating characteristics. The tested coatings were evaluated in terms of cohesive strength (method based on tensile strength test). Final fractures were evaluated by optical microscopy together with scanning electron microscopy and EDS analysis. As expected higher cohesive strength showed metallic coatings with top results of coating Stellite 6. Carbide coatings showed approximately third of the cohesion strength in comparison with metal based coating.

1. Introduction

This paper is based on research which was conducted with aim to develop simple and fast method allowing to measure cohesive strength of coatings. Another condition was that the method has to be able provide reputable results with low costs. The study is part of more complex research focused on influence of coating on mechanical properties of substrate material (mainly fatigue life).

Reason for development of such method was demand of customers which asks for precise specification of mechanical properties of coatings used commercially.

The method described further in this paper proved to fulfil all requirement and is able to provide all necessary data together with sufficient repeatability. There are few drawbacks related to measurement of carbide based coatings which leads to a slightly higher volatility of measured results. The reasons for this deviation are described further in this paper.

This issue is nowadays solved by use of Scratch test method [1] which is not completely sufficient for such kind of testing. The demand was for test as close to standard tensile testing as possible. As it was mentioned above, this method will be used with combination with other mechanical properties evaluation processes. This complete overview of properties is necessary to determine the influence of coatings on fatigue life of coating/substrate system. As it is clear, there are many factors affecting fatigue life. One of them is residual stress mainly located around interface between coating and substrate



material. This factor can also play role in affecting nucleation of cracks in case of cohesive (tensile) stress test [2,3,4].

Furthermore, cohesive strength is one of at the most influencing factor determining wear mechanism of coated parts and it is possible to find correlation between them [5].

2. Experiment

The following paragraphs describes design of experiment samples and the method they were used.

2.1. Experimental equipment

Selected coatings were tested on cohesion strength properties using newly constructed device. The method is based two cylindric arts inserted in to each other (shown in Figure 1). During the spray process both parts of the sample are tightened together by threaded bolt. Dividing plane are coated with appropriate coating in 40 mm width and with 400 μm thickness. Afterwards the sample is subjected to tensile test (in this case provided by device ZWICK Z250 in laboratories of VZÚ Plzeň). Design of this sample together with appropriate sample mounting should provide elimination of shear force during the test procedure.

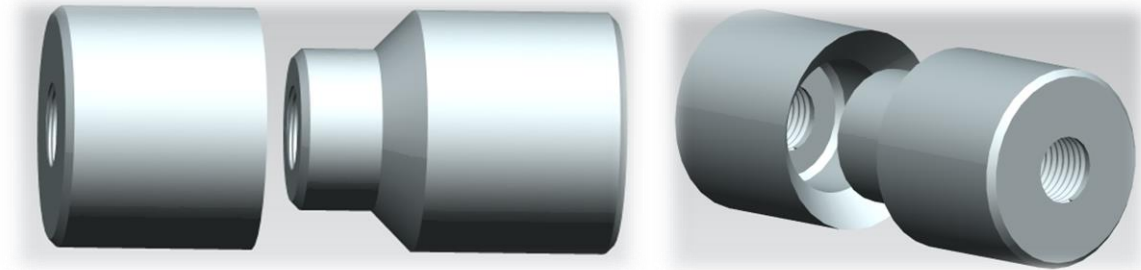


Figure 1. Design of test sample.

The coatings were deposited by system HP/HVOF TAFA JP5200 in laboratories of VZÚ Plzeň using previously optimized parameters. Material of substrate samples was 316L stainless steel. Before coating process samples were degreased and grit blasted with brown corundum (with particle distribution F22).

After the tensile tests the samples were further examined. First of all, the microstructure of each coating was captured and evaluated by scanning electron microscopy (SEM – FEI Quanta 200). The fracture surface was examined using Dyno-Lite AM7000 portable microscope.

2.2. Measurement conditions

The measurement conditions during tensile test were as follows:

- Preload 10 MPa
- Load sped 0,0001 1/s

3. Results and discussion

Each of the selected coatings were sprayed using standard pre-optimized parameters which are used for commercial contract and thus are the most representative for further testing and properties evaluation. Powders used for deposition of selected coatings are commercially available and this paper uses the designation according to company Flame Spray Technologies.

