The mechanical properties of coatings sprayed by electric arc for use in coal power plants

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Abstract. The components in coal power plants such as fire sides in boilers, preheaters, or heat exchangers are significantly mechanically and chemically stressed. The main stress originates from high temperature corrosion caused by the aggressive atmosphere inside the boiler, but other influences such as erosion and abrasion by coal and flying ash, heat shocks, etc. also have significant negative effect. One of the options for increasing the service life and improving the utility properties of these components is a thermal spray coating. Because the disassembly of these components is impossible, the mobile TWAS deposition technology was used. In this paper, different types of TWAS-sprayed coatings suitable for application in such environment are compared and evaluated. Two types of coating materials were evaluated, FeCr-based ones and NiCr-based ones, in terms of microstructure and mechanical properties such as hardness, adhesion, abrasion and erosion resistance. The SEM microscopy evaluation was used to evaluate the wear mechanism. It was found that the coatings with lower hardness but higher toughness resist the solid particle erosion better than hard but more brittle coatings. The experiences with the application of these coatings in selected areas on the fire side inside the boiler in the coal power plant are briefly reported.

1 Introduction
In a coal-fired power plant, there are a lot of components whose service life and performance can be increased by the appropriate use of modern technologies of surface protection. One of the options of this protection is to apply coatings with specific properties by thermal spraying. This paper is focused on proper choice of coatings materials that should serve as a protection of surfaces of components in coal-fired power plant which are significantly chemically and mechanically stressed. These components include, for example the fire side of water wall in boilers, components of superheaters, reheat, or evaporators. Most of these components are impossible to disassemble, or the disassembly is very difficult. Because of this, the method Twin Wire Arc Spraying for coating of these components has to be used. The spraying device only needs a supply of electricity and compressed air to operate, and thus it can be used for spraying outside a specialized workplace.

In this paper, the commercially available materials for this application are described and their mechanical properties are evaluated and compared. These materials can be divided into two groups: FeCr-based and NiCr-based. The number of mechanical properties such as adhesion of coating, microhardness, abrasion and erosion wear resistance was tested and the results are described in this paper. The advanced SEM microscopy analysis was done for evaluating wear tracks.
2 Materials of coatings

Fe28Cr (+SiMnB) is a composite wire which produces a highly alloyed chrome steel alloy coating. This coating is a hard, abrasion and corrosion resistant, useable up to 925°C and it has also exhibited the unique quality of increasing hardness in service. This material finds its application for example for coating of exhaust fans, pump components, coal-fired boilers, superheaters, economizer waterwalls, or boiler tubes. [1]

Fe18Cr (+NiCAI/VS) make a thermally stable austenitic steel alloy coating, which is finding its application for power generation boiler tubes and waste-to-energy boiler tubes. The coating is erosion and corrosion resistant even at high temperatures (600°C). The significant advantage of this coating is a readability of the thickness of the coating by standard electromagnetic thickness gauge on as-sprayed coating and also on coating exposed up to 800 °C in one calibration of the thickness gauge. [2]

NiCrFeSi is a composite wire which can be used to protecting the components from high-temperature corrosion and erosion wear. Compared to similar coatings, the coating made by this material is harder, and more wear resistant. [2]

The coating made by NiCr wire is high temperature corrosion and erosion resistant. Its typical application is such as bond coat under ceramic coatings in high temperature or chemically aggressive environments. The amount of chromium is about half (20%) compared to next, very similar, evaluated material (NiCrTi) [3].

Next material of the coating is nickel alloy with a composition similar to Inconel 625. Coating made by this material is appropriate for oxidation and hot gas corrosion at elevated temperatures up to 870 °C and it has also a very good erosion resistance. This coating is finding its application for example for restoring components made by nickel-based superalloys, or bond coat for ceramic coating. [3]

NiCrTi is a wire developed specifically for boiler applications. This coating is highly corrosion resistant to sulfur/vanadium atmospheres up to 980 °C. The material is pre-alloyed with titanium to produce superior bond strengths. The amount of chrome (more than 40%) is sufficient to form enough chromium oxide to prevent the breakdown of nickel into nickel sulfide which is not a protective layer. [4]

3 Experimental

The microstructures for each material were evaluated with using an optical microscope on sample’s cross sections, which were ground and polished by standard metallographic procedure. For testing mechanical properties of these coatings, four tests were done. The adhesion was tested according to ASTM C633 – 13 [5]. Hardness was tested according to ČSN EN ISO 6508-1 (420360) [6]. Wear resistance was investigated by Erosion resistance test [7] and by Dry Sand/Rubber Wheel abrasion test [8]. For these two tests, the abrasive/erosive medium was white corundum with grain size F70. The tracks after the wear test were analyzed by scanning electron microscope. The abrasion resistance was tested according to the ASTM G-65. The evaluating factor is cumulative volume loss per abrasive distance. Three samples were tested for each material and the resulting value is the average of these three measurements. During the Erosion resistance test the erosive medium impacted the samples at different angles (90°, 60°, 45°, 30° and 15°). For each material of coating, two samples were tested. Three cycles were done for each sample. The duration of one cycle was 2 minutes. The average volume loss per one cycle was evaluated.

