STUDY OF WEAR RESISTANCE OF COATINGS DEPOSITED BY HIGH VELOCITY OXYGEN FUEL (HVOF) TECHNOLOGY

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Abstract
The contribution deals with the evaluation of wear resistance three types thermally sprayed coatings deposited by HVOF spraying. The wear resistance of these coatings was evaluated by simulation of erosive wear. Erosive wear was simulated by abrasive blast cleaning process using abrasive - brown corundum. Simultaneously there was studied influence of various impact angles on wear resistance of HVOF coatings. Study of properties the coatings was supplied also by measuring thickness, adhesion, microhardness and by EDX analysis. Construction and structure of coatings were studied using optical and electron microscopy. The research results showed that all coatings exhibit comparable resistance against erosive wear, greater weight loss was observed at impact angle 75°. v Adhesion of coatings after heat load slightly decreased, but within 10 thermal cycles stayed relatively stable. Despite these results, it is not possible to recommend to the operational conditions with high and fluctuating temperature neither coating WC-Co-Cr by reason of its thermal cracking nor WC-17Co coating for its strong oxidation during thermal cyclic loading. The best properties in conditions of high temperature showed coating Cr_3C_2-25NiCr.

Keywords: HVOF spraying, HVOF coatings, adhesion, erosion, thermal loading

1 Introduction

Thermally-sprayed coatings belong to the dynamically developing field of surface engineering. These high-quality functional coatings are applied in the basic industry, as well as in renovations [1,2,25], mainly due to their excellent properties, which are characterized by high wear resistance [1-14], corrosion resistance [12,15] and resistance against high temperatures [10,16-21]. Thanks to wide range of different combinations coating–substrate material, thermal spraying offers as many possibilities as no other technology of coatings deposition. HVOF (High Velocity Oxygen Fuel) is one of the technologies, which formed coatings with very small porosity (<1 %) compared with the basic material [26] and high adhesion strength (> 80 MPa) [22,27]. There are minimal thermal changes of substrate during spraying and also roughness of coating surface is low. Recently this coating technique is considered as a promising candidate for the replacement of the traditional electrolytic hard chrome (EHC) plating which pollutes the environment and causes lung cancer by toxic hexa-valent Cr^{6+}. The HVOF spraying WC-based cermet hard coatings such as WC–Co, WC–CoCr and others have been investigated for

obtaining the coatings of high hardness, wear resistance, thermal stability and corrosion resistance. [3]
The erosion performance of thermally spayed WC coatings has been investigated by many workers. [1,2,7,9-13] The erosion behaviour of these coatings compared with bulk sintered WC–Co is further complicated by the inhomogeneous microstructure, which leads to wide variations in mechanical properties, and the phase transformations of the starting material, which take place during spraying. Up to 50% of the WC–Co starting material is known to decompose and transform during the spraying process. The most common transformations are $WC \rightarrow W_2C$ and $WC–Co \rightarrow Co_3W_3C$. It has been found that the addition of Cr to WC–Co inhibits to a large extent the decomposition of WC–Co as well as having a beneficial effect on the erosion resistance. Of the various spraying processes, the high-velocity oxy-fuel (HVOF) method has been found to deposit coatings with significantly lower levels of carbide decomposition and phase transformation. Consequently, this results in higher quality, more wear-resistant coatings, with higher levels of retained WC and less porosity. The effect of these phase transformations is generally deleterious to the abrasive wear performance of HVOF WC–Co coatings. However, the effects of powder morphology, type of HVOF spray system and spray parameters have all been shown to affect the coating microstructure and, in turn, the wear resistance. [1,4]
Tungsten carbide and chromium carbide-based coatings are frequently used for many of the applications in gas turbine, steam turbine and aero-engine to improve the resistance to sliding, abrasive and erosive wear. The former is used up to 500°C and the latter up to 800°C. Also, for sliding wear and abrasive wear resistance, the carbide coatings are considered to be a viable alternative to hard chrome platings due to the strict environmental regulations and cost concerns with regard to the electroplating process. These cermet coatings are deposited by plasma spray, high velocity processes and detonation gun spray processes. [5]
In order to reduce coating variability in industrial HVOF thermal spray processes, it is important to implement excellent real-time process diagnosis and control which could suppress the influence of external disturbances. Despite the recent progress on the modelling of various phenomena that affect droplet motion, deposition, solidification and microstructure development in HVOF thermal spray processes, at this stage, there exists no systematic framework for integrated on-line diagnosis and control of the HVOF thermal spray process which will be capable of achieving precise regulation of the microstructure and ultimate mechanical and thermal properties of the sprayed coatings.[23]
The item presents experimentally obtained results aimed at assessing selected coatings applied by HVOF technology. The coatings were subjected to cyclic thermal stress. Their tribological properties were evaluated in conditions of erosive wear. The quality of coatings was evaluated by pull-off test, measuring the microhardness, and by EDX analysis. Conditions of experimental works were chosen in order simulate the operating conditions in the iron manufacturing in basic oxygen furnace (BOF).

