

Study of the Wear and Corrosion Performance of Hard Coatings Applied by Different Processes on Low Carbon Steel

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Abstract

Most of materials used in applications that require high wear resistance also undergo corrosive action of the service environment. The damage caused by the combination of both processes on the materials leads to huge economic losses in industry. Hard coatings are widely used as engineering solution to increase the lifetime of components operating in conditions of wear combined with corrosion. Nowadays, the most versatile techniques for applying such coatings are welding and thermal spraying. This work evaluates and compares the properties of coatings obtained by thermal spraying and welding using selected feeding materials. The performance of the coatings in corrosion and erosive wear tests is discussed. From the erosion tests performed for impact angle of 90°, a similar performance for the thermally sprayed tungsten carbide coatings and the welded stainless steel coatings with higher input energy was observed. Welded samples presented the best performance in corrosion test.

Keywords

Hard Coatings, HVOF, Welding, Erosive Wear, Corrosion

1. Introduction

One of the leading causes for degradation and failure of equipment parts is wear in its diverse forms as abrasion

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or erosion [1]. Frequently, in several industries, the erosive environment presents corrosive agents making the search for failure prevention still more challenging. Tribo-corrosion is encountered in several technological areas causing damages to equipment parts and compromising safe operation [2]–[4]. As a less costly alternative to parts fully made of wear and corrosion resistant materials, coatings have become a very important element for equipment manufacture and repair. Equipment can achieve improved performance if properly coated. The recovery of pumps, valves and other parts of industrial machinery using engineered coatings constitutes today one of the most important engineering alternatives [5] [6]. Coatings are thick films and can be applied by several techniques like welding, physical or chemical vapor deposition, electroplating and thermal spraying [7] [8]. There are a number of different welding processes requiring the selection of the process (or processes) suitable for a given application [9] [10]. Normally elected for the application of coating overlays, Gas Metal Arc Welding (GMAW) uses heat from an electric arc between a naked electrode, fed continuously, and the base metal [11]. Problems like discontinuities, lack of fusion, lack of penetration, slag inclusions, cracks and pores can occur [12] [13].

Thermal spray processes are very suitable to obtain coatings of high performance for protection or repair of components [14] [15]. All thermal spray processes use a gas generator as kinetic component. The balance between heat energy and kinetic energy can vary in large proportions, which results in coatings of different properties depending on the technique used for thermal spraying [16]. The combination of a structurally adequate substrate material and a proper coating has proven to be a highly flexible and economical manufacture strategy, mainly for the use in highly aggressive environments [7] [14]. Coatings using WCCo alloys, deposited by the thermal spray process, have been widely employed in applications against wear and corrosion by combining several advantages such as high hardness, resistance to abrasive and erosive wear, and corrosion resistance in various media. Cr_3C_2 -NiCr coatings offer superior corrosion and oxidation resistance and have a high melting point. In operating conditions, they also retain high hardness, strength and wear resistance up to temperatures around 900°C [17]. There is technical feasibility of using coatings of WCCo composites deposited by HVOF (High Velocity Oxygen Fuel) due to the excellent mechanical properties, wear and corrosion resistance, high deposition rate and superior surface finish compared to other processes deposition. By this process, the coatings have extremely low porosity (typically $< 1\%$) and high adhesion strength compared to conventional spraying processes. The coatings deposited by HVOF thermal spraying confer an excellent ability to protect the substrate [18]. The aim of this work is to evaluate and compare the wear and corrosion properties of coatings obtained by thermal spraying and welding using selected feeding materials.

2. Materials and Methods

The substrate material used in this work was an AISI 1020 low carbon steel. The materials for application in the coatings were chosen looking for a combined resistance to erosive wear as well as corrosive environments. Commercial powders of WC17Co (Praxair, Concord, NH, USA), $-45\ \mu\text{m} \pm 15\ \mu\text{m}$ and Cr_3C_2 -25NiCr (Praxair, Concord, NH, USA), $-45\ \mu\text{m} \pm 15\ \mu\text{m}$ were applied by HVOF. A stainless steel wire AWS 308LSi (BELGO, São Paulo, BR), 1.6 mm diameter, was used for GMAW coating deposition. The chemical composition of the applied substrate and feedstock materials are presented in [Table 1](#). GMAW process with inert gas (MIG) was used for welding overlay. The power source used was an adapted MTE DIGITEC 600 with double wire (IMC/LABSOLDA, Uberlândia, MG, BR). The three distinctive sets of process parameters used for welded coating deposition are presented in [Table 2](#). For HVOF spraying, the equipment used was a TAFA-JP 5000 (Praxair, Concord, NH, USA) with the parameters listed in [Table 3](#).

Microhardness measurements were performed on Shimadzu computerized equipment with a capacity of 0.01 kg to 2 kg in Vickers scale. All the welded samples were obtained from deposits and zones of interest in the form of prismatic bodies of $10 \times 8 \times 4\ \text{mm}$. Because of the high roughness of the as welded coatings, all the welded samples were grinded and polished with sand paper to 1200 mesh while the sprayed coatings were kept in the as sprayed condition in order to evaluate the samples without additional grinding and polishing work. Surface roughness measurements were carried out through a Mitutoyo digital Roughness TIME TR-200, with precision of 0.001 microns and processed through the interface for TIMESURF TR 200 V1.4. The results are presented as a mean of ten measurements. Surface roughness of the obtained coatings measured in the as sprayed condition for thermal sprayed samples and after polishing for welded samples. For image analysis and microstructure evaluation Scanning Electron Microscopy was applied (JEOL-JXA-840 and HITACHI TM

Table 1. Chemical composition of used materials (wt.%).

