

HIGH TEMPERATURE EROSION-OXIDATION BEHAVIOR OF THERMAL SPRAYED NICKEL-CHROMIUM AND CHROMIUM CARBIDE COATINGS

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1. **ABSTRACT:** *This paper presents the high temperature erosion-oxidation (E-O) behavior of HVOF coatings of Ni20Cr alloy and Cr₃C₂-25(Ni20Cr). The E-O measurements were made in a test rig in the temperature range 500-850° C, using alumina particles as the erodent at impact velocities in the range 2.5–19.5 ms⁻¹. At low impact velocities the coatings did not exhibit any change in E-O behavior up to 500-600° C, compared to that at 100° C. However at higher temperatures, wastage increased with temperature, reaching a maximum at 700° C and then decreased with further increase in temperature up to 800° C. At temperatures above 800° C, wastage increased again. The E-O mechanism of these two coatings was quite similar. Changes in E-O wastage are attributed to regime change from 'substrate dominated' to 'oxide modified'. At higher erodent impact velocities a significant increase in E-O wastage of the coatings was observed. Using surface roughness as the criterion to compare E-O behavior of the coatings, E-O maps were constructed for the two coatings. Regions corresponding to low, moderate and severe wastage were defined and shown in the maps to aid in qualitative selection of conditions for safe use of the coatings.*

1. INTRODUCTION

The erosion behavior of metallic materials and ceramics at room temperature has been extensively studied [1,3,6,7]. A vast amount of information is also available about the oxidation behavior of various metals and alloys at high temperatures [15]. However, only limited information is available about the conjoint effect of erosion and oxidation at high temperatures. Erosion-oxidation (E-O) interactions were first described in terms of regimes by Hogmark et al. in 1983 [2]. Kang et al. proposed the existence of four regimes as a function of increasing temperature, based on E-O studies of pure metals [4]. Modifications to these regimes and other interpretations about the existence of a variety of other sub E-O regimes have been proposed [5,10]. The use of ceramic coatings addresses both erosion and oxidation resistance. The 'high velocity oxy fuel' (HVOF) process has been used to apply metal matrix composite coatings of Ni, Cr, Co or other alloys reinforced with carbides like WC or Cr₃C₂ on a variety of metallic substrates. These coatings impart increased wear resistance, especially at high temperatures, to the substrates. Nickel based alloys are often used for high temperature applications and contain sufficient chromium to form an external layer of chromium dioxide. Under cyclic oxidation conditions this oxide spalls due to stresses in the oxide and differences in the coefficient of thermal expansion between the oxide and the underlying alloy. Nickel-chromium based alloy coatings reinforced with ceramic particles of WC and Cr₃C₂ have been used in many industrial applications to minimize degradation due to E-O [14]. Many attempts have been made to explain the wear of these coatings and the interactions due to E-O that are involved in the overall process [8,13].

This paper presents the high temperature erosion-oxidation behavior of HVOF coatings of Ni20Cr alloy and Cr₃C₂-25(Ni20Cr). The E-O measurements were made in a test rig in the temperature range 500-850°C, using alumina particles as the erodent at impact velocities in the range 2.5–19.5 ms⁻¹.

2. METHODS AND MATERIALS

The HVOF process was used to apply coatings on AISI 310L sheet specimens 50 mm x 20mm. Powders with compositions corresponding to Ni20Cr and Cr₃C₂-25(Ni20Cr) were used to produce the coatings. An E-O test rig was used. In this rig a specimen assembly was rotated through a fluidized bed of erodent particles. Alumina powder with particles in the size range 212-150 μm was used as the erodent. The fluidized bed of particles was obtained by pumping pre-heated air through a porous plate supporting a bed of erodent particles. Fluidization of the erodent particle was done within a furnace and the erodent impact velocity on the test specimens was controlled by a motor that rotated the specimen assembly. The E-O test conditions were: 500-850° C, two specimen rotation speeds with corresponding average erodent impact velocities of 3.5 and 14.8 ms⁻¹ at an impact angle of 90°. Tests were also carried out at 100° C to evaluate erosion behavior in the absence of oxidation. After the tests, the specimens were weighed, examined in a scanning electron microscope, the surface reaction products analyzed by EDS and x-ray diffraction analysis and the surface roughness measured.