3.1. Scanning electron microscopy evaluation

The reason to analyse microstructure was to prove that the samples were prepared under same conditions as commercially produced coatings, and to prove that there is no difference between test sample microstructure and commercially produced microstructure of coating. Difference in microstructure (pores, particle distribution, etc.) would lead to not corresponding results. All tested coatings prepared for this experiment shown satisfactory comparable microstructure with our standards. Examples of individual microstructure in cross-section is shown in following figures (figure 2-5).

3.1.1. $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating

Commercially available carbide based powder (FST 588.071) was used for deposition of this coating. Following figures (figure 2) represent microstructure captured by SEM microscopy. The resulting microstructure was acknowledged as suitable and identical to commercially produced coatings.

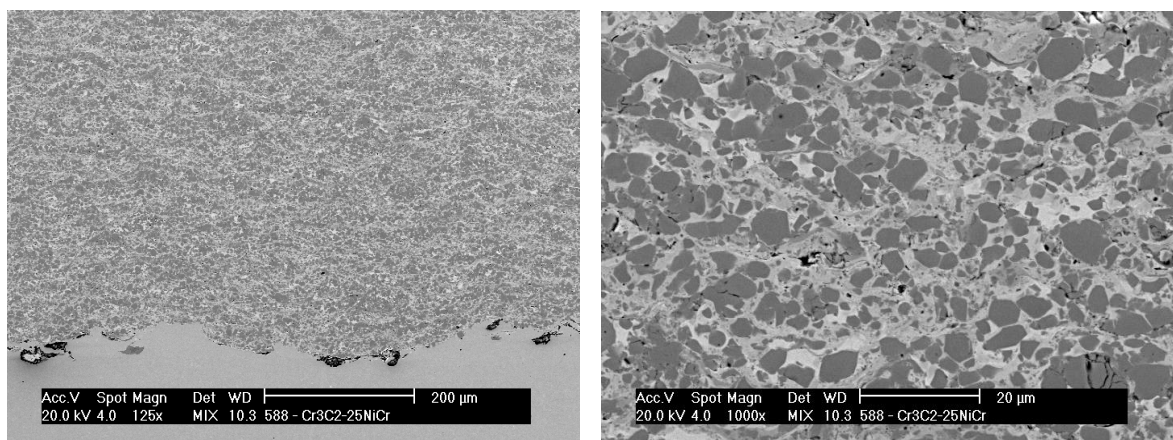


Figure 2. CrC-NiCr coating microstructure cross-section; b) 125 magnification, a) 1000 magnification.

3.1.2. *Hastelloy C-276* coating

Commercially available alloy based powder (FST 341.33) was used for deposition of this coating. Following figures (figure 3) represent microstructure captured by SEM microscopy. The resulting microstructure was acknowledged as suitable and identical to commercially produced coatings.

