



Solid particle erosive wear behaviour of flame sprayed EVA based polymeric coatings

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Abstract

Flame spraying of polymers allows obtaining functional coatings for protecting against wear and corrosion. Among many engineering polymers, the Ethylene-Vinyl Acetate (EVA) copolymer attracts attention with its superior mechanical and chemical properties. EVA, which has high chemical resistance, high impact resistance and mechanical flexibility, high friction coefficient, is among the candidate coating material that can be used in aerospace, automotive, marine, chemical and manufacturing industries to protect metallic surfaces. The use of polymeric coatings in applications is often restricted when large surfaces need to be coated or if the coating needs to be applied in the openair field. Flame spraying is one of the most cost-effective methods in the production of polymeric coatings. The curing process and solvent use required in conventional polymeric coating applications are not required in thermal spray coating applications. Contact of polymeric surfaces with solid surfaces and abrasive solid particles reduces polymer life and performance. In this study, solid particle wear behaviors of EVA coatings on stainless steel produced by flame spraying is investigated and then tested in different erosive wear test conditions. The erosive wear rates were compared with stainless steel. The main wear mechanism in the polymeric coatings is associated with micro-deformation, micro-cratering and micro-crack formation.

1. Introduction

Thermally sprayed polymer coatings are standing out in many industries, including the petrochemical, pump, automotive, marine, steel construction and aircraft industries. These coatings are being used for surface protection against corrosion and aggressive chemical attacks. Thermal spraying is a unique, environmentally compliant, coating method for the application of polymers and polymer composites because it overcomes processing limitations of other polymer coating methods. Flame spray technology is generally used in the production of polymer coatings. Flame spray polymer coating applications are not restricted by the size of the work part being coated and coatings can be readily applied in the open field, which is an important consideration for industrial use. Coating performance is strongly influenced by spray parameters. The coating structure and thickness can be controlled by optimized spray parameters. The important point at this point is to prevent the polymeric particles from overheating with the flame. Otherwise, the coating structure deteriorates and the surface quality is negatively affected. As can be seen in the bottom pictures in Table 1, different colors of polymeric coatings were successfully produced. The most important parameters affecting the coating quality are: spraying rate, spray distance, gas flow rate, powder feed rate and substrate temperature. Flame spraying is a unique, environmentally compliant,

technique for the application of polymers and polymer composite coatings because it overcomes processing limitations of other polymer coating techniques.

Table 1. Flame spray process parameters.

Spray system	IBEDA F311 FX-S flame spray system
Flame spray parameters (optimized)	Value
Substrate temp.	180°C
Spray dist.	150 mm
Gas pressure ratio	1/2
Powder feed rate	10 g·min ⁻¹
Surface roughness, (Ra)	2 µm

Many polymeric materials can be used as feedstock material in thermal spraying for protection against corrosive and abrasive attacks. Polymeric materials such as PVC, EVA, Nylon can be easily sprayed and deposited on metallic surfaces. Ethylene vinyl acetate or EVA is an ethylene and vinyl acetate copolymer. It is a highly elastic and rigid thermoplastic materials with high solid particle impact resistance. Vinyl acetate content determines degree of elasticity. Besides; EVA is high chemical resistant, low cost material and adhere well to metal surface. In order to answer many industrial