Material	C	Cr	Mn	Si	Co	Fe	Ni	W	Other
AISI 1020	0.25	0.0	0.6	0.35	0.0	Bal.	0.0	0.0	0.1
308LSi	0.03	19.4	0.9	0.8	0.0	68.7	9.9	0.0	0.002
WC17Co	5.3	0.0	0.0	0.0	17.0	0.0	0.0	Bal.	0.0
Cr ₃ C ₂ 25NiCr	11.0	Bal.	0.0	0.0	0.0	0.0	19.0	0.0	0.002

Table 2. Welding parameters for GMAW coating deposition.

Sample	V weld (cm/min)	V feed (m/min)	Voltage (V)	Energy (Kj/cm)	Feeding material	Dilution (%)
1	80.0	14.0	30.0	0.212	ER308LSi	29.06
2	60.0	12.0	30.0	0.255	ER308LSi	35.02
3	80.0	12.0	30.0	0.192	ER308LSi	30.00

Table 3. HP-HVOF deposition parameters.

Feedstock material	Oxygen		Kerosene		Air		Feed rate (g/min)	Stand off distance (mm)
	Pressure (bar)	Flow rate (SLPM)	Pressure (bar)	Flow rate (SLPM)	Pressure (bar)	Flow rate (SLPM)		
WC17Co	10.0	944	8.6	0.378	3.4	12	76	350
Cr ₃ C ₂ 25NiCr	10.3	873	6.9	0.378	3.4	12	38	250

3000).

Erosion tests were accomplished in an adapted mass testing machine designed by Erosive Welding Lab, Federal University of Uberlândia, BR. The testing machine was designed based on similar equipment developed by Desale *et al.* [19] and incorporating some details and procedures of the ASTM G73-10 [20], but did not specifically following that standard. The scheme of the erosion testing machine is presented in Figure 1. The samples for testing were obtained from deposits and zones of interest in the form of prismatic bodies of $10 \times 8 \times 4$ mm. All the welded samples were polished with sand paper to 1200 mesh in order to reduce the characteristic surface irregularities. For pure erosion testing the abrasive was a mixture of 4 liters of water and abrasive particle concentration of 400 g/liter.

The used abrasive were particles of ferric oxide, HRC = 40 - 50, 600 μ m diameter. The design of the specimen allows evaluating the impact angle of abrasive particles at 90° and 30°. In this work, only 90° impact angle was tested. The impact velocity of the abrasive particles was calculated as $v = 31$ m/s. As mentioned above trials were performed for each condition at a time of 2 hours, at intervals of 20 minutes, during which wear rates were determined. The wear was determined by difference in weight before and after test employing a precision analytical balance (0.1 mg). Each test was repeated under the same conditions 3 times getting the average value results for each sample.

The polarization curves for the different materials tested were obtained in a potentiostat AUTOLAB PGSTAT 302N (Metrohm Autolab, Utrecht, NL) connected to an interface and GPES professional package, which allows the choice of the electrochemical technique to use, graphical options and determination of the main parameters test (corrosion potential, passivation current, corrosion rate, etc.). As corrosive medium NaOH was used in concentration of 1 mol (PH = 14). For measurements, a platinum counter electrode and a reference electrode of Ag/AgCl were employed to a scanning speed of 1.66 mV/s from -800 to 900 mV with respect to corrosion potential.

3. Results and Discussion

3.1. Mechanical Properties

Table 4 shows the average surface roughness and microhardness results for the obtained coatings. From the

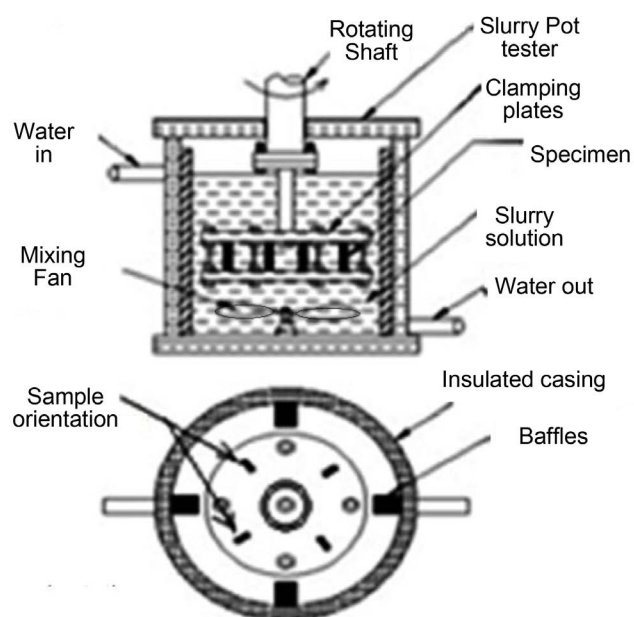


Figure 1. Schematic representation of the erosive wear test.

Table 4. Surface roughness and microhardness results for thermal sprayed and welded coatings.