4 Results and discussion

The microstructures of each coating are shown in Figure 1. The structures of all coatings are without any cracks, however, typical to a coating made by TWAS: laminar, with well-distinguishable particular splats and with a content of pores and oxides. Pure NiCr and NiCrTi have the most significant content of oxides at splat boundaries because of a chemical reaction of molten particles during spraying. On the other hand, the Fe-based coatings are mostly without oxides.
For the correct evaluation of the results of the Adhesion/Cohesion Strength Test, it is necessary to know the location of initialization of the crack, and due to this the measured value is related to the adhesive or cohesive strength. For all evaluated coatings, the locations of initialization of the crack were inside the coating, so the values shown in Figure 2 – left are related to cohesive strength. The NiCrFeSi and NiCr coatings had excellent cohesive strength (more than 50 MPa). The cohesive strengths of other coatings are adequate. [9]

![Microstructures of coatings](image)

**Figure 1.** The microstructures of coatings

The results of microhardness are shown in Figure 2 – right. The highest microhardness had coatings made by composite wires: Fe-based coating with a 28% Cr and NiCrFeSi because of highly-alloyed coating. The lowest microhardness have ductile NiCr and NiCrTi coatings.

![Adhesion / Cohesion and Microhardness](image)

**Figure 2.** The result of Adhesion/cohesion Strength Test (left) and Microhardness HV0,3 (right)

The result of this test is shown in Figure 3. The best abrasion resistance had the NiCrFeSi coating and the Fe28Cr. These results are in correlation with the results of microhardness and their good abrasion resistance is caused by a high hardness of the coating. Tough NiCr based coatings had lower
abrasion resistance. The abrasive wear tracks were evaluated by SEM microscopy (Figure 4). The wear tracks of coatings of hard coating (Fe28Cr and NiCrFeSi) are smoother with a minimum visible plastic deformation compared to tough materials (NiCr, Inconel 625 and NiCrTi).

Figure 3. The result of Abrasive Resistance Test

The results of the Erosion Wear Resistance test are shown in Figure 5. All coating proved a really good erosion resistance. The higher volume loss was lower than 3.5 mm$^3$ per 2 minutes of intensive actuation of the erosive medium. The lowest erosion resistance had the Fe28Cr coating because of lower cohesion strength (as also shown the result of the Adhesion/Cohesion Strength Test). The dependence of volume loss per angle of impaction is different for different materials. For the Fe28Cr coating the volume loss is decreasing with decreasing angle of impaction. The same relation, although not as significant, had the NiCrFeSi and Fe18Cr coatings. This dependence is typical for brittle material because the material is removed due to the formation and intersection of cracks that extend from the point of impact of the particle. Therefore, these coatings had lower resistance when the angle...
of impaction of erosive media is perpendicular. This phenomenon also confirms the SEM analysis (Figure 6) of the surface after the impaction of erosive media at 90° angle, where the delamination of whole splats for these materials is visible. The dependence of volume loss per angle for tough materials is converse. In this case, the wear mechanism is characterized by plastic deformation (Figure 6), in which the material of coating is removed or the material is cut out by particles of the erosive medium, therefore, the volume loss is increasing with decreasing angle of impact. This dependence is well noticeable for NiCr, NiCrTi and Inconel 625 coatings. The best erosion resistance had NiCr coating.

![Erosion Wear Resistance Test](image)

**Figure 5.** Result of Erosion Wear Resistance Test

![SEM analysis of surface after Erosive Wear Resistance Test](image)

**Figure 6.** SEM analysis of surface after Erosive Wear Resistance Test

5 **Real application**

As a part of the experimental program, these coatings were applied on the fire side of water wall inside the coal-fired boiler to prove the coatings applicability outside the specialized workshop. The coatings
were applied to selected areas where the water wall is significantly stressed by mechanical and chemical strain. To further increase the service life, the protective ceramic coating was applied on top of all thermal sprayed coatings.

The revision of these coatings was done after one year of operation of the boiler. The coatings were evaluated visually and their thicknesses were measured. The results of this revision showed, that different areas inside the boiler are exposed to different levels of stress. Therefore, it is not possible to determine precisely the degree of degradation of each coating, however all these coatings showed great resistance in these difficult conditions.

6 Conclusion

The results of selected tests of mechanical properties of TWAS-sprayed coatings for application in coal power plant boilers are described in this paper. All of the tested coatings showed prominent erosive resistance, very good abrasive resistance, and adequate microhardness and cohesive strength. These coatings can be divided into two groups: hard, brittle coatings and tough coatings. The Fe28Cr coating had the highest microhardness and really good abrasive resistance, but the lowest erosive resistance caused by lower cohesive strength and delamination of splats. Similarly, the NiCrFeSi coating showed high abrasive wear resistance due to the high microhardness. Moreover, this coating was also resistant against erosion wear thanks to the higher cohesive strength. On the other hand, ductile NiCr, Inconel 625 and NiCrTi have a lower hardness and abrasive resistance. The dependence of volume loss per impact angle during the Erosion Wear Resistance Test was typical for this type of materials: increasing with decreasing impact angle. The NiCrTi coating has higher hardness and better abrasive and erosive resistance compared to the NiCr coating. It is probably caused by the double content of chromium in the material composition. The applications of these coatings inside the coal-fired boiler showed a great resistance in these difficult conditions. However, is not possible to exactly evaluate the comparison of tested coatings because the chemical and mechanical load varies in different areas inside the boilers.

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