requirements (economic, environmental), polymeric coatings have become more and more attractive for improving properties of metallic parts. For these reasons, EVA can be used as a candidate coating material on metallic surfaces exposed to particle erosive wear. Thermal spray technology can successfully apply polymer coatings to a wide range of different substrate materials at various thicknesses. Flame spraying is a basic and cost-effective member of the thermal spray coating family that produces high quality surface coatings using heat, from the combustion of a fuel gas with oxygen, to melt a spray coating material which is propelled onto a substrate. The deposition of semi-molten polymer particles onto heated metallic surface whereby process heat causes the particles to flow and coalesce into a complete cohesive polymer coating. The flame spray polymeric coating technology has advanced considerably in the past 50 years. Flame-spraying equipments, specific hardwares, nozzles and other accessories have been designed for various functional polymeric coating applications. [1-5]. Thermoplastic based coating powders can be applied by flame spraying because they only need to melt and they do not need to cross-link [6,7]. Although the flame spray process is a practical and economical solution, it requires technical expertise and process optimization during spray application. Prolonged residence of the polymeric powder material in the flame jet may lead to structural degradation and oxidation. This adversely affects the coating quality and can lead to coating defects. The control of particle temperature and spray rate determines the coating quality and performance. Pinhole, porosity, adhesion problems increase and surface degradation in coating structure due to unsuitable spray particle velocities and temperatures. The decomposition temperatures of the polymers are around 250°C and are of very low and critical importance. Flame spray polymer coatings are very attractive for on-site applications in open atmospheric conditions and for the protection of very large steel-based constructions. The flame spray polymer coatings can be applied in several industrial fields as aviation, marine, metal manufacturing, pump, chemical, petrochemical, energy and automotive industries. Successful deposition of polymer coatings by flame spraying involves careful consideration of polymeric material limitations and the capabilities of individual spraying process [6-9, 10-17].

Solid particle erosive wear is the progressive loss of material due to the impact of solid particles, a liquid or a mix of solid particles and liquid. Several research studies and tests on erosive wear on engineering polymers or polymeric coatings have been investigated and discussed over the years due to their importance in mechanical applications [6-10]. In this experimental study, solid particle erosive wear behaviors and wear rates of EVA coatings are examined and compared with stainless steel. The following sections describe the manner of coating preparation, the method of testing and the erosion results.

2. Experimental: materials and methods

Combustion based (as powder flame spraying) thermal spray processes use hot gas flows to accelerate and melt/soften powder particles in-flight and to propel them towards the surface to be coated. Traditionally, thermal spraying has been used to deposit metals, oxides and composites and also recently has been applied to polymers. The flame spray process was the first thermal spray technique used to deposit polymers. Because of its simplicity, process control capability and low capital investment. Several industrial examples of flame sprayed polymer coatings include pipe coatings, valves, pumps, steel constructions, vessels, boat hulls, wastewater surge tanks, railroad parts and exhaust systems for submarines and various automotive parts. It has been reported that some polymeric materials can be partially degraded/oxidized in-flight during the flame spray process. Polymeric coating can be applied easily by controlling particle temperatures by means of special design nozzles and equipment of flame spray. The velocity of the main process gas at the nozzle exit can be adjusted in the range of 25 to 100 m·s which is used to control particle in-flight residence time as well as the intensity of forced convection heat over the substrate and/or previously deposited coating layers. Polymer based feedstock material in powder form is injected down stream of the main process gas using a carrier gas that can be air or an inert gas. Deposition by flame spraying may require careful practice and optimization of spray parameters to develop suitable and cost-effective functional polymer coatings on metal structures. In this experimental study, it was used as 316 grade stainless steel substrate material in the form of 100 x 100 x 4 mm plate. Pre-heating (50°C) was done after surface cleaning and sand blasting before spraying. The surface condition and the wetting characteristics of the substrate play an important role in the morphology of polymeric splats and adherence to substrate. Higher surface quality induces higher adherence of the substrate. EVA coating powders are globular form and in the range of +45-200 µm (red and blue color). Polymer coatings can be applied in the desired colors.

