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The Effect of Post-Heat Treatment on The Mechanical Properties of FeCrBMnSi Coatings Prepared by Twin Wire Arc Spraying (TWAS) Method on Pump Impeller From 304 Stainless Steel

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ABSTRACT

The Twin Wire Arc Spray (TWAS) is one of the most widely used types of thermal spray coating because of its low cost, high efficiency and can also be used for mass production. However, heat treatment after the Fe-based amorphous coating process uses the TWAS method on pump impellers made of 304 stainless steel are not well documented. The purpose of this study is to determine the effect of post heat treatment after FeCrBMnSi coating with the TWAS method to increase wear resistance on pump impeller materials made of 304 stainless steel. In this study, NiAl and FeCrBMnSi were used as bond coats and top coats. Before the coating process, the substrate materials were sandblasted to obtain a surface roughness of 75 - 100 µm. The coating process is carried out by setting parameters of current spraying (A), voltage spraying (V), compressed air pressure (Bar), and standoff distance (mm) each of 150; 28.4; 5; and 400. Post heat treatment was carried out at a temperature of 500°C and 700°C for 3 hours using Furnace Chamber Thermolyne F6010. Tests of thickness, microhardness (ASTM 92-82), wear rate (ASTM G99-95A), micrography (ASTM E3), SEM, and adhesive strength (ASTM D- 4541) have been completed. The results of this study indicate specimens with post-heat treatment produce a coating layer with better mechanical properties than specimens without post-heat treatment. Specimens with post-heat treatment at a temperature of 700°C for 3 hours resulted in the smallest total wear rate of 6.6×10^{-4} mm³/s.

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1. Introduction

Pump is a type of fluid machine that is widely used in everyday life and industrial activities. This tool is used to move fluid from one place to another through a piping medium. The use of pumps was initially limited to providing water for daily needs, but with the development of technology in industry today, pump is widely used for needs in various industrial sectors such as the chemical industry, the textile industry, the oil industry, the power generation industry, irrigation, clean water companies, for building services, flood control and others. The presence of sand and other impurities in the fluid transferred by the pump is something that cannot be avoided. This is what causes pump components such as the impeller to wear frequently [1].

The particle impingement angle and solid concentration on the fluid have a dominant effect on the wear that occurred on the impeller blade [2]. Meanwhile, fluid flow pattern has a big influence on friction and acidity that occurs along the impeller blade, impeller trailing edge, tip clearance and side plate. The impeller is part of the pump that rotates and functions to convert engine power into kinetic power. The presence of sand and other impurities in the displaced fluid results in a collision with the impeller which occurs repeatedly and results in wear and tear of the impeller [3,4]. The power that occurs in the pump components will result in a decrease in the efficiency and lifetime of the pump. In addition, production costs will increase due to the large maintenance costs required to repair damaged pump components [1,4].

Currently, many methods have been developed to increase service life as well as to overcome wear, cavitation, and corrosion of pump impellers, one of which is the twin wire arc spray (TWAS) coating method with Fe alloy such as FeCrBMnSi as a coating material [4]. The use of FeCrBMnSi material as a coating material produces a coating layer with better yield strength, hardness, wear resistance, and corrosion resistance [4,5]. The TWAS method is one of the most widely used types of thermal spray coating because of its low cost, high efficiency, and can be used for mass production [4]. However, the TWAS coating method has several disadvantages such as high porosity (%) and uneven grain size in the coating layer which causes low adhesive strength, hardness, and fracture toughness [6].

The post heat treatment after the application of thermal spray coating at the crystallization temperature range of the coating material (top coats) used is one the treatment that can overcome these disadvantages [7]. A previous study investigated post heat treatment effect after FeCrBMnSi coating performed using the TWAS method. It was found that post heat treatment at 500°C, 600°C and 700°C can increase the hardness and adhesive strength of the coating layer. This occurs due to reduced porosity and oxide formed in the coating layer. The as-sprayed coating (without post heat treatment) had a microhardness of 910 HV, which was raised to a maximum of 1150 HV after post heat treatment at 700°C. In addition, the adhesive strength after post heat treatment at 500°C, 600°C, and 700°C increased by 4%, 10%, and 18%, respectively [6]. A similar result was found by Lin *et al.,* [8], reporting that increasing the post heat treatment temperature after FeNiCrBSiNbW coating performed using the arc-spraying method also resulted in reduced porosity and increased microhardness. The as-sprayed coating (without post heat treatment) had a microhardness of 898 ± 67 HV, which was raised to a maximum of 1245 ± 109 HV after post heat treatment at 650°C [8]. Other studies reported that the temperature increases in the post heat treatment process after the Fe based amorphous coating performed using the thermal spray method which results in increased microhardness of the coating layer and results in excellent abrasive wear resistance [9-12]. The post heat treatment after the coating process results in crystallization of the amorphous phase of the coating material. With an increase in temperature in the heat treatment process, the diffusion and sintering that occurs in the coating layer is getting better, so that the porosity of the coating layer is getting smaller. The smaller the porosity value in the coating layer, the better the hardness, adhesive strength, and wear resistance [6-12].