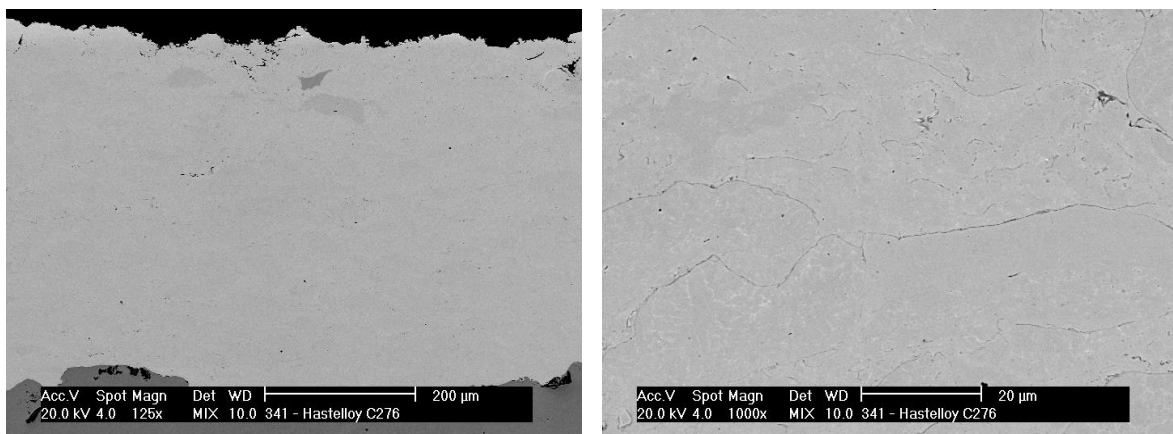


Figure 3. *Hastelloy C-276* coating microstructure cross-section; b) 125 magnification, a) 1000 magnification.

3.1.3. NiCrBSi coating

Commercially available alloy based powder (FST 771.33) was used for deposition of this coating. Following figures (figure 4) represent microstructure captured by SEM microscopy. The resulting microstructure was acknowledged as suitable and identical to commercially produced coatings.

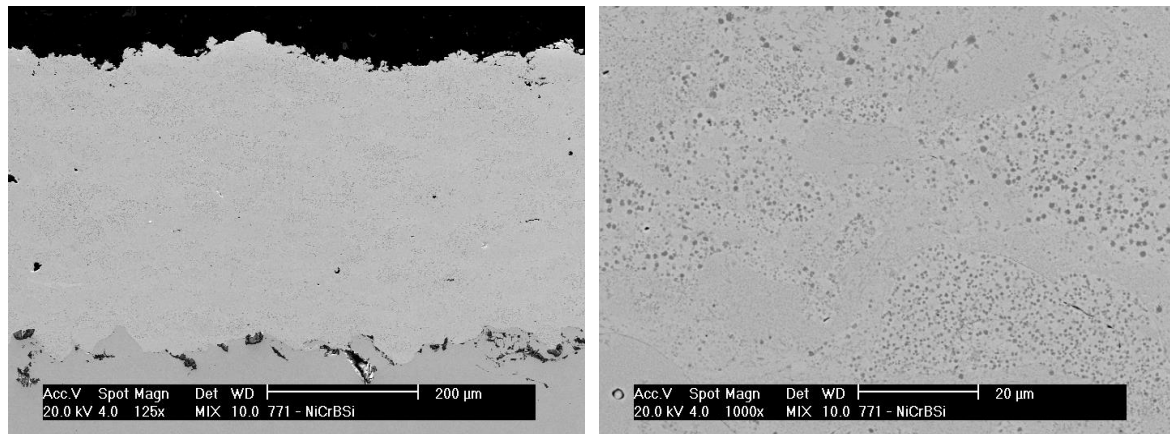


Figure 4. NiCrBSi coating microstructure cross-section; b) 125 magnification, a) 1000 magnification.

3.1.4. Stellite 6 coating

Commercially available alloy based powder (FST 484.33) was used for deposition of this coating. Following figures (figure 5) represent microstructure captured by SEM microscopy. The resulting microstructure was acknowledged as suitable and identical to commercially produced coatings.