There is no difference between colored coating properties. Coating process was carried out with IBEDA F311 flame spray unit (Figure 1). exhibits spray unit, the optimum spray parameters and technical properties of the EVA powder (Table 1, Table 2). Figure 2 shows macro image of top surface of coatings produced with optimized spray parameters

The solid particle erosion testing was performed in accordance with the ASTM G76-95 standard. The abrasive particles used were sharp-edge alumina with a particle size of 120 mesh (90-125 µm). The tests were performed between 15° and 90° impingement angle with a blast air pressure of 1.5 bar in a specially designed vacuum assisted test rig (Figure 3). The EVA coating samples were located a distance of 20 mm from the nozzle exit. Abrasive solid particle exposure time for each sample were 10-20 s. Three repetitions were achieved for every test and average of mass loss was calculated. Before

and after solid particle erosion tests, samples were cleaned with air blasting and mass loss was measured by using an electronic balance with an accuracy of ± 0.1 mg. After the wear test, the erosion tracks and surface roughness were examined with a laser profilometer. Solid particle erosion test parameters are given in Table 3



Flame Spray System and Spraying gun

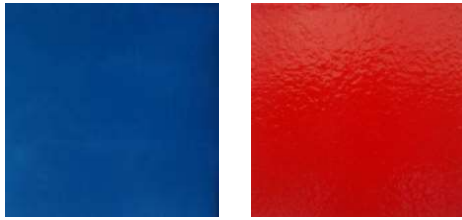
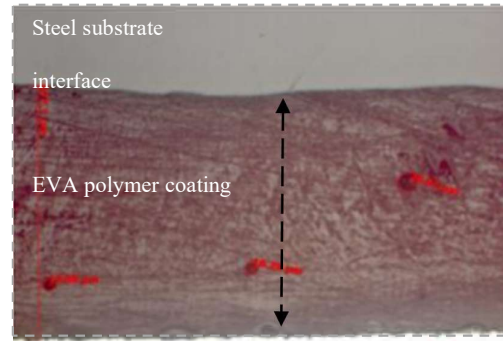


Figure 1. Flame spray unit and coated samples.



(a) top surface macro images



(b) cross section images

Figure 2. (a) Flame spray EVA coated samples macro images and (b) cross section image after metallographic preparation under microscope.

Table 2. Properties of EVA copolymers as feedstock material.

Properties of EVA copolymers	
Chemical and physical properties of EVA copolymer	Entecopolymers granules powder size: +50-200 μm
Chemical formula	$(\text{C}_2\text{H}_4)_n(\text{C}_4\text{H}_6\text{O}_2)_m$
Density	$0.92 \text{ g}\cdot\text{cm}^{-3}$
Hardness shore D	15-45
Elongation at break	200-900%
Ductile-Brittle Temperature	-69°C
Colour	blue or red

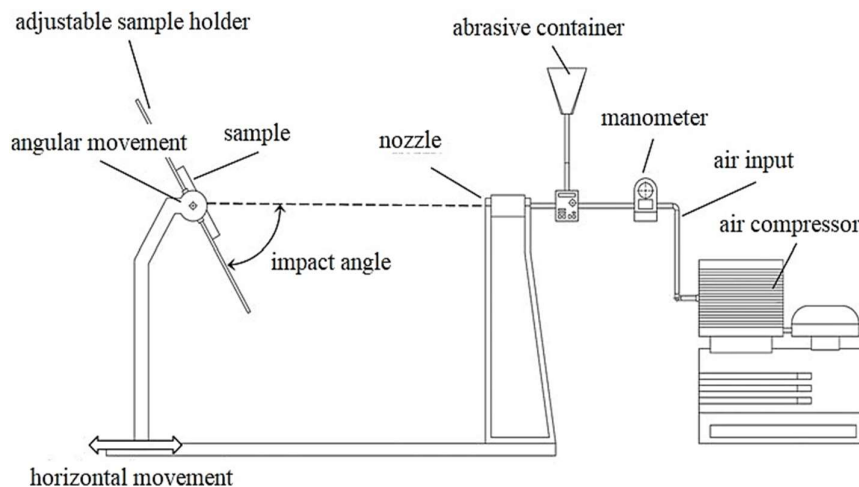


Figure 3. Schematic solid particle erosion test rig.

Table 3. Solid particle erosion test parameters.