Sample	Roughness-Ra (μm)	Microhardness HV _{0.5}
ER308LSi 1	0.86	386
ER308LSi 2	0.96	404
ER308LSi 3	0.85	342
WC-17Co	3.12	1042
Cr ₃ C ₂ -25NiCr	5.44	692

Note: Results are presented as the mean value of 10 measurements with a maximum standard deviation of 10%.

analysis of **Table 4**, it can be observed that a coating with high hardness was achieved by using the HVOF spraying in the case of WC17Co, 1042 HV, about 62% higher than the other HVOF coating of Cr₃C₂25NiCr.

The microhardness of the three ER308LSi stainless steel welding coatings was around 36% of the maximum value for WC17Co alloy. The welded material is basically constituted of iron with almost 20% of chromium in its composition, which contributed to a high hardness. Cr₃C₂25NiCr that has higher Cr content (almost 70%) has presented the second higher hardness. WC17Co has essentially tungsten in its composition with a high content of WC, which also contributes to that high hardness. It should be observed that the roughness of HVOF coatings was measured in the as sprayed condition while GMAW welded coating was machined and abraded before measurement. Cr₃C₂25NiCr coatings have presented the highest surface roughness in comparison with the other coatings. The typical microstructure of the obtained coatings can be seen in **Figure 2** for welded and HVOF sprayed samples. **Figure 3** shows the cross sectional images of the welded (typical) and thermally sprayed coatings.

It can be observed that, as expected, a typical casting structure results for welded coatings. Since the tested samples were obtained from the center of the welded beads, that includes the fusion zone and the heat affected zone, as showed in **Figure 3(a)** and **Figure 3(d)**, a very homogeneous microstructure is exposed to the erosion and corrosion tests. From the coatings applied by HVOF spraying, the lamellar structure is dominant and presents certain level of pores and oxides, as presented in the enlarged detail of **Figure 3(b)** and **Figure 3(c)** for Cr₃C₂25NiCr and WC17Co, respectively. It can be also observed differences in carbide size and distribution for Cr₃C₂25NiCr and WC17Co. Tungsten carbide coatings (**Figure 3(e)**) present a smaller carbide size than Chromium carbide (**Figure 3(f)**) and then a higher amount of carbides in the microstructure.

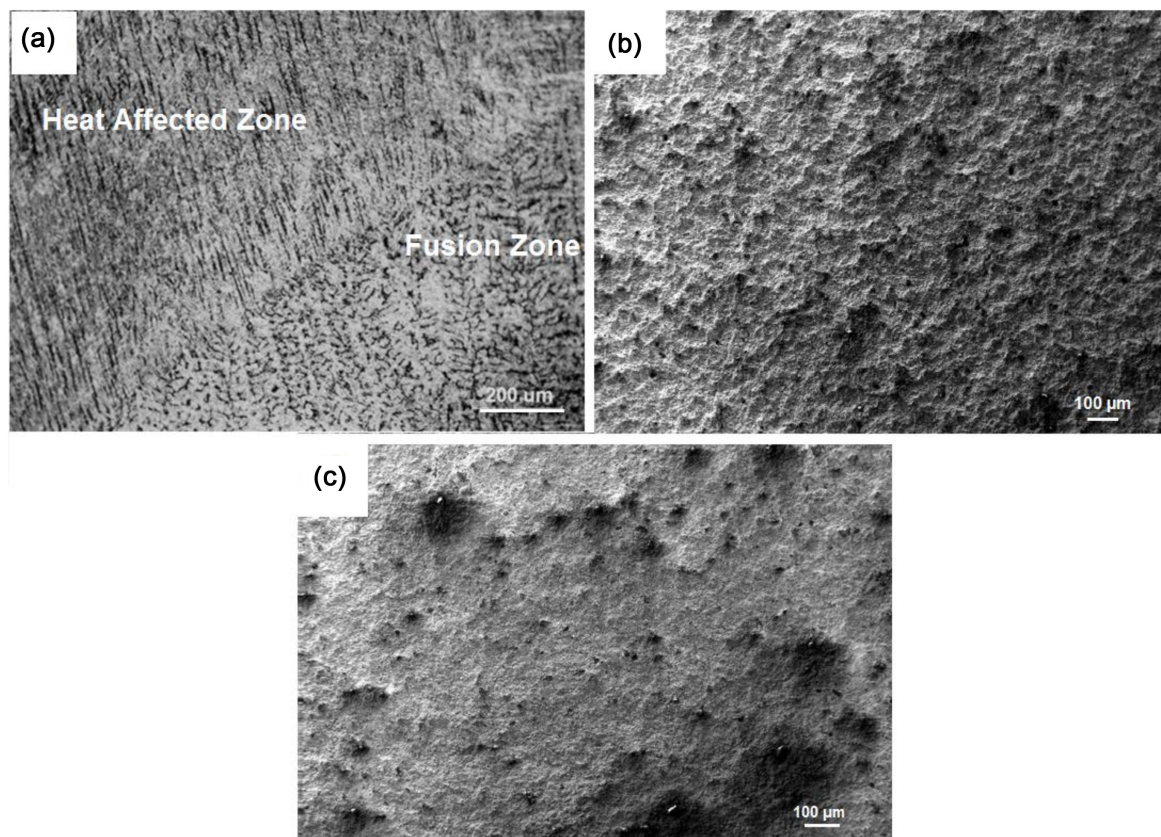


Figure 2. SEM surface images of the coatings of ER308LSi obtained by welding showing (a) the typical welded microstructure of samples, and the HVOF sprayed coatings of (b) WC17Co and (c) Cr₃C₂-25NiCr.