However, no one has examined the effect of heat treatment after Fe-based amorphous coating using the TWAS method on pump impellers made of 304 stainless steel. Hence, it is crucial to study the post heat treatment on mechanical properties of coating layer in pump impeller materials to enhance wear resistance. Based on the discussion above, this study investigates the effect of post heat treatment after FeCrBMnSi coating with the TWAS method on increasing wear resistance of the pump impeller material made of 304 stainless steel.

2. Methodology

This study used 304 stainless steel strip plate with a size of 1000 mm x 100 mm x 6 mm. The Everising S-12H machine shown in Figure 1 is used to cut 304 stainless steel strip plates into substrate material with dimensions of 100 mm x 100 mm x 6 mm as shown in Figure 2(a). The sandblasting process used dark aluminum oxide and adheres to the NACE No. 2. The surface roughness of the substrate materials after sandblasting is 75 - 100 µm. The substrate materials that have been sandblasted are shown in Figure 2(b). The coating on the substrate materials used the Twin Wire Arc Spray (TWAS) coating method which was carried out at the workshop of PT Cipta Agung, Surabaya, Indonesia.

Fig. 1. Everising machine S-12H

(a) (b)

Fig. 2. Substrate materials (a) before and (b) after sandblasting

In this study, NiAl and FeCrBMnSi materials were used as bond coat and top coat. NiAl and FeCrBMnSi, materials in the form of wire with a diameter of 1.6 mm were obtained from PT. Cipta Agung is shown in Figure 3(a) and Figure 3(b) respectively. The coating process used the TAFA 9000 Electrical Wire-Arc Spraying Machine. The working principle of this machine is to melt the two wires on the cathode and anode sides using electric power and to attach the droplets to the substrate using compressed air. The parameter settings of the coating process for the bond coat and top coat materials on the substrate are shown in Table 1. To find out the mechanical properties of the coating layer on the substrate material, tests of thickness, microhardness (ASTM 92-82), wear rate (ASTM G99-95A) were carried out, micrography (ASTM E3), SEM and adhesive strength (ASTM D-4541).

(a) (b)

Fig. 3. (a) NiAl wire (b) FeCrBMnSi wire

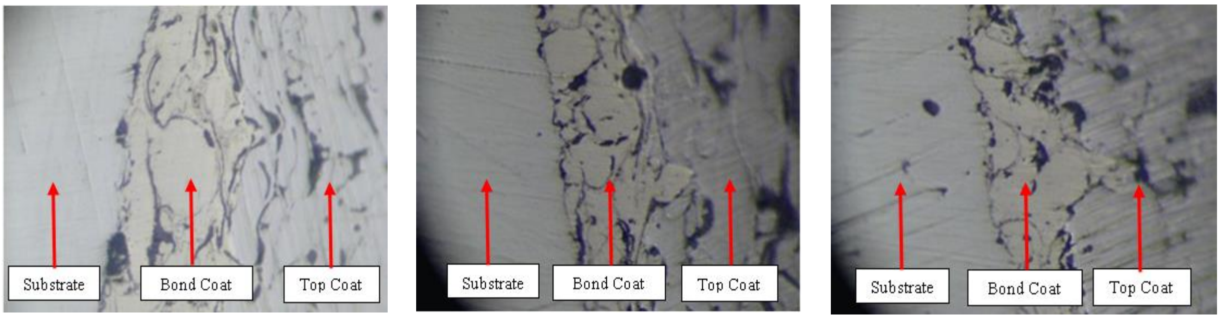
Table 1
TWAS process parameters

Current Spraying (A)	Voltage Spraying (V)	Compressed Air Pressure (Bar)	Standoff Distance (mm)
150	28.4	5	400

The post heat treatment process is carried out on the substrate that has been coated using a Thermolyne Furnace Chamber F6010. The post heat treatment process is carried out at a temperature of 500°C and 700°C for 3 hours then left to room temperature in the furnace. To determine the effect of post heat treatment on the mechanical properties of the coating layer on the substrate material, tests of thickness, microhardness (ASTM 92-82), wear rate (ASTM G99-95A), micrography (ASTM E3), SEM and adhesive strength (ASTM D- 4541).