Solid particle erosion test parameters.	
Erodent type	Alumina (Al_2O_3)
Erodent size	120 mesh (90-125) μm
Particle impingement angle	15°, 30°, 45°, 90°
Acceleration/blast gun pressure	1.5 bar
Test temperature	25°C±2°C
Test Duration	10 s, 20 s
Stand-off distance	20 mm

3. Results and discussions

The most critical point in the application of polymer coatings with flame spray technique is the optimization and application ability of the coating parameters. During the spray application, spray distance, flame jet properties and powder feeding system parameters should be carefully selected. Depending on the experience of the operator, the application speed and distance should be kept under control. As can be seen in Figure 2, EVA based polymeric coatings with the desired smooth surface quality have been successfully produced by flame spray gun. Interface between substrate and coating shows good adherence. Coating defects, contaminations and delamination were not observed at the interface. Under the control of optimum spray parameters, coating of desired thickness and surface quality can be obtained. In spraying process, gas flow ratio, spray distance, substrate temperature are the most important parameters. These parameters control the melting and acceleration of the polymeric particles fed in the flame jet. The effect of unsuitable parameters causes color changes in coating surface, deposition and adherence problems and formation of structural and surface degradation. As a result, poor adhesion, poor surface quality and limited strength properties are obtained. Another important factor is that the coating thickness is not homogeneous. This is directly dependent on operator skill and relative spraying speed and number of passes. If the coating thickness is too high, the surface quality deteriorates. With the effect of increasing thickness and long application time, increasing temperature causes structural degradation. In the initial spray trials, the deposition of the coating on the substrate surface, the adhesion of the coating and the quality of the coating surface was not successful. Then, repeatable quality coatings were obtained by optimizing the spray parameters.

Although polymeric coatings are generally used for corrosion resistance, hard and solid abrasives cause rapid abrasive wear, especially on metallic surfaces in contact with solid particles. Some polymeric coatings (as EVA copolymer) withstands high resistance to chemicals, abrasion, impacts and extreme mechanical loads. EVA has an excellent adhesion to metal. In this study, erosive wear properties and performances of EVA coatings were investigated. The wear tests tried to understand the solid particle erosive wear performance and wear mechanism

of the flame sprayed EVA coatings. The most important consequence of solid particle erosion is mass loss in the target material. Mass loss in the target material; depending on many parameters such as abrasive solid particle size, abrasive particle velocity, impact angle, abrasive particle feed rate, target material chemical composition and hardness. The fact that the target materials are in brittle and ductile structures causes the resulting maximum wear amounts to appear at different impact angles. Erosive wear behavior of polymeric materials differs according to metallic and ceramic materials. There are some possible possibilities depending on the energy and mass of the solid particles. These are the particles hit the surface at high speeds and bounce back, the particles are embedded in the surface, the particles cut the surface and cause cratering. The polymeric surface can reduce impact energy after contact with the solid hard particle or cause the particle to be embedded on the surface. It is thought that micro-cutting and deformation occur on the polymer surface due to abrasive particle type and geometry. In this experimental study, EVA coated stainless steel samples are tested under different test conditions.

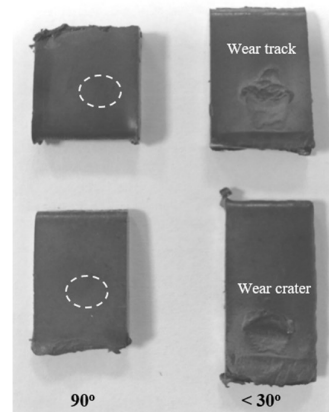


Figure 4. Macro wear track images on EVA coated samples after erosive wear test.