3.2. Corrosion Results

The results of the polarization tests can be seen in **Figure 4**. The result for the substrate alone is also presented for comparison. The Tafel slope analysis of each one of the coatings is detailed in **Table 5**.

In a general way, all the coatings have presented a very low oxidation rate that is probably related to the characteristic impedance of the coatings, as defined by Toma *et al.* [21]. From the analysis of the results showed in **Figure 4** and **Table 5**, it can be observed that the best performance was that of the ER308LSi samples, followed by WC17Co. Comparing the corrosion results for the three welded samples, it is possible to observe a variation of two orders of magnitude among the samples that could be credited to the differences in dilution and formation of carbides.

The worst result was for the Cr₃C₂-25NiCr sample, with a corrosion rate much higher than the welded samples and about twice the WCCo sample. It has to be stressed that the corrosion results of the thermally sprayed samples are even worse than the results for the carbon steel substrate. These results can be justified by the corrosion resistance and passivity of the respective binder in the carbide sprayed coatings. As stated by Souza and Neville [22], corrosion proceeds primarily by dissolution of the Co or NiCr binder phase.

It could be expected a better corrosion performance for the Cr₃C₂-25NiCr that has about 20% of Cr when compared to carbon steel. Then, an additional explanation for such results can be the differences in the surface roughness of these coatings, exposing a much larger surface area for the corrosion agent, as discussed by Çelik *et al.* [23]. It has to be stressed that the original roughness of the Cr₃C₂-25NiCr coating was kept in the as sprayed condition exactly to allow this comparison.

3.3. Erosive Wear Results

The erosive wear results are presented in **Figure 5** for an impact angle of 90°. Thermally sprayed samples were tested with initial surface roughness values corresponding to that of the as deposited coating, *i.e.*, 3.12 μm and