3. Results

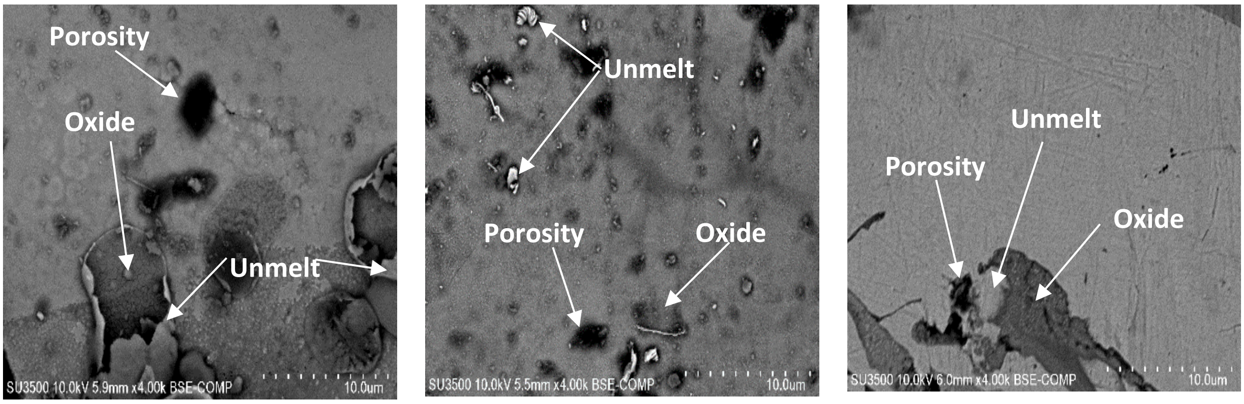
Micrographic testing using LOM (Light Optical Microscope) by following ASTM E3. The results of micrographic testing in this study showed the presence of a top coat, bond coat, and substrate layers in all specimens. The deposition results of bond coat (NiAl) and top coat (FeCrBMnSi) on the substrate looked quite good because there were no gaps found in each layer. The micrographic results of the specimens before and after post heat treatment with a magnification of 100x are shown in Figure 4(a) to Figure 4(c). The micrographic results of the specimens after the post heat treatment process resulted in a darker color than specimens that were not subjected to post heat treatment.



(a) (b) (c)

Fig. 4. Micrography with 100X magnification on (a) specimens without post heat treatment, (b) specimens with post heat treatment at 500°C, (c) specimens with post heat treatment at 700°C

SEM testing is carried out to determine the morphology of the coating surface on the substrate material. SEM test results with a magnification of 4000x were analyzed with imageJ software to determine the percentage of porosity and unmelt material in the coating layer. In this study, the surface of the coating layer on all specimens showed porosity, unmelt materials, and oxide as shown in Figure 5(a) to Figure 5(c). The appearance of porosity, unmelt, and oxide on the surface of the coating layer is caused by the presence of the coating material which has not melted completely when it adheres to the substrate surface [4,8,13].



(a) (b) (c)

Fig. 5. The results of the coating layer morphology test on (a) specimens without post heat treatment, (b) specimens with post heat treatment at 500°C, (c) specimens with post heat treatment at 700°C

Determination of the percentage of porosity and unmelt materials in this study using imageJ software based on the initial image gray scale and gray value (black to white) histogram on gray scale of 0–40. The binarization process in SEM images is carried out using the thresholding procedure. After proper threshold, use the Analyze menu, and click measure to find out the amount of porosity and unmelt (%). ImageJ analysis results are shown in Figure 6(a) to Figure 6(c). The effect of post heat treatment on the coating layer on the percentage of porosity and unmelt material is shown in Figure 7. The values of porosity and unmelt materials were mostly found in materials without post heat treatment with a value of 19.7%. Meanwhile, the smallest % of porosity and unmelt material was found in materials with post heat treatment at a temperature of 700°C of 17.2%. The results of this study indicate that post heat treatment greatly affects the percentage of porosity and unmelt materials in the coating layer.