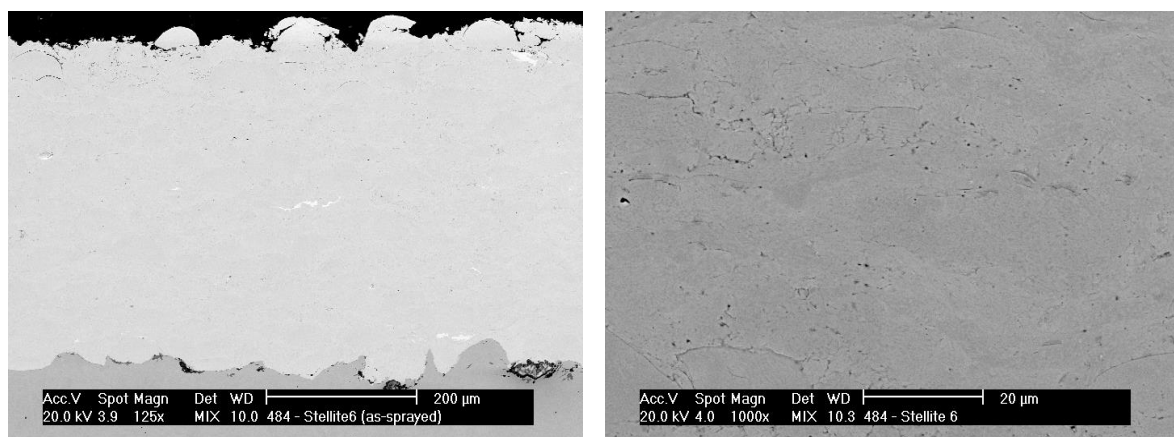


Figure 5. Stellite 6 coating microstructure cross-section; b) 125 magnification, a) 1000 magnification.

3.2. Cohesion strength test

Following section of this paper represents results of cohesion strength testing conducted according to previously mentioned parameters. Figures 6-9 represents results of cohesion strength testing of each selected coating separately. Results of average values for each coating are provided in table 1 and figure 10. Each coating was tested seven times to ensure relevant results. The lowest and the biggest

value obtained for each and single coating was excluded. This procedure should ensure more accurate results. Results of coating CrC-NiCr (see figure 5) were the most volatile from all measurements. Also, this coating shown lowest cohesive strength from all tested materials. The reason of this results is the most inhomogeneous microstructure of all tested coatings (as shown in figure 2). Carbide particles embedded in metallic matrix acts as tension concentrator and serves as initiator of fracture cracking.

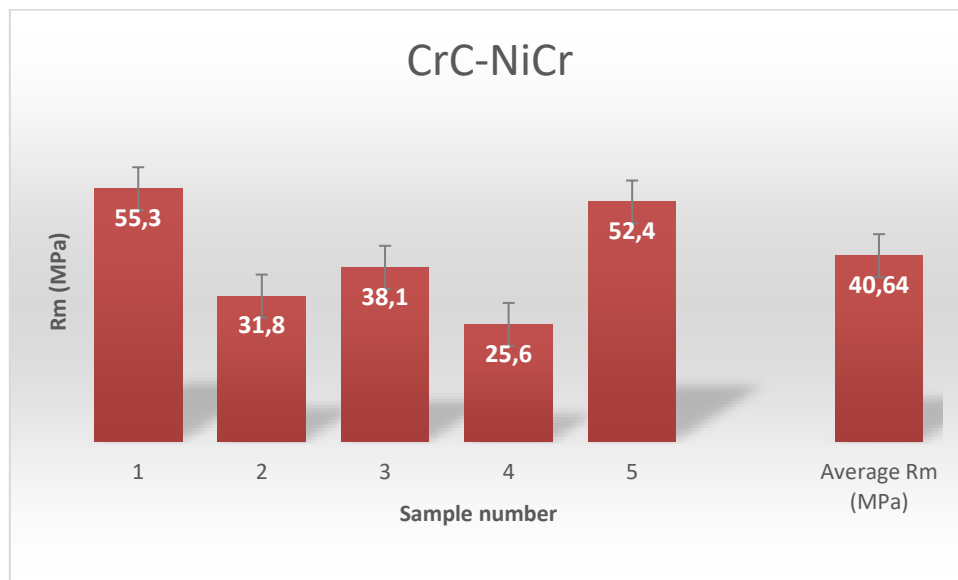


Figure 6. Cohesive strength results of coating $C_{3r2}C$ -NiCr.

Coating Hastelloy C-276 (results shown in figure 6) provided lower results than expected but with low deviation. Expectations ranged to be somewhere around Stellite 6 results (displayed further in this paper). The reason for this behaviour is still unclear because even the microstructure (figure 3) is fine and homogenous. Causes of this behaviour will be further examined.