3. RESULTS AND DISCUSSION

3.1. Erosion-Oxidation Behavior of Coatings

The E-O behavior, expressed as wastage or weight loss, of the two coatings as a function of temperature is shown in Table 1. At particle impact velocity of 3.5 ms⁻¹ the coatings did not exhibit any change in E-O behavior at temperatures up to 500-600° C, compared to that at 100° C. However at higher temperatures, wastage increased with temperature, reached a maximum at 700° C and then decreased with further increase in temperature up to 800° C. At temperatures above 800° C, wastage increased again. This E-O behavior is considered to be due to the formation of a spinel layer of NiCr₂O₄^[12]. This layer increases the ductility of the matrix (NiCr) and consequently, the E-O resistance. At particle impact velocity of 3.5 ms⁻¹, no significant differences in wastage between the Ni20Cr alloy coating and the Cr₃C₂-25(Ni20Cr) coating were observed. This indicated that the mechanism of E-O of these two coatings was quite similar. The formation of the protective spinel type surface oxide prevented erosion of the coating. This E-O mechanism corresponds to the 'substrate dominated' regime^[10]. Increased wastage is observed between 600 and 700°C, due to erosion of the oxide and corresponds to the 'oxide modified' regime^[10] or 'erosion affected by oxidation' regime^[11]. At these temperatures, the oxidation rate is higher and consequently, the oxide layer thickness also higher, but the internal stresses in the oxide (which is also higher), aids in the removal of surface oxide upon erodent impact. Beyond 700° C, an increase in E-O resistance is observed as the oxidation rate is higher than the rate of removal of oxide by erosion. Oxidation tests revealed that oxidation rates increased at temperatures beyond 700° C indicating that the E-O behavior in this temperature range corresponds to 'oxidation controlled erosion'^[11] or 'oxide dominated' erosion^[10].

Table 1. Erosion-oxidation wastage of the two coatings, as a function of temperature at the two erodent impact velocities.

Temperature (° C)	Wastage (x10 ⁻¹ mg.mm ⁻²)			
	3.5 ms ⁻¹		14.8 ms ⁻¹	
	Ni20Cr	Cr ₃ C ₂ -25(Ni20Cr)	Ni20Cr	Cr ₃ C ₂ -25(Ni20Cr)
100	0.25	0.27	0.75	0.7
500	0.25	0.27	1.2	1.55
600	0.27	0.1	1.3	1.75
700	0.5	0.35	1.4	2.0
800	0.0	0.2	4.5	1.4
850	0.27	0.3	-	-

Above 800° C wastage rates increased. This behavior, still within the ‘oxidation controlled erosion’ regime was not mentioned in the early studies on erosion at high temperatures. One probable explanation for this behavior is that the oxide growth rate is higher at this temperature and the oxide thickness reaches a stage where the internal stresses in it are sufficient to promote spalling aided by erodent impact. Comparison of the E-O behavior of the 2 coatings reveals that the Cr₃C₂-25(Ni20Cr) coating is more resistant to E-O. Toma et al. reported the presence of NiCr₂O₄ oxide in as-deposited 75Cr₃C₂-25NiCr HVOF coatings, decrease in grain size and the formation of a nanocrystalline structure [12]. These factors are also considered to contribute to the E-O resistance of this coating.