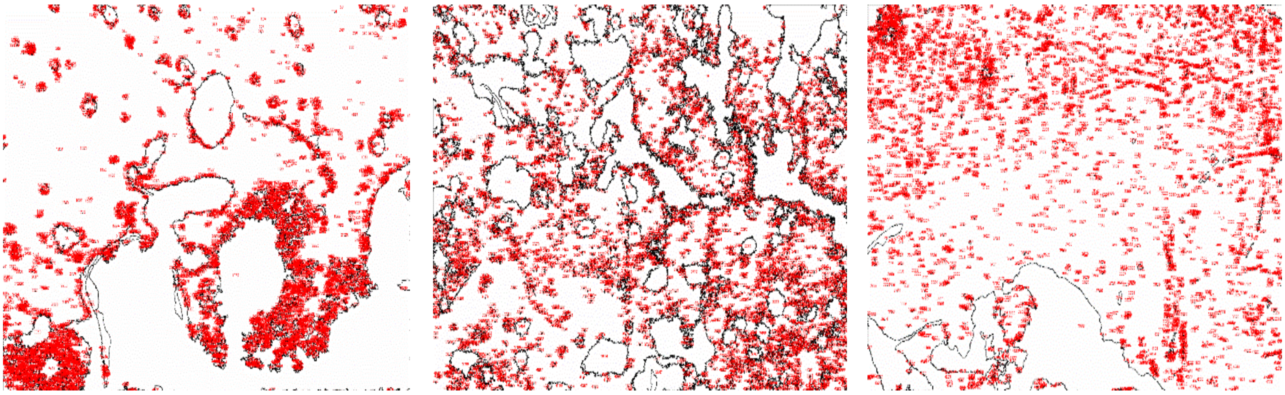


Fig. 6. ImageJ analysis results on (a) specimens without post heat treatment, (b) specimens with post heat treatment at 500°C, (c) specimens with post heat treatment at 700°C

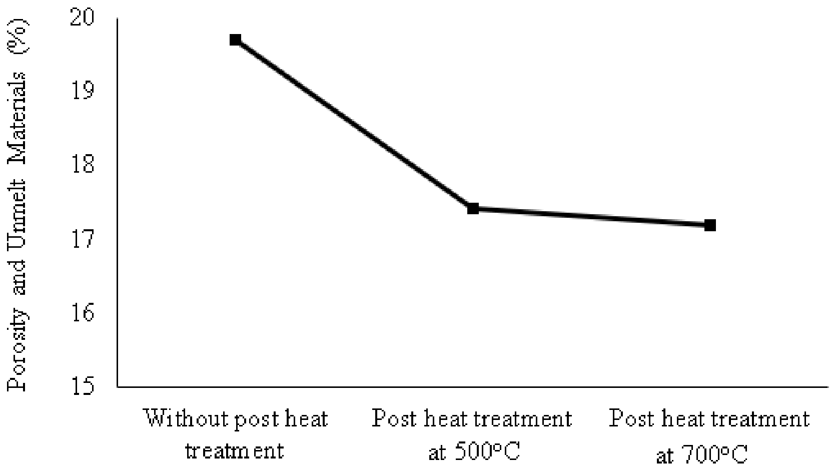


Fig. 7. The effect of post heat treatment on porosity and unmelt (%) of the material in the coating layer

The higher the post heat treatment temperature is used, the smaller the porosity and unmelt materials in the coating layer. This happens because the higher post heat treatment temperature results in diffusion between the coating layer materials. This diffusion phenomenon occurs due to the movement of particles from high concentrations to low concentrations and filling the void that occurs in the coating layer [6]. In another reference, it is stated that post heat treatment carried out at higher temperatures will result in the surface of the coating layer being denser as the sintering continues [8,9]. This shows that during the post heat treatment process there are diffusion, oxidation and sintering processes which result in a decrease in the amount of porosity and unmelt of the material because the surface of the coating layer is getting denser [8-10]. In addition, the higher the post heat treatment temperature results in the transformation of the amorphous phase into a crystalline phase in the coating material [9,10]. The results of this study are consistent with literature Irawan [6], Yuan [7], Lin *et al.,* [8], Fu *et al.,* [9], Zheng *et al.,* [10], Liu *et al.,* [11], Cheng *et al.,* [12], and Liu *et al.,* [13].