Figure 4 illustrates the coating macro surface images after the erosive wear test. As can be seen, there are two conditions on the wear tracks depending on the angle of impact of the solid particles. It causes some particles to

scatter back from the surface or are embedded into the surface. Therefore the wear mechanism is quite complex. At low impact angle, EVA coating is eroded by microploughing, microcutting and an extensive cratering. As mentioned earlier, hard and sharp particles hit the surface by high energy can cause significant damage to the surface. Figure 4 (right column) shows the cratered regions on surface. Once the particles begin to cut the coating and form a crater, it is buried and stacked. Therefore, the wear mechanism becomes very complicated. As can be seen from Figure 5, the erosive wear behavior on both coating and stainless steel is the same as ductile materials. The increase in solid particle impact angle on both the coating surface and the bare metal surface causes the erosion rate decreased. The erosion rate is defined as the ratio of mass loss to mass of erodent particle, which is a dimensionless quantity. Erosion rates are very close at large impact angles ($>75^\circ$). The maximum wear rate is observed at low impact angles ($<30^\circ$). The most obvious difference of wear rate being observed at 30° and 45° angles. Generally, it has been recognized that peak erosion exists at low impact angles ($15\text{-}30^\circ$) for ductile materials and at a high impact angle (90°) for brittle materials.

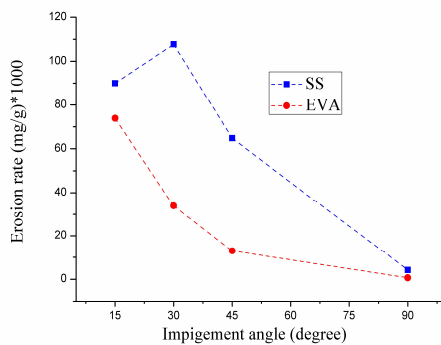


Figure 5. Effect of impact angle on erosion rate of EVA coatings and stainless steel (SS) surfaces.

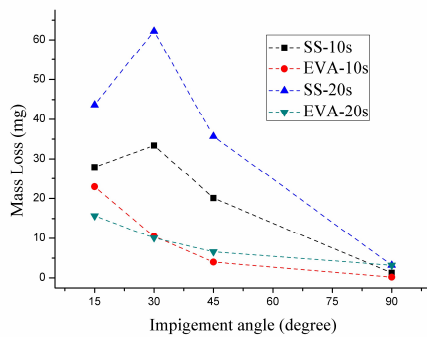


Figure 6. Change of mass loss for different impact angle and duration of erosion test on EVA coated and bare stainless steel surface.

Figure 6 shows a comparative mass loss change due to test duration. Especially in erosive wear tests performed on uncoated stainless steel surface, if the test time increases from 10 s to 20 s, wear and mass loss at low angles is quite high. As can be seen from the graphic,

the change of wear losses is also displayed depending on the angle of impact. Both surface show that mass loss is reduced by increasing the impact angle. It is observed that wear mass loss in stainless steel samples is higher than EVA based polymeric coatings. As a result of the rapid impact of solid particles on metallic surfaces, wear craters form on the surface and wear rate increases rapidly on the surface. However, polymeric coatings absorb impact energy. This affects the reduction of wear. The polymeric coating exhibits similar wear behavior to stainless steel at low angles. There are differences between wear tracks and surface profiles. Solid particles embedded in the coating surface act as abrasive and occasionally combine or scatter with incoming particles. It is quite difficult to control this behavior and wear mechanism.

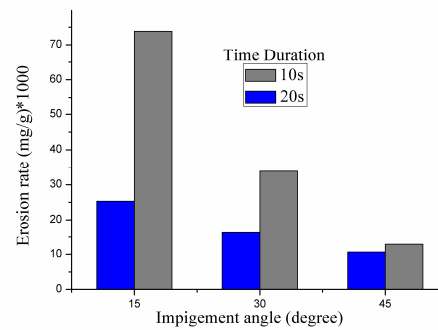


Figure 7. Time-dependent erosion rate of EVA coatings at different impact angles.

