Properties of protective NiCr coatings, deposited by Cold Spray technology

Š Houdková¹, P Šulcová¹, A. Keslová¹, K Lencová¹ and J Duliškovič¹
¹ Výzkumný a zkušební ústav Plzeň, s.r.o., Tylova 46, Plzeň, 301 00, Czech Rep.
houdkova@vzuplzen.cz

Abstract. The NiCr coatings, deposited by modern Cold Spray technology, and by well-established Twin Wire Arc Spraying and High Velocity Oxygen Fuel technologies, was studied in terms of microstructure, mechanical, tribological and corrosion properties. Compared to other thermal spraying technologies, CS coatings achieve higher cohesive strength and associated tribological properties. The dense structure is responsible for the coatings’ high corrosion protection ability. The influence of CS technological parameters was found negligible, except the usage of nozzle for internal diameter spraying, which results to significant increase of coatings porosity.

1 Introduction
The Ni-based alloys are used in the most demanding environments to beat the corrosion, high temperature oxidation, wear and their mutual combinations namely in power industry [1,4-7]. Due to their high costs, they are often applied as coatings, providing the superior surface protection to the coated components made from less noble materials. Various technologies, such laser [2] or Plasma Transferred Arc (PTA) [3] overwelding or thermal spraying [4-6] are utilized for deposition of Ni-based protective coatings. The final properties of coatings then varied in dependence on specifics of used deposition technology and also in dependence on the chemical composition of specific alloy.

From the group of Ni-based alloy, the Ni-20%Cr alloy is one of the possible candidates for protective coating. It has been designed to withstand oxidation and corrosion to temperatures up to 900 °C. The HVOF sprayed Ni20Cr coating indeed provide protection for steel pipes at high temperatures [4], as well as excels with high protection against solid particle erosion [5].

The Cold Gas Dynamic Spraying (CGDS) or simply Cold Spraying (CS) belongs to the family of thermal spraying technologies. From them, it differs by eliminating the high temperature for melting of deposited particles during deposition. Instead of temperature, it uses supersonic velocities of particles stream. After impacting the substrate, the kinetic energy of the impact transform into the heat, and cause not only the plastic deformation of the particles, but is also responsible for creation of local microwelds on the boundaries. The principle of CS is described in detail in [8].

Although the portfolio of applied materials is growing rapidly, thanks to the principle of application, it is still used primarily for materials with a good ability to deform plastically, such as copper, aluminium, and its alloys.

The Ni-based alloys can be also successfully deposited by the Cold Spray technology [7, 9,10]. The low spraying temperature can help to avoid the occurrence of oxides inclusions, commonly present in
thermally sprayed coatings, deposited by Twin Wire Arc Spraying or Atmospheric Plasma Spraying. Thanks to the high impact energy, the amount of porosity can be also significantly decreased.

Although some information regarding the properties of cold sprayed NiCr coatings are available, the cold sprayed coatings application to the high-valuable components of power or aircraft industry should be preceded by further research. The more detailed study is needed to reveal the influence of various factors, that can take part during cold spraying.

Presented study focusses on the influence of basic technological parameters on the microstructure and selected mechanical and tribological properties. While the process parameters were kept constant, the size of the NiCr particles, deposition angle and distance were varied to simulate the non-ideal deposition condition. Moreover, the use of nozzle for deposition of coating in the inner diameter of pipes (ID nozzle) were tested and the resulted coatings microstructure is presented.

2 Experimental

2.1 Coatings deposition

The cold sprayed coatings were prepared in Impact Innovations company in Germany, from Sandvik Ospray NiCr powder (-32 +10 and -25+5 µm mesh). The surface of carbon steel substrates (200 × 100 × 5 mm) was grit blasted by Al₂O₃ using Impact Innovation Cold Spray system. The previously optimized spraying parameters and nitrogen as a carrier gas were used to deposit the coating with the final thickness around 1 mm. After the deposition, the coated substrate was cut to obtain testing samples with required dimensions. The denomination of samples with respect to the variable deposition parameters are summarized in Table 1.

Table 1. Denomination of Cold Sprayed samples

| NiCr powder mesh | Angle of deposition | Deposition distance | Type of the nozzle |
|------------------|---------------------|--------------------|--------------------|
| CS1 -32+10 µm    | 90°                 | 30 mm              | Impact Gun 5/11    |
| CS2 -25+5 µm     | 90°                 | 30 mm              | Impact Gun 5/11    |
| CS4S -32+10 µm   | 45°                 | 30 mm              | Impact Gun 5/11    |
| CSDS -32+10 µm   | 90°                 | 15 mm              | Impact Gun 5/11    |
| CSDL -32+10 µm   | 90°                 | 45 mm              | Impact Gun 5/11    |
| CSID -32+10 µm   | 90°                 | 5 mm               | Impact ID Gun      |

For comparison, the properties of NiCr coatings deposited by TWAS and HVOF technologies were subjected to the similar experimental procedure. The HVOF and TWAS sprayed samples were produced in Výzkumný a zkušební ústav Plzeň s.r.o. (The Research and Testing Institute in Plzen, Ltd.), using Oerlikon Metco Smart Arc and Praxair HP/HVOF TAFA JP5000 spraying guns and Metco 8450 wire and Metco AMDRY 4535 powder. The 600 µm and 350 µm final coatings thicknesses were reached for TWAS and HVOF coatings, resp.

2.1 Coatings characterisation

The microstructures were evaluated on the coating’s cross sections, prepared by the standard metallographic procedure. Both the optical (OM) and scanning electron (SEM) microscopy was used for microstructure evaluation. The microhardness was measured on the coatings polished cross-sections using the HV0.3 method. For each coating, at least 7 indents were done, and the average value is reported. The adhesive – cohesive strength of the coatings was evaluated by tensile test in accordance to ASTM C-633. For each coating, 4 tests were provided, and the average values are reported.