The results in this study show that the thickness of the coating layer is getting thinner with an increase in post heat treatment temperature as shown in Figure 8. Post heat treatment carried out at higher temperatures will result in a decrease in the number of porosity and unmelt materials (%) in the coating layer so that the resulting coating layer is denser and thinner [4,8,14]. In addition, the decrease in thickness when increasing the temperature is due to the sintering shrinkage between the substrate and coating materials [15]. In this study, the thinnest coating layer was found in specimens with post heat treatment at a temperature of 700°C with a coating layer thickness of 0.718 mm.

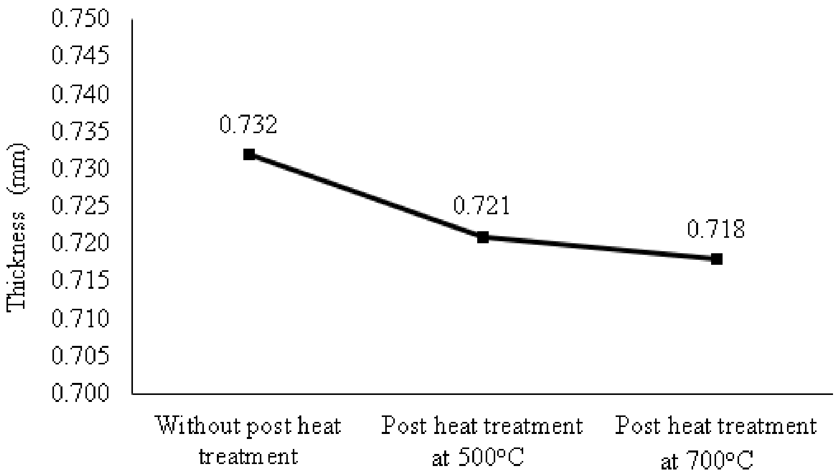


Fig. 8. The effect of post heat treatment on layer thickness

The specimens with post heat treatment at 700°C have the thinnest coating because the porosity and unmelt materials (%) are getting smaller. The increase in post heat treatment temperature will result in more expansion of the sprayed splats and stress relieving on the coating layer resulting in a decrease in the porosity and thickness of the coating layer which results in a smaller residual stress. The smaller residual stress shows that the tensile nature of the coating layer is getting smaller so that the adhesive strength of the coating layer increases [16]. In other words, decreasing the thickness of the coating layer will reduce the residual and increase the adhesive strength [4,17,18]. The results in this study indicate that the adhesive strength increases with an increase in post heat treatment temperature as shown in Figure 9. The greatest adhesive strength in this study was found in specimens with post heat treatment at a temperature of 700°C with a value of 16.62 MPa. The specimen without post heat treatment had an adhesive strength of 11.84 MPa. In this study the adhesive strength of the coating layer increased 35% and 40% at post heat treatment temperatures of 500°C and 700°C, respectively.

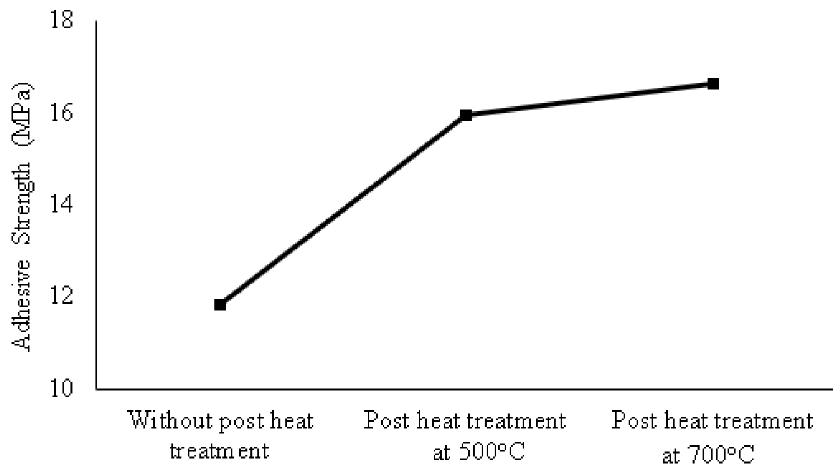


Fig. 9. The effect of post heat treatment on the adhesive strength of the coating layer