Tests carried out at average erodent impact velocity of 14.8 ms⁻¹ revealed a significant increase in E-O wastage of the coatings. At this higher impact velocity the wastage increased, indicating changes in regime. In the case of the Ni20Cr coating, a steady increase in wastage is seen and the ‘oxidation controlled erosion’ regime is not observed. This indicates that the oxide formed at temperatures up to 850° C, is not sufficient to decrease wastage under these conditions. In the case of the Cr₃C₂-25(Ni20Cr) coating, wastage at temperatures between 700 and 800° C is to the same extent, and the E-O resistance at 800° C slightly higher, indicating that oxide growth rate is higher than its removal by erodent impact.

3.2. Surface roughness and erosion-oxidation behavior

The thickness of the coatings after the E-O tests were measured to correlate wastage as a function of temperature and particle impact velocity and to confirm the results obtained from weight loss measurements. The thickness change data were not coherent, due mainly to the non-uniform thickness of the HVOF coatings. Therefore, surface roughness profiles of the coatings after the E-O tests were determined. Overall it was observed that wastage was inversely proportional to surface roughness.

Table 2. Limiting surface roughness values, Ra (µm), that define low, moderate and severe wastage zones for the different coatings, based on criteria adopted.

Coating	Wastage		
	low	moderate	severe
Ni20Cr	5,0 > Ra > 2,2	2,2 > Ra > 1,5	1,5 > Ra
Cr ₃ C ₂ -25(Ni20Cr)	2,1 > Ra > 1,3	1,3 > Ra > 0,6	0,6 > Ra

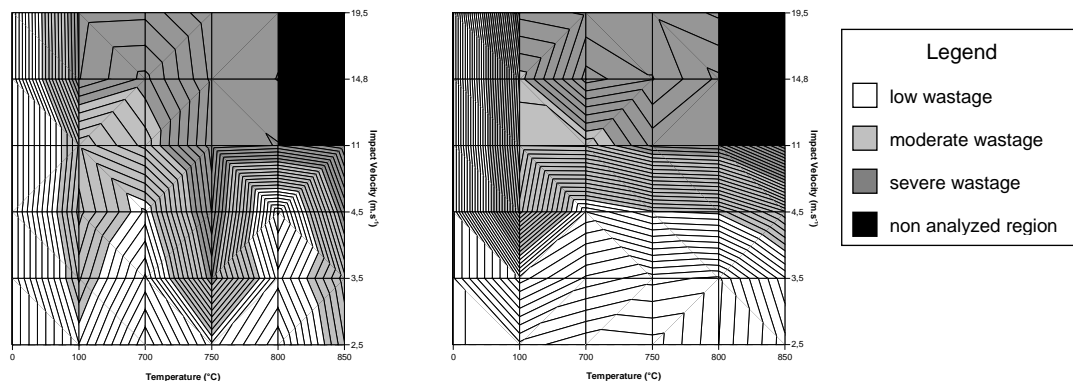


Figure 2. E-O maps of HVOF coatings of Ni20Cr (left) and Cr₃C₂-25(Ni20Cr) (right).

The limiting values of the mean surface roughness Ra (μm), that defined low, moderate and severe wastage zones were specified as shown in table 2 . These values indicate basically that if wastage is sufficient to remove material from the surface (coating or the oxide formed on it), to decrease the coating's roughness, then its E-O resistance can be considered to be low. Based on these values, E-O wastage maps shown in figure 2 were constructed for the two coatings.

4. CONCLUSIONS

2. Erosion-oxidation tests revealed that $\text{Cr}_3\text{C}_2\text{-25(Ni20Cr)}$ coatings were more resistant to high temperature E-O. This is due to the increased resistance of the oxide formed on the coatings surface.
3. The E-O wastage regimes for the coatings were identified at the two erodent impact velocities.
4. At the higher erodent impact velocity, the E-O wastage of the two coatings was significantly higher, indicating that the surface oxides formed at high temperatures did not impede wastage.
5. Using surface roughness as the criterion to compare E-O behavior of the coatings, E-O maps were constructed for the different coatings. Regions corresponding to low, moderate and severe wastage were defined and shown in the maps to aid in qualitative selection of conditions for safe use of the coatings.

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