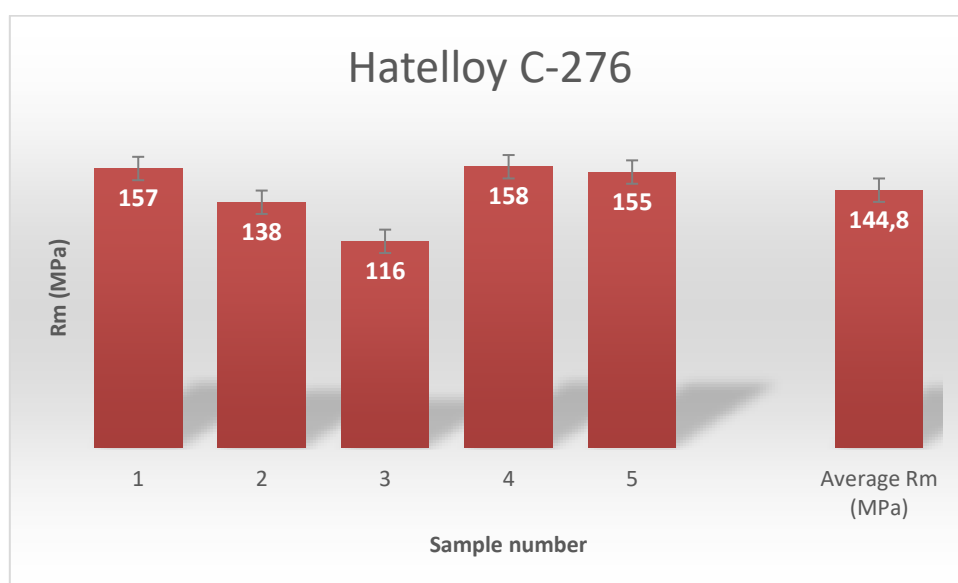


Figure 7. Cohesive strength results of coating Hastelloy C-276.

Alloy based coating NiCrBSi (figure 7) showed average values between all tested coatings with decent result deviation. It is expected that reason for lower values of this coating is formation of new structures in microstructure (figure 4).

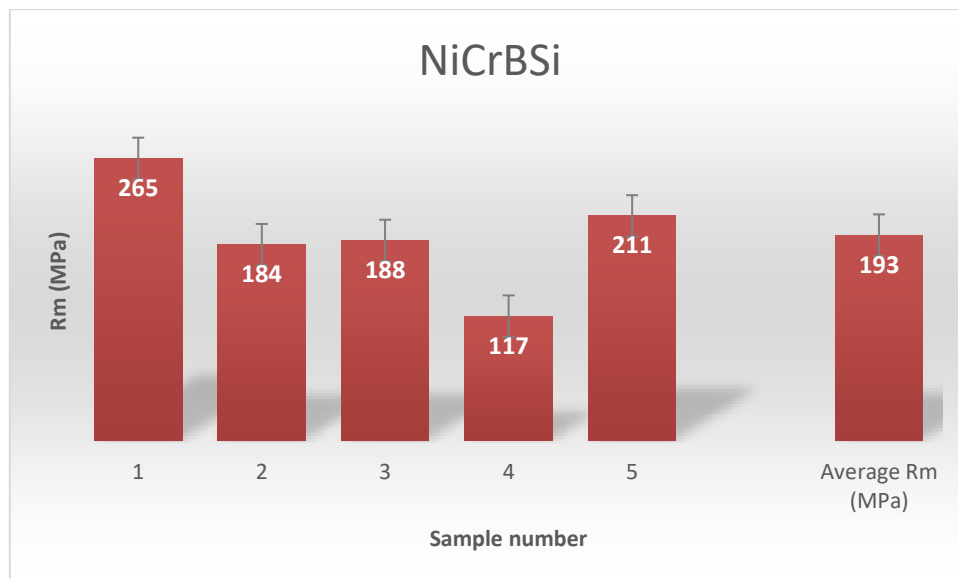


Figure 8. Cohesive strength results of coating NiCrBSi.

Last but not least alloy based coating Stellite 6 (figure 9) provided best results according to expectance. Low deviation of values ensures reproducibility of the test. This results also points at well done optimisation of thermal spray process ensuring fine microstructure with low share of flaws and defects.