In addition to increase the adhesive strength of the coating layer, the decrease in coating thickness results in an increase in post heat treatment temperature also results in an increase in the hardness of the coating layer. Decreasing the thickness of the coating layer, the hardness of the coating layer increases [4,19,20]. The hardness test of the coating layer used a microhardness vickers tester (Mitutoyo HM-21) with a load of 500 gf and an indentation time of 10 s. The effect of post heat treatment on the hardness and wear rate of the coating layer is shown in Figure 10.

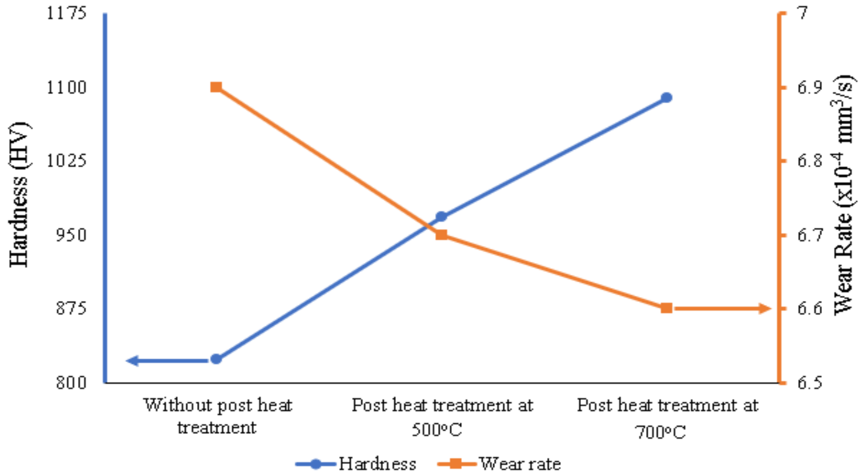


Fig. 10. The effect of post heat treatment on the hardness and wear rate of the coating layer

The hardness of the coating layer on the specimen without post heat treatment is lower than the hardness of the coating layer on the specimen with post heat treatment. The higher the post heat treatment temperature, the hardness of the coating layer will increase due to the smaller residual stress and crystallization of the amorphous phase in the coating layer [8]. The hardness of the coating layer increased 17% and 32% at post heat treatment temperatures of 500°C and 700°C, respectively. The results of this study are consistent with literature [6-11,25]. The increased hardness of the coating layer caused the wear rate to decrease. The wear test in this study used the abrasive method with a pin on disk tool. The silica carbide paper used is 100 grit in size. This test was carried out with 10,000 revolutions, a change of sandpaper every 500 revolutions, a disc rotating speed of 100 rpm and a load of 300 grams. The effect of post heat treatment on the total wear rate of each specimen is shown in Figure 10. The total wear rate of the coating layer on specimens without post heat treatment is higher than the total wear rate of the coating layer on specimens with post heat treatment. The higher the post heat treatment temperature, the hardness of the coating layer will increase due to the smaller residual stress and crystallization of the amorphous phase in the coating layer so that wear resistance increases and the total wear rate decreases [20-24]. The smallest wear rate is found in specimens with post heat treatment at a temperature of 700°C. This happened because the specimens had the greatest coating hardness caused by a decrease in the thickness of the coating layer, porosity and unmelt materials (%) [9,11,13].

4. Conclusions

In the present study, effect of heat treatment on the mechanical properties of FeCrBMnSi coatings were investigated. The TWAS method used in this study is able to form a coating layer on 304 stainless steel as a substrate material. Specimens with post heat treatment produce a coating layer with better mechanical properties than specimens without post heat treatment. The higher temperature in the post heat treatment process can produce a thin coating layer because the porosity and unmelt materials (%) are reduced. The decrease in coating thickness resulted in increased hardness and adhesive strength. Increasing the hardness of the coating layer will decrease the total wear rate and increase the wear resistance of the specimen. In this study, specimens with FeCrBMnSi coating and post heat treatment at 700°C for 3 hours resulted in the smallest total wear rate of 6.6 x 10^{-4} mm^3/s.

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