2 Materials and methods

Substrate for application the coatings was made of structural carbon steel C15E (1.1141). Chemical composition of the steel is listed in **Table 1**.

Table 1 Chemical composition of the steel substrate (mass %)

C	Mn	Si	P	S
0,12 – 0,18	0,30 – 0,60	0,15 – 0,40	max 0,035	max 0,035

Mechanical properties of the steel substrate: tensile strength 740 – 880 MPa, yield strength ≥ 440 MPa. The test samples were made from round bar Ø50 mm with a height of 15 mm.

Substrate pre-treatment

Roughness of substrate prior to HVOF deposition, as a mean of improving the mechanical bonding of the coating, on the fatigue life of the coated system [24].Test samples were pre-treated by air grit blasting: air pressure of 0,5 MPa, abrasive - brown corundum, grain size 1,00 mm.

Material of coatings

There were deposited three types of coatings by HVOF technology on pretreated samples. On the first group of samples coating of WC-729-1/**1343** VM (WC-17Co) was applied, on the second group of samples coating of WC-731-1/**1350** VM (WC-Co-Cr) was deposited and on the third group of samples coating CRC-300-1/**1375** VM (Cr_3C_2-25NiCr) was deposited. Materials were supplied as a powder, agglomerated and sintered, produced by Praxair, Inc., USA. **Table 2** shows chemical composition of the powders.

Table 2 Chemical composition of the powders sprayed [%]

Coating	**C**	**Co**	**Fe**	**W**	**Cr**	**Ni**
WC-17Co/**1343**	5,5	16,2	0,036	78,4		
WC-Co-Cr/**1350**	5,5	9,9	0,02	80,58	3,9	
Cr_3C_2-25NiCr/**1375**	10				68,5	21

For the coating deposition equipment JP-5000, Praxair TA was used; it deposits coatings using system HP/HVOF (High Pressure / High Velocity Oxygen Fuel) with System Powder Feeder 1264. The surface of deposited coatings was not further modified after spraying. Parameters of spraying are listed in **Table 3**.

Table 3 Parameters of spraying

Particle velocity	**Adhesion**	**Oxide content**	**Porosity**	**Deposition power**	**Typical coating thickness**
mps	**MPa**	**%**	**%**	**kgph**	**mm**
600 ÷ 1000	< 70	1 - 2	1 - 2	3 - 6	0,2 - 2

Thickness of the coating was determined by magnetic thickness gauge.

Thermal cyclic loading of the coatings

Samples were subjected to cyclic thermal load in electric chamber furnace according to the following mode:

1. heating of the samples in electric chamber furnace at 900 °C,
2. dwell in the furnace for 20 minutes,
3. free cooling of samples on still air to ambient temperature.

Samples were subjected to 10 thermal cycles, and after the 3rd, 5th, 8th and 10th thermal cycle samples were collected to evaluate the adhesion of coatings. Construction, structure and chemical analysis of examined coatings was studied using scanning electron microscopy (SEM)

JEOL JSM – 7 000 F. Chemical analysis was conducted using the EDX analyzer INCA, which allows local EDX chemical analysis of the material.

Microhardness of the coatings
To determine the basic properties of coatings ”as-sprayed” and after thermal cycles microhardness was measured according to STN ISO 4516 on Shimadzu HMV-2E test equipment, load 980,7 mN (10 g), dwell time 15 s.

Adhesion of the coatings
Adhesion of coatings was evaluated by pull-off test according to STN EN 582 with help of tensile machine ZDM 10/91. After pull-off adhesion test, tensile stress necessary to rupture the weakest inter-phase (adhesive fracture) or the weaker component (cohesive fracture) of the test arrangement and also the nature of fraction were determined.