In Figure 7, the erosion rates of EVA coating at the different impact angle are compared according to the test duration. By the higher impact angle decreases the erosion rate. The wear rate in polymeric coatings at low angles is quite high. At higher impact angles the erosive wear rate is relatively lower. It can be understood from here that wear accelerates in the first stage and then it is not affected by the increasing time. At this point, the highest probability; particles embedded in the surface prevent embedding of particles from behind. There is no significant change in the effect of the duration with the increase in the angle of impact.

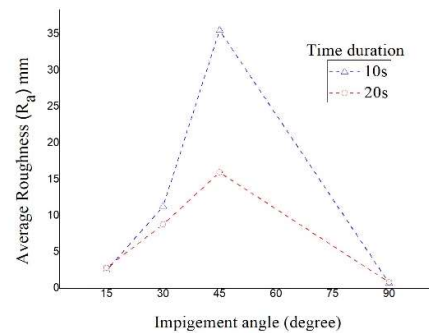


Figure 8. Change in average roughness values over time on EVA coatings.

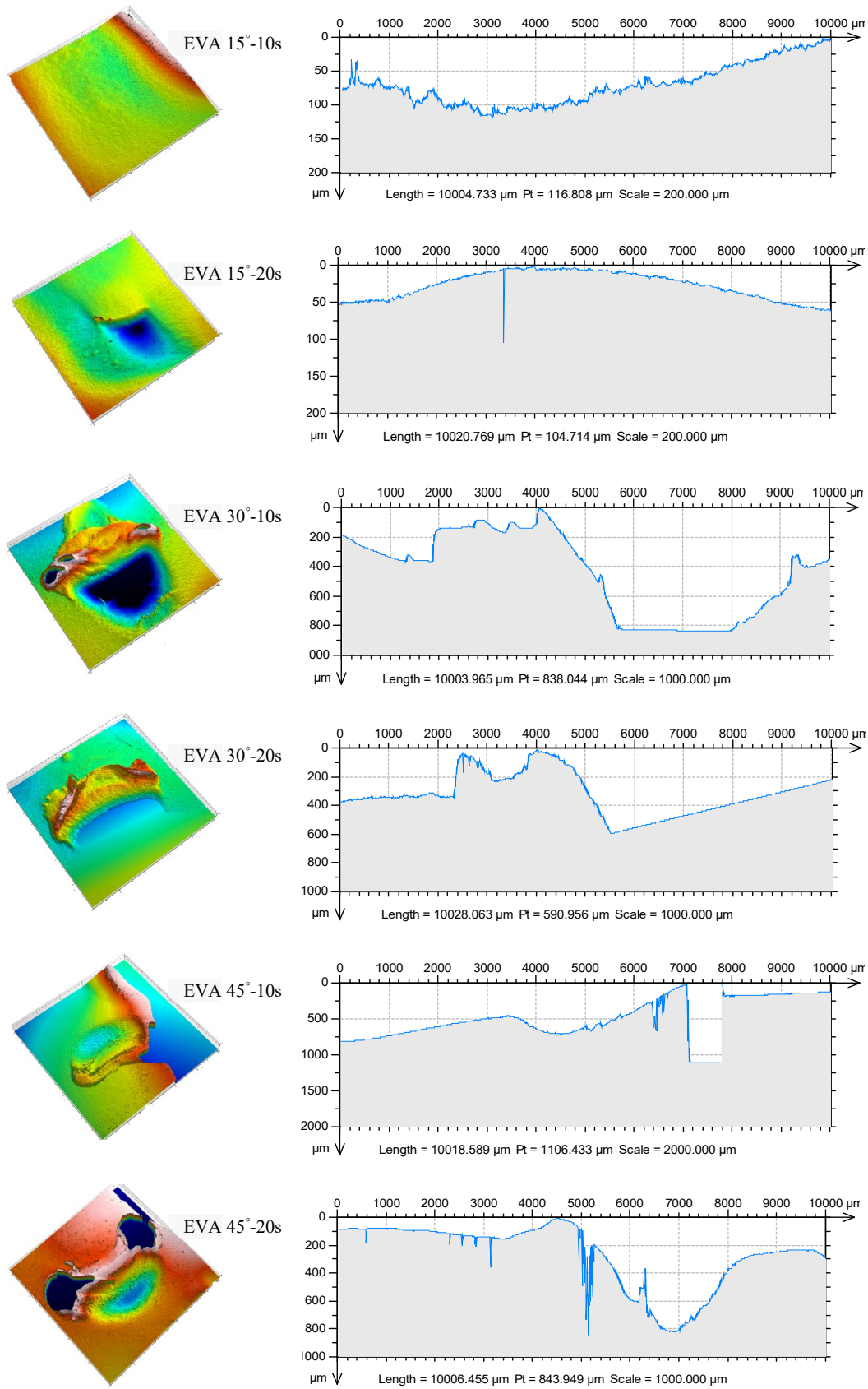


Figure 9. The wear track profile images.

Solid particles in contact with the surface change the surface morphology and roughness. It can be clearly seen that the surface profile changes after the test. After the erosive wear tests on the EVA coating, surface roughness and morphology analysis were performed with contactless laser profilometer and comparative results were given. Figure 8 shows the change of surface roughness after the wear test. The erosion crater and the wear track depth were investigated. The highest surface roughness values ($R_a: 35 \mu\text{m}$ at 10 s) were determined at 45° on coating surfaces. Whereas the roughness at 15° and 90° is very low and the measurement results are close to each other. Surface roughness results are highly variable due to particles embedded in the coating. However, it is used in the analysis of wear tracks. Although roughness values on the uncoated substrate surface give more meaningful results, the situation is different in polymeric coating. Shear forces, which occur depending on the low angle of impact, can cause tearing and deformation of the polymeric coating.

Surface profilometry analysis is a very useful method in the investigation of changes in cratering depth and surface morphology. Figure 9 shows the wear track profile images and profiles obtained with the laser profilometer. The short-time, the low-angle erosive wear test results shows a somewhat deeper crater. When the wear track profiles are examined after 10 and 20 s for the 15° impact angle, the crater has formed in the first 10 s. After 20 s, it started to deform the coating. Deformation and cratering increased when the impact angle increased from 15° to 45° . On the surface profile images, clearly tracks of wear can be observed in detail. It is observed that at very low and high angles, the wear loss decreases or relatively reduces its effect.