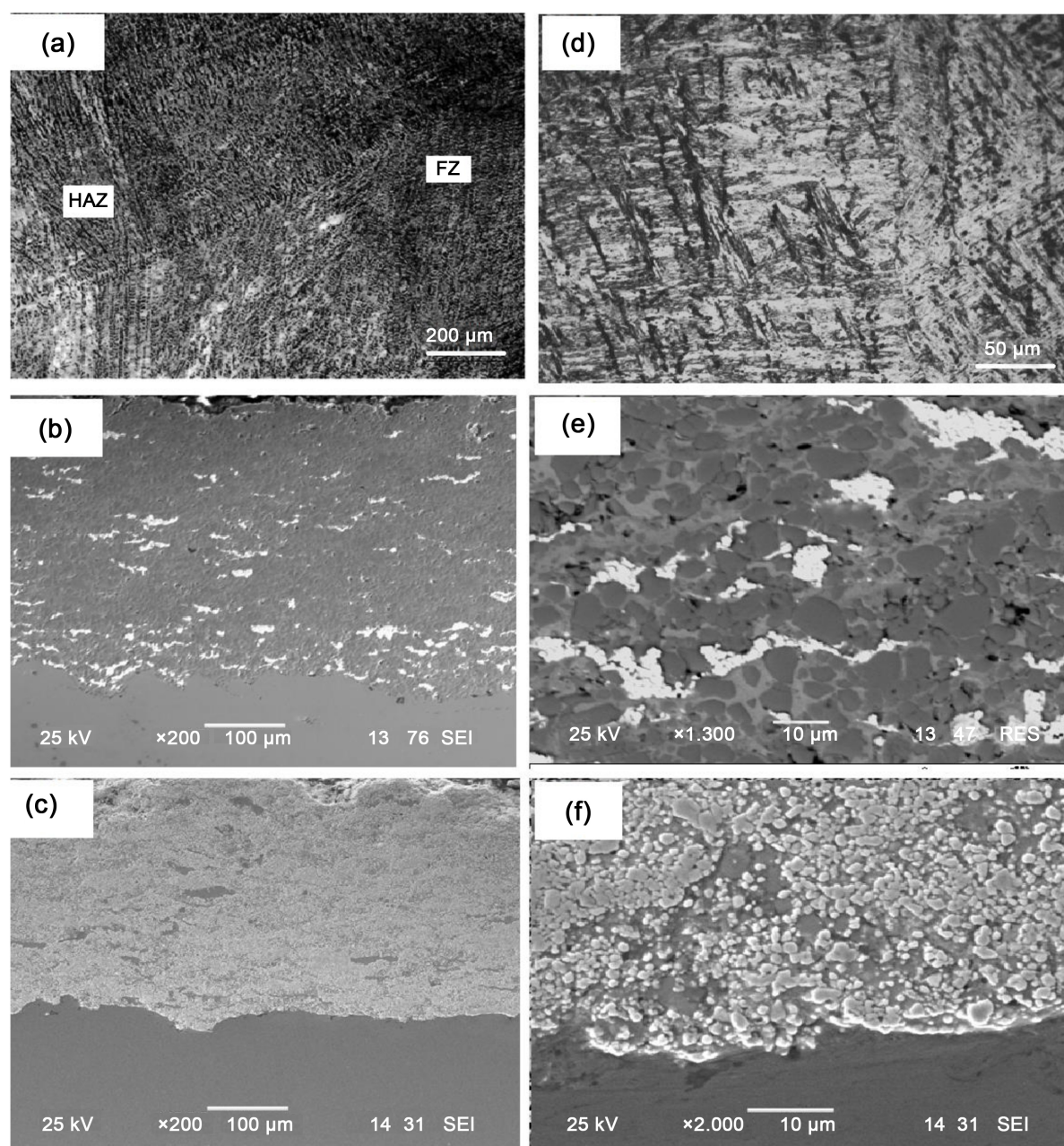
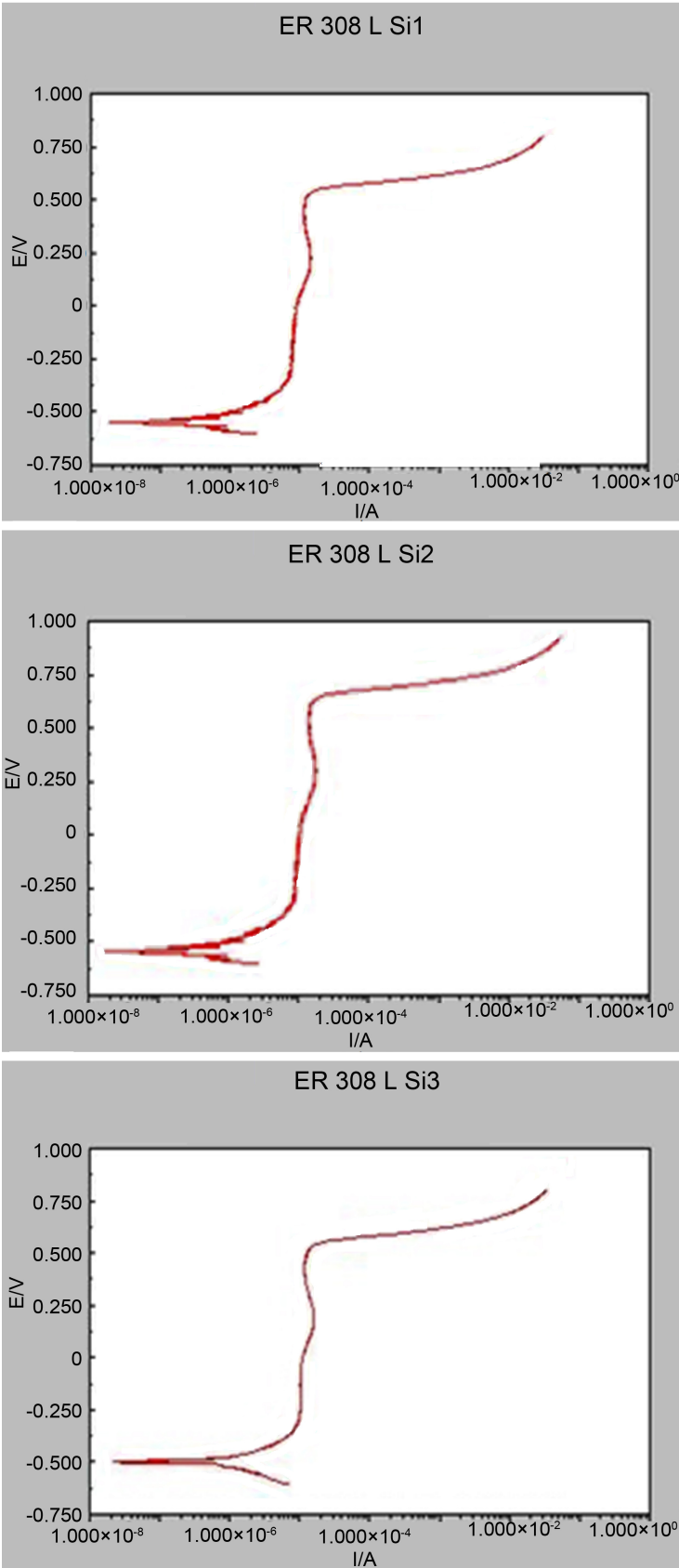


Figure 3. SEM cross sectional typical images of the (a) welded ER308LSi, (b) $\text{Cr}_3\text{C}_225\text{NiCr}$ and (c) WC17Co thermally sprayed coatings showing the typical casting and lamellar structures. Detailed microstructures are observed in images (d), (e) and (f) for the coatings on the left, respectively. Larger carbide size can be observed for $\text{Cr}_3\text{C}_225\text{NiCr}$ (e) in comparison with WC17Co (f).

5.44 μm for WC17Co and $\text{Cr}_3\text{C}_225\text{NiCr}$, respectively. Because of the extremely high roughness characteristic of the welded deposits, the ER308LSi tested samples were grinded and polished to 1200 mesh, reaching a much lower roughness around 1 μm . Observing the microstructure of the coatings (Figure 3), it is possible to infer an analogy between the structure and behavior in erosive wear.