Erosive wear of the coatings
To simulate the working conditions in BOF (the impact and flowing of oxides in BOF gas) coatings were subjected to erosion wear in abrasive impact angles 45° and 75°. To simulate the process of oxide impact a laboratory mechanical blasting device KP-1 was used, which allows monitoring the circulation of abrasive. Abrasive used - brown corundum (Al_2O_3), grain size 1 mm. Intensity of coatings wear was evaluated using gravimetry (mass loss of the coating). Peripheral speed of blasting wheel was 51,0 mps and output speed of abrasive was 70,98 mps. One erosive cycle means application of 500g abrasive by abrasive grit blasting technology.

3 Results and discussion

Thickness of the coatings
Thickness of the coatings as sprayed, were as follows: 1343 – 234 μm, 1350 – 356 μm and 1375 – 393 μm.

Microhardness of the coatings
The highest microhardness values (as sprayed) was shown by coating 1350 (1447 HV 0,1) which was caused by a high content of tungsten and addition of cobalt compared to the coating 1343, which also contains tungsten but at lower concentrations and had lower values of microhardness (1010 HV 0,1). The lowest microhardness values were shown by coating 1375 with a high content of chromium, tungsten-free (975 HV 0,1). During thermal cyclic loading microhardness of coating 1350slightly increased, for other coatings varied, and then slightly decreased compared to as sprayed, **Fig. 1**.

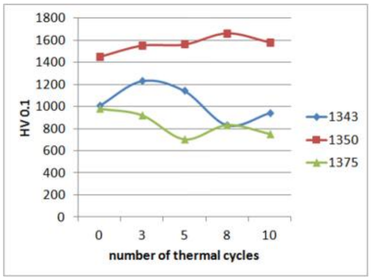


Fig.1 Microhardness of coatings during thermal cyclic loading

Adhesion of the coatings

Before pull-off test of the coating, all releasing layers (after thermal loading) were mechanically removed and samples were degreased with methanol. Results of coatings adhesion are shown in **Fig. 2**.

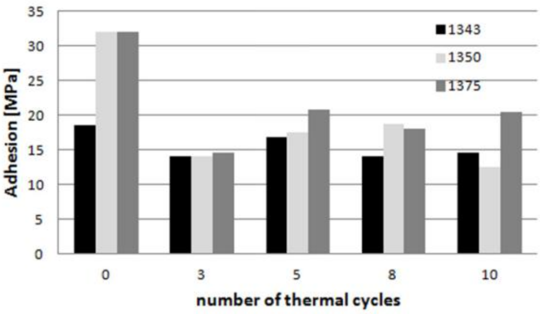
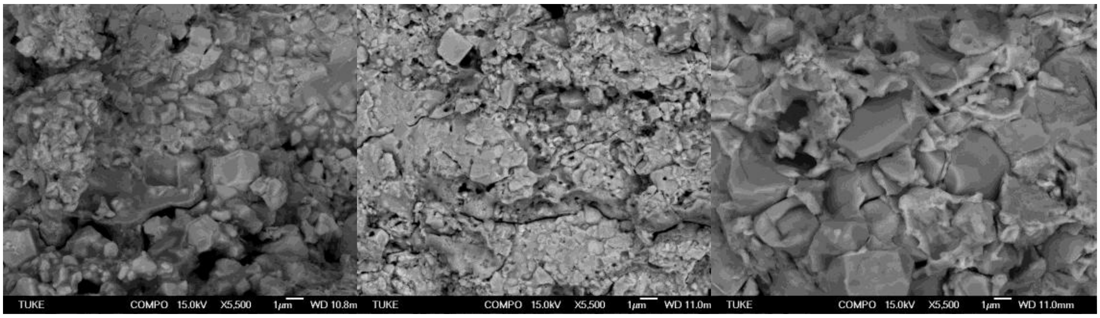