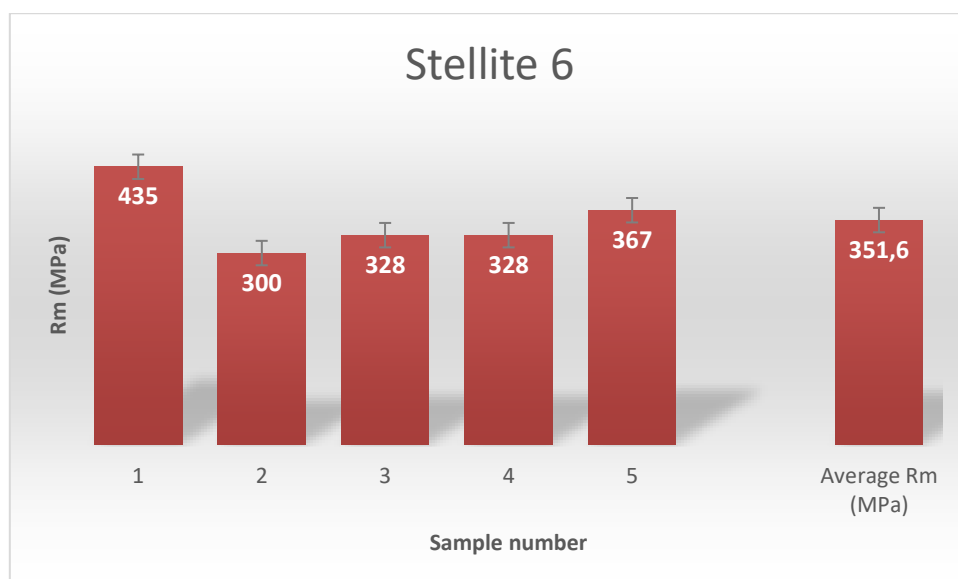
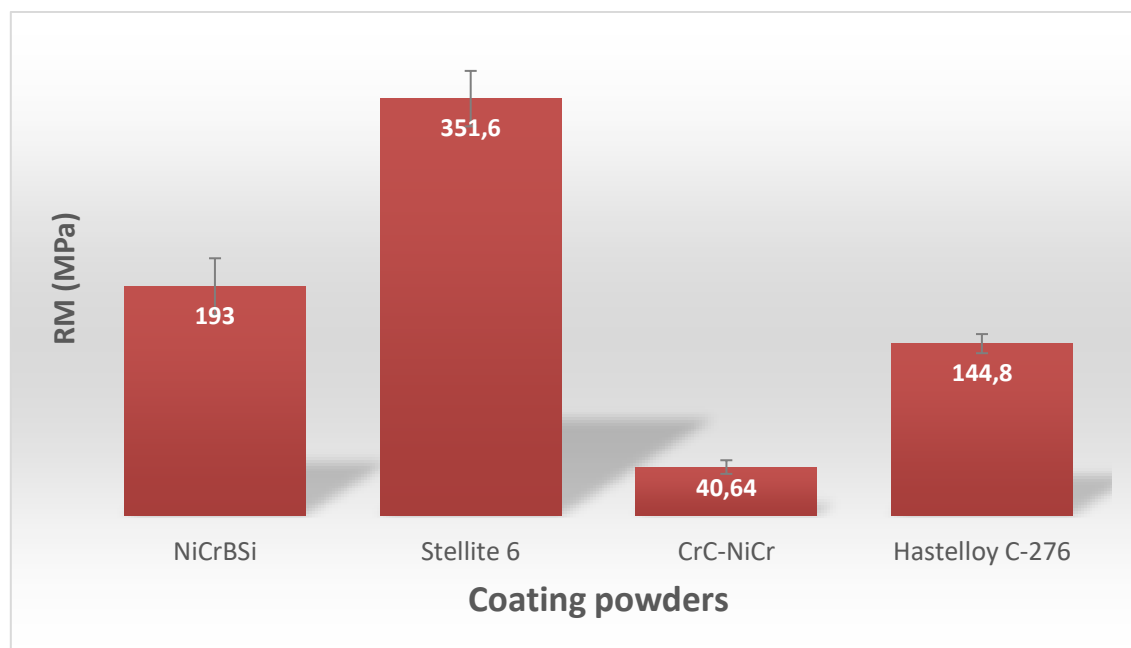


Figure 9. Cohesive strength results of coating Stellite 6.