A regular homogeneity in the distribution of the carbides in the matrix of cobalt can be seen in the WC17Co (Figure 3(f)) as well as higher hardness may explain its high wear resistance. Differences in carbide sizes could also explain the higher resistance, as evidenced by Yang *et al.* [24] who show an increased rate of wear with increasing grain size of carbides. In the case of the $\text{Cr}_3\text{C}_225\text{NiCr}$ coating, a structure with relatively high porosity



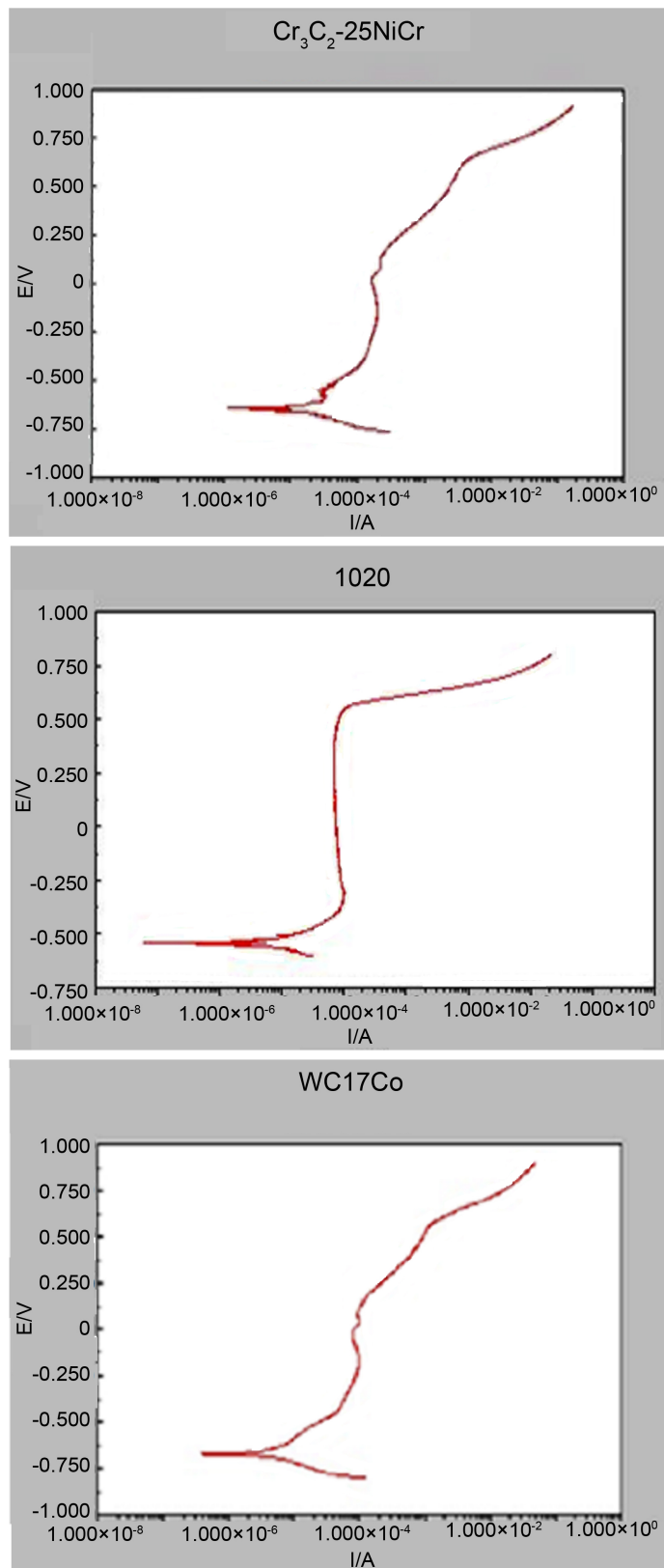


Figure 4. Corrosion results from polarization tests for the tree welded ER308LSi samples, the AISI 1020 substrate and the two HVOF sprayed samples.