The wear resistance against three-body abrasion and solid particle erosion were measured using the Dry Sand/Rubber Wheel test in accordance to ASTM G-65 and centrifugal erosion test [11]. The impact angle of erosive media (Al₂O₃; F70) varied between 15°-90°. The coatings volume loss was
determined from mass loss using the values of density, previously determined by Archimedes method. For each coating at least 3 independent measurements were done, and the average value is reported. The worn surfaces were subsequently observed by SEM.

The protective properties of the coatings wear tested by salt fog corrosion test in accordance to ČSN EN ISO 9227 and also in high temperature aggressive environment of Na$_2$SO$_4$Fe$_2$(SO$_4$)$_3$. The details of high temperature test are described in [12].

3 Results and discussion

The optical micrographs of cold sprayed coatings cross section are shown in the Figure 1 and 2.

The structure of cold sprayed coatings deposited at optimized parameters, is dense, without any pores, regardless the size of the original powder (Fig. 1a and 1b). Small amount of porosity appeared if the coating was deposited at 45° declination of the nozzle (Fig. 1c), as well as if the deposition distance was too short (Fig. 1d). The longer deposition distance does not contribute to the change of porosity (Fig. 1e). On the other hand, use of nozzle for internal diameters has led to a significant increase of porosity (Fig. 1f). Nevertheless, except the CSID, the differences are negligible compare to TWAS (Fig. 2a) and HVOF (Fig. 2b).

![Figure 1. Cross section microstructures of CS1 (a); CS2 (b); CS45 (c); CSDS (d); CSDL (e) and CSID (f) Cold Sprayed NiCr coatings](image)

The adhesive-cohesive strength of the cold sprayed samples exceeds in all cases the strength of used glue, and reached almost 60 MPa. On the contrary, the cohesive strength of TWAS sprayed samples was measured to be 40 ± 13 MPa, as well as the HVOF sprayed coatings 40 ± 5 MPa. In agreement with expectations, the measured microhardness values corresponded to the coatings microstructures. The higher the obvious porosity, the lower the microhardness value and higher value scatter. The CS coating microhardness varied between 330 and 430 HV0.3, being highest for CS2, and lowest for CSID (339 HV0.3) and CS45 (393 HV0.3). The TWAS NiCr coating microhardness reached only 231 HV0.3 and HVOF 345 HV0.3 microhardness values.
The results of wear tests are shown in the graphs in the Figure 3. The Dry Sand Rubber Wheel tests result (Fig. 3a) of CS samples did not varied at all – the technological parameters had no noticeable influence. All evaluated CS coatings shown higher wear rate, compare to TWAS coating and the HVOF coating, which performed the best. Such unexpected observations are not in agreement with the results of tensile tests and microhardness measurements and the reason for such behavior has to be further studied. On the other hand, the solid particle erosion test (Fig. 3b) pointed out to significantly higher resistance of CS coatings to erosion wear, compare to TWAS and HVOF sprayed coatings. Moreover, the test revealed a positive influence of finer original powder (CS2) and shorten deposition distance (CSDS). The results didn’t include the highly porous coating, deposited by nozzle for internal diameters, which become a subject of following in-detail research study. The volume loss of TWAS and HVOF coatings was multiplied higher, as well as the scatter of the values.

The SEM of the worn surfaces (Fig. 4) shown the mechanism of erosion wear: in the case of CS, the surface is plastically deformed, number of erosive particles are embedded in the coating surface, namely in the case of perpendicular particles impact. In the case of TWAS, as well as HVOF, the
delamination of whole splats took place after the repeated perpendicular impact of solid particles. If the particles impact the surface at low angle, the major abrasion-like mechanism, demonstrated by grooving of the surface, can be observed. Nevertheless, namely in the case of TWAS, the whole splat delamination also took place.

![Figure 4](image1.png)

**Figure 4.** The SEM of eroded surfaces: CS2-90°(a); TWAS-90°(b); HVOF-90°(c); CS2-15°(d); TWAS-15°(e); HVOF-15°(f)

The salt fog test of coating corrosion resistance proved the protective properties of CS coating. Even though the NiCr alloy itself is corrosion resistant, the TWAS and HVOF sprayed coatings does not fully protect the underlaying substrate from the influence of surrounding media (Fig. 5). The remaining porosity can enable the penetration of surrounding atmosphere to the interface between substrate and coating and cause the substrate corrosion. Nevertheless, the application of coatings decrease the corrosion attack compare to uncoated surface significantly.

![Figure 5](image2.png)

**Figure 5.** The coatings surfaces after the salt fog tests CS2 (a); TWAS (b) and HVOF (c)

The high-temperature corrosion test in aggressive salts shown similar results regardless the used deposition technology. The mass gain, representing the amount of coatings surface oxidation, was comparable for all tested coatings. The ability to protect the substrate was not evaluated, as the substrate material for the test is corrosion resistant.
4 Conclusion

The influence of technological parameters on the properties of cold sprayed NiCr coatings was evaluated. Based on the realized tests, only a small variation of evaluated properties was found regarding the deposition angle and distance. The microstructure and microhardness of coating, deposited by nozzle for internal diameters spraying, was significantly lower. The influence of increased porosity on the functional properties, namely on ability to protect the substrate from corrosion, is the subject of current research. Compare to the NiCr coating, deposited by TWAS and HVOF deposition technologies, the CS coatings provides higher resistance against the solid particle erosion and offer better corrosion protection of the underlaying substrate.

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