Table 1. Cohesive tensile strength average values.

Coating	Rm (MPa)	Standard deviation
NiCrBSi	193	23,8
Stellite 6	351,6	23,4
CrC-NiCr	40,6	5,7
Hastelloy C-276	144,8	8,0

**Figure 10.** Comparison of average cohesive strength of tested coatings.

3.3. Fracture surface

Following paragraph is focused on example of characteristic representatives of two fracture surfaces. Figure 11a shows fracture surface of alloy based coating Hastelloy C-276. Each of tested alloy based materials exhibited same fracture surfaces and it is redundant to display all of them. The picture also shows fragile fracture mechanism with small plastic areas. This behaviour is based on microstructure of coating which is mainly consisted from splats mechanically bonded together.

On the other hand, carbide based coating CrC-NiCr is great representative of this category of coatings. Figure 11b shows fracture surface of this coating and it is clear, that the mechanism of cracking is plainly based on fragile cracking together with splatation and delamination.

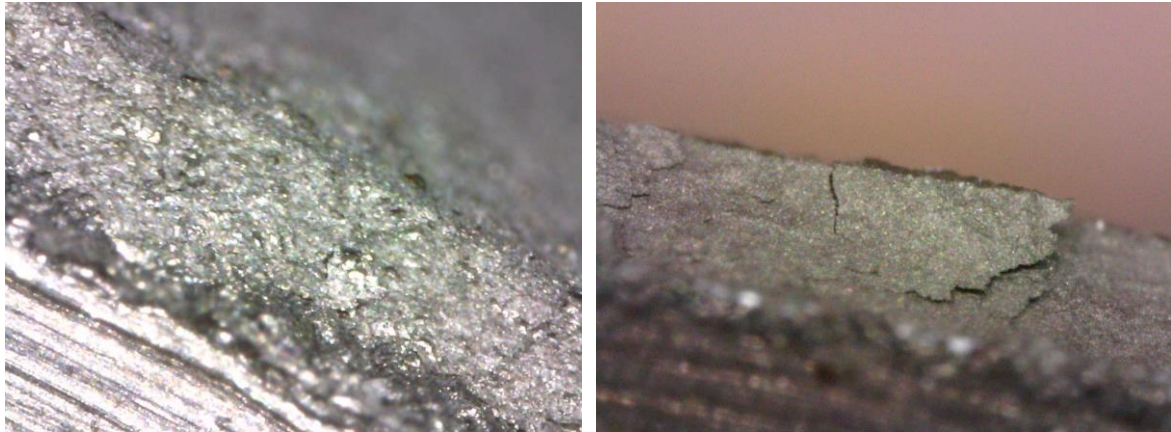


Figure 11. Fracture surfaces (230 magnification); a) Hastelloy C-276, b) CrC-NiCr.

4. Conclusion

Results obtained by this research proved, that there are still new ways how to evaluate mechanical properties of thermally sprayed coatings. Quick, cheap and reliable determination of cohesive strength of coatings is important from many perspectives. Excluding the customers demand to know exact properties of delivered coating there are other useful applications for this method.

It is possible to correlate cohesive strength with mechanism of wear which allows to predict the behaviour of specific coating under defined stress conditions. On the other hand, this method can be used to correlate fatigue properties of coated system.

Results indicate that this method is primarily suitable for alloy based coatings where it provides replicable measurements. Alloy based coatings exhibit low volatility in measured values with low standard deviation in proportion to measured values. For this reason, this method seems to be reliable for such use.

Results obtained measuring carbide based coatings are less convincing but still the 12.5% deviation is acceptable.

The research will continue as mentioned above and will focus on other carbide based coatings to prove or disprove usefulness of such method for this type of coatings. Furthermore, the correlation between cohesive strength and wear mechanism will be examined together with influence of residual stress influence.

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Acknowledgement

The paper was prepared thanks to the project of Technology Agency of the Czech Republic no. TE01020068.