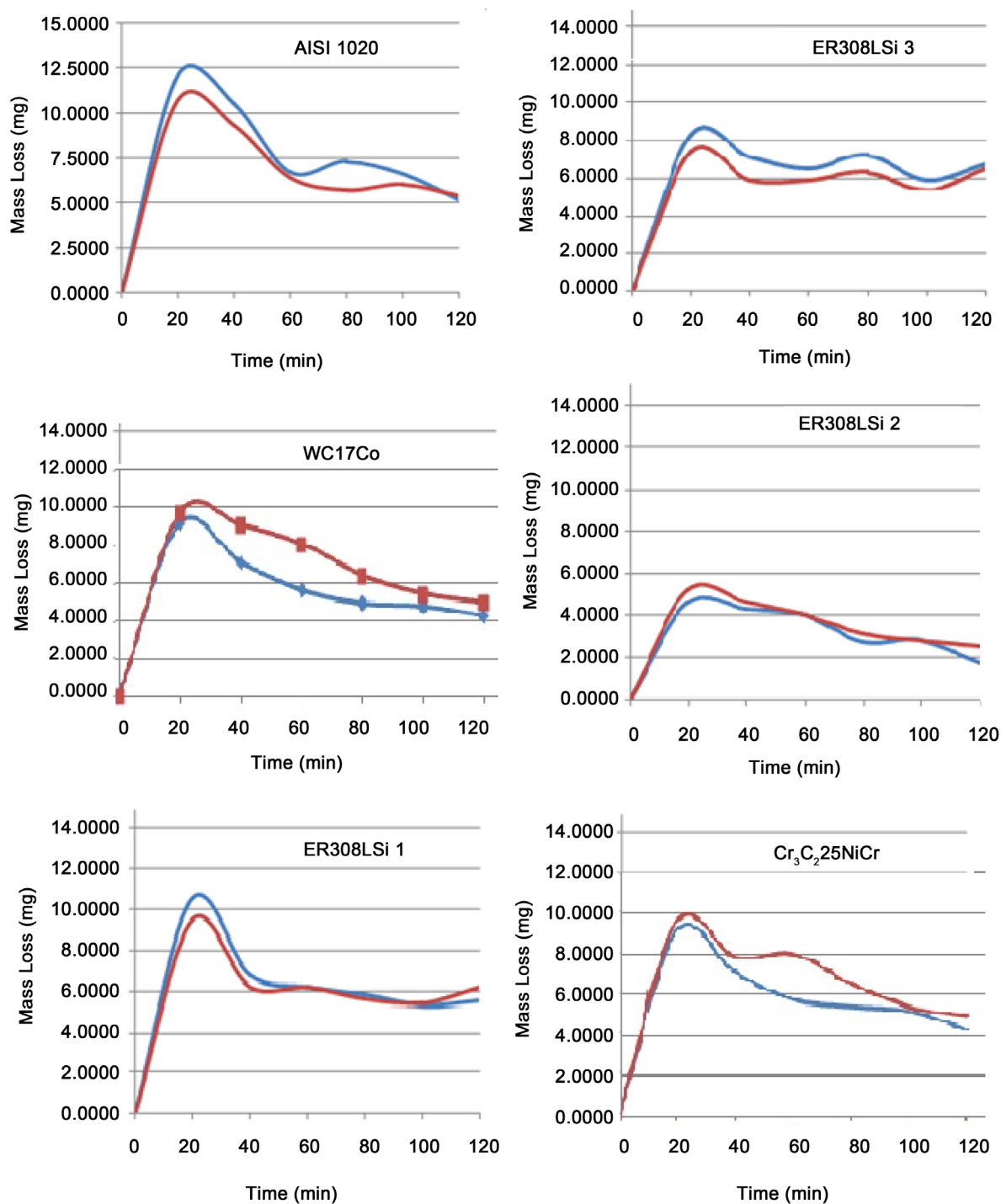


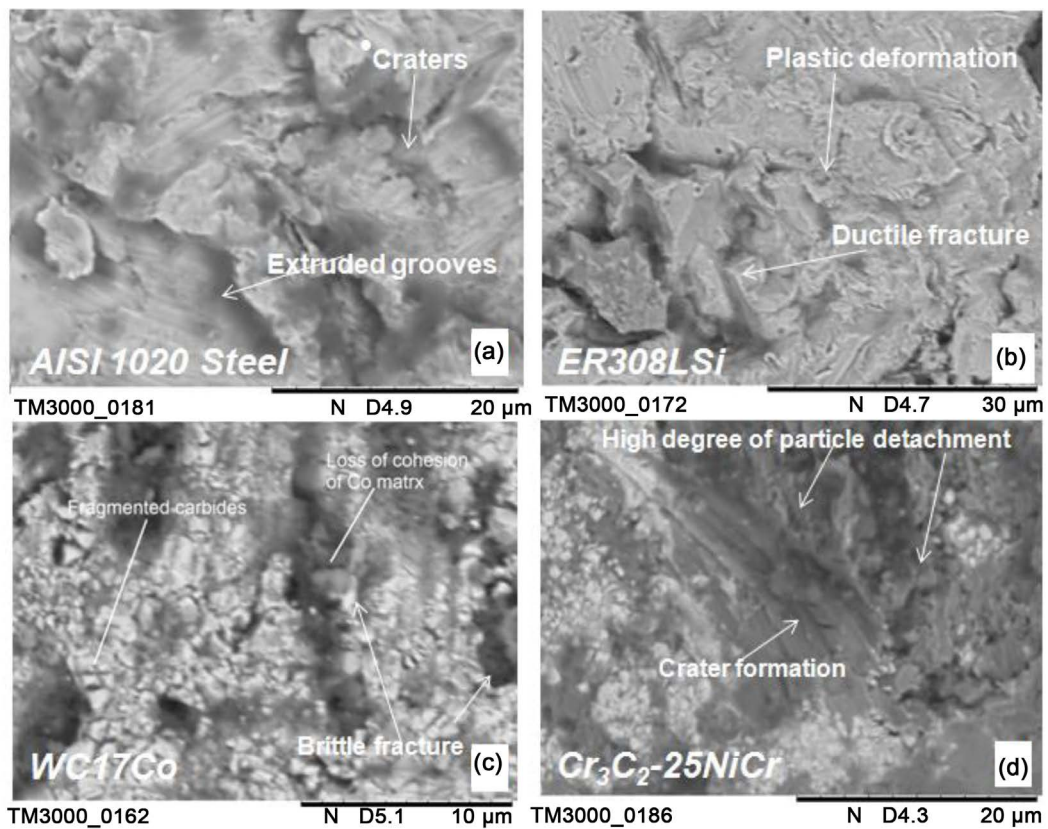
Figure 5. Mass loss for the AISI 1020 substrate, ER308LSi, WC17Co and Cr₃C₂25NiCr coated samples in the erosive wear tests.

and low carbide homogeneity distribution (**Figure 3(e)**) associated with large carbide size can justify its performance in wear tests.

The analysis of the worn surface (**Figure 6**) showed a high degree of detachment of particles with formation of craters and subsequent destruction of these craters and borders (**Figure 6(d)**), then justifying the low wear resistance. In all cases the stabilizing period is characterized by an intense wear of the coating, and this has been

Table 5. Corrosion test results of polarization curves from Tafel slope analysis.