Fig.2 Adhesion of coatings after thermal cycles



Fracture of coatings as-sprayed

Surface of coatings after 10 thermal cycles

1 343 1 350 1 375

Fig.3 Fractures and appearance of surface the coatings after thermal cycles

The above results show that the adhesion of coatings has decreased already after three thermal cycles, which remained almost stable during the next thermal loading. The measured values of the adhesion of the coating as-sprayed and the type of fracture showed that in neither case the damage of the coating occurred, therefore the observed initial adhesion values do not correspond to the actual adhesion of coatings, which is definitely higher. Due to very high adhesion of coatings formed by HVOF technology is difficult to determine a real adhesion, because the properties of adhesive used are limiting factor. Although during thermal cyclic loading the coating 1343 showed a fracture in the coating (90 %), in fact after the pull-off test on the test dolly side only a very thin layer of coating remained due to strong chalking and oxidation and we cannot talk about the fracture in coating volume. The coating 1350 after pull-off test has cut off from the substrate along crack area. The coating 1375 has not been fractured after pull-off test, so we expect a higher adhesion than the value listed for this coating. **Fig. 3** shows fractures and appearance of surface the coatings after thermal cycles.

Composition of the coatings

EDX spectral analysis of the coating 1343 showed the presence of two basic phases - solid particles WC and cobalt surrounding WC particles, which corresponds to the chemical composition of powders for coatings production. EDX spectral analysis of the coating 1350 shows the presence of WC particles and chrome and cobalt matrix surrounding WC particles. EDX spectral analysis of the coating 1375 again confirmed the presence of large particles of Cr_3C_2 and the most extensive component of coating 1375 - nickel-chromium matrix. Matrix and hard particles of WC and Cr_3C_2 are well visible on cross-sections and also on fractures of the coatings, Figure 3.

Despite its high hardness, coating 1350 after 3 thermal cycles showed thermal cracking, see fig. 3. Surface of coating 1343 during the thermal cyclic loading was covered with a layer of blue oxides with a strong chalking. Coating 1375 after thermal cycles retained its aesthetic and tactile qualities.

Wear resistance of the coatings

Fig. 4 depicts the dependence of erosive wear on the different impact angles of abrasive. For all types of coatings very similar dependences were achieved. Higher weight losses were recorded at an impact angle of 75° in all types of coatings. The references show that for the harder material, which also the evaluated coatings belong to, more intensive wear occurs at a larger impact angles, as confirmed by experiment.

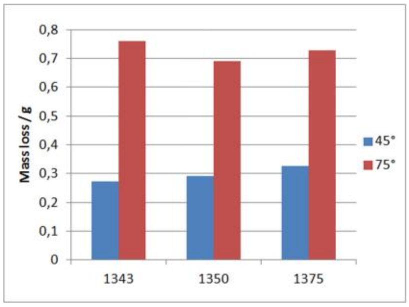


Fig.4 Erosive wear of the coatings after 10 erosive cycles

Intensity of erosive wear is influenced mainly by the ratio of the coating and abrasive hardness together with the structural characteristics of the coating. In work [7] it has been found that also finishing of the coatings surface can affect the characteristics and performance of carbide coatings: surface grinding improved the erosion resistance. Wear intensity of all evaluated coatings was almost the same, higher at impact angle 75°. At larger impact angles, forging effect of the abrasive prevails while at smaller impact angles prevails grooving effect of the abrasive. Wear mechanism of coatings also corresponds to the mentioned facts.

4 Conclusion

Based on the results of the experiments it can be said that the coating WC-Co-Cr (1447 HV 0,1) showed the highest hardness and the coating Cr_3C_2-25NiCr (975 HV 0,1) showed the lowest. During thermal cyclic loading microhardness of coating WC-Co-Cr slightly increased in the case of other coatings varied, and then slightly decreased compared to as-sprayed coatings. To the environment of BOF with high and fluctuating temperatures coating WC-Co-Cr cannot be applied, because of its cracking after a few thermal cycles and thereby disruption of its barrier protective effect what creates a precondition for high temperature corrosion of the substrate. In high temperature the coating WC-17Co showed strong chalking, which may cause significant losses in weight (and consequently in thickness) of the coating and its low durability. Coating Cr_3C_2-25NiCr compared with the previous coatings showed a lower hardness, but during the thermal cyclic loading maintains its integrity and adhesion, any other qualitative changes didn't occur. Resistance to erosive wear of all coatings is approximately the same.

Based on the experimental results obtained, it is possible to recommend for renovation components stressed by extremely high and cyclic temperatures and erosion coating Cr_3C_2-25NiCr (Cr_3C_2-25NiCr).

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