4. Conclusions

In this study, solid particle erosive wear behavior of EVA polymer coatings by flame spray method was investigated in detail. EVA based polymeric powders were successfully deposited onto 316 grade stainless steel substrates with optimized spray parameters. The obtained polymeric coatings have formed a dense and smooth deposit with good adhesion between metal and polymer layer and no significant coating degradation or interface defect is observed. The erosive wear resistance of the Eva coating is compared with the bare stainless steel. Coated and uncoated test samples exhibited similar erosive wear behavior. Especially when the test results are examined, it is observed that the wear is higher at low angles than at high angles. The main difference between them is the wear mechanisms. The erosive wear mechanisms for polymeric coatings are mostly in the form of micro-cutting, deformation, embedding of the particles. AISI 316 exhibited the poorer erosion resistance in comparison with EVA. Eva coatings were able to absorb the energy of the incoming particles quickly. In this case, some hard particles bounced off the surface, some were buried, and some caused cratering with a micro-cutting effect. Erosive

wear rate is very high at the first stage in a short time at low angles ($<45^\circ$). With the increase of time (10 s to 20 s), the erosion rate decreases partially. Wear at high angles ($>45^\circ$) often decreases on both surfaces. The lowest wear loss was observed at 90° . As can be seen from the surface profile graphics after erosive wear, the surface quality is negatively affected by the cratering and deformation effect. Nevertheless, it is thought that the polymeric coating acts as a shield by reducing the impact energy of the solid particles. As a result of the analysis made in accordance with these data, it has been understood that EVA coatings produced with flame spray can be easily used in reducing the erosive wear effects on the surface of stainless steels.

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