Parameters	Substrate	Thermally sprayed coatings			Welded coatings	
	AISI 1020	WC-17Co	Cr3C2-25NiCr	ER308SLi 1	ER308SLi 2	ER308SLi 3
I_{corr} (A)	4.026E-7	4.737E-6	1.288E-5	2.588E-7	2.590E-7	1.198E-7
L_{corr} (A/cm ²)	5.033E-7	5.921E-6	1.61E-5	3.234E-7	3.866E-7	1.498E-7
R_p (Ohm)	1.352E+4	3.046E+3	3.863E+2	5.690E+3	1.043E+4	1.251E+2
$E_{corr, obs}$ (V)	-0.475	-0.677	-0.530	-0.512	-0.538	-0.491
$E_{corr, cal}$ (V)	-0.483	-0.683	-0.502	-0.509	-0.545	-0.497
Corr Rate (mm/year)	5.370E-4	2.800E-3	6.737E-3	3.451E-4	2.314E-4	1.598E-4

**Figure 6.** SEM images of the eroded surfaces of (a) AISI 1020 substrate, (b) ER308LSi, (c) WC17Co and (d) Cr₃C₂25NiCr coated samples.

reflected by the literature [25] [26]. From the analysis of the eroded surfaces, it could be observed that the mechanism dominating the erosion process is brittle fracture type whose value is maximum for normal impact angle.

The erosive wear of the welded coatings is preceded by fast surface hardening as evidenced by a previous comparison of systematic microhardness measurements in the eroded coatings throughout the coating thickness, from the substrate to the top surface, compared to the measurements of the as coated samples. The damage mechanism is ductile fracture characteristic of such materials where material detachment is preceded by plastic deformation, hardening and then loosening of wear particles as result of certain number of cycles, as stated previously by several authors [27]-[29].

Figure 7 shows a comparative result for the volumetric wear of the tested samples in erosion. The calculation was performed by dividing the average of accumulated mass loss of the samples by the density of each material.

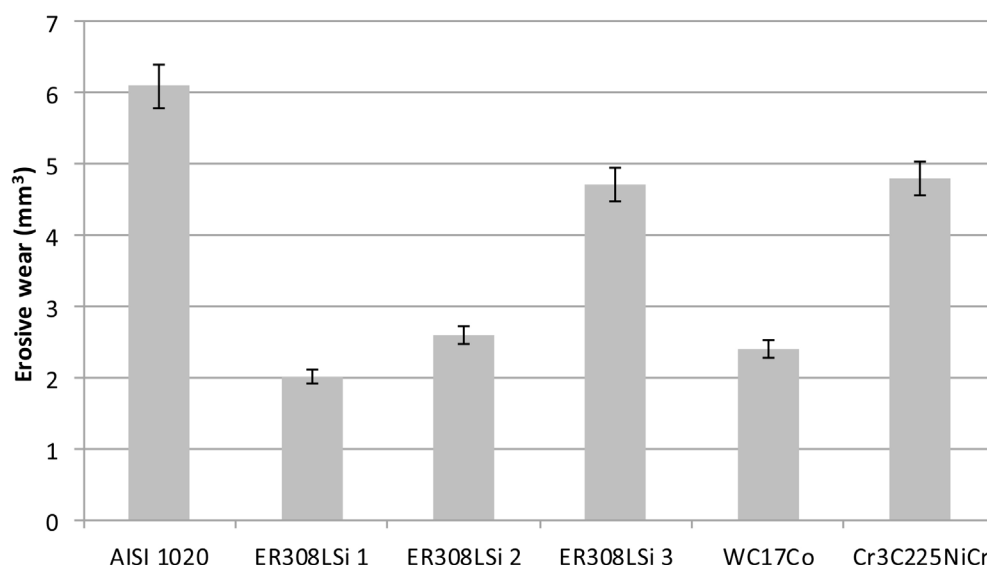


Figure 7. Volumetric erosive wear results of tested materials ($t = 2$ h, impact angle 90°).

The densities were obtained from the manufacturers of the materials: 7.85 g/cm^3 , 7.9 g/cm^3 , 4.6 g/cm^3 and 7.1 g/cm^3 for AISI 1020, ER308LSi, WC-17Co and $\text{Cr}_3\text{C}_2\text{-25NiCr}$ respectively.

The best performance is that of the sample ER308LSi1. The behavior is very similar for the WC17Co applied coating that shows a slightly better result compared to the second stainless steel sample. $\text{Cr}_3\text{C}_2\text{25NiCr}$ has presented the lowest erosive wear response for the coated samples, just compared to welded ER308LSi3. However, considering that the tests were performed only for impact angle of 90° , the results for 30° of impact angle have to be determined in order to fully evaluate the erosion performance of the applied materials.

4. Conclusions

Tungsten and chromium carbides alloys and stainless steel were deposited onto low carbon steel by thermal spraying or welding processes. The obtained coatings have shown a smooth microstructure without relevant level of defects. The best corrosion performance in polarization tests was for ER308LSi welded coatings, followed by WC17Co HVOF applied coatings.

The lowest corrosion resistance was obtained for $\text{Cr}_3\text{C}_2\text{-25NiCr}$ sample that had performed even worse than the uncoated carbon steel. This not expected result was mainly credited to the huge difference in roughness of the thermal sprayed coatings compared to the polished welded coatings.

From the erosion tests performed for impact angle of 90° , it was found that the erosion resistance of the ER308LSi welded sample was the best one, followed quite closely by WC17Co HVOF sprayed sample, which had performed better than the other two welded samples.

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