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THE EFFECT OF SiC IN NiCrBSi-SiC COMPOSITE COATING ON THE MICROSTRUCTURE, HARDNESS, AND OXIDATION RESISTANCE

Many industrial parts degrade, which reduces plant reliability. Waterwall tube is part of the circulating fluidized bed (CFB) boiler that often degrades caused by the bed materials' erosion. Therefore it requires a material with resistance to corrosion, abrasion, and high oxidation and economically feasible. One of the solutions is to coat the tube with hard ceramic materials by using thermal spraying. In this present work, composites of NiCrBSi-SiC were used to coat low carbon steel in order to study the possibility of used in boiler application. The coating process was carried out using the high-velocity oxygen fuel (HVOF). The amount of SiC was varied from 0% to 40% SiC to study their effect on coating properties. Then microstructure examination was done using an optical microscope on the surface with a cross-section to see the coating results in the form of density, porosity, and the bond between the layer and the substrate. Hardness testing with the Vickers method was carried out on the cross-section to determine the hardness value of the coating. The oxidation test is carried out to determine the oxidation resistance of the coating at high temperatures. Results show that the addition of SiC will increase the hardness and oxidation resistance. The porosity that appears is influenced by the SiC powder that does not melt entirely during the coating process due to differences in particle size. The amount of porosity will also affect the oxidation resistance of the coating.

Keywords: *Carbon Steel, Coating, HVOF, NiCrBSi, SiC, Oxidation Resistance*

1. INTRODUCTION

In a steam power plant, a boiler is a steam generating device to convert water in the tubing system into steam. The steam is used to drive the turbines and turn generators. Circulating fluidized bed (CFB) is one of the boiler types in which coal is mixed with bed materials, in many cases sand materials, to achieve good heat mixing and perfect combustion [1,2]. In the CFB boiler, the fuel and the boiler bed's material are burned using high-pressure air blowing from the bottom grate, making it easier for combustion to occur. The mixing between coal, limestone, and silica sand produces a flow of liquid-like fluid called fluidization. In this case, turbulence and flow materials mixture causes abrasion, erosion, and oxidation [3]. The continuous abrasion and erosion will reduce the thickness of the water wall tube. Repairing or replacing a damaged component will require very high costs, and if this damage is not handled immediately, it will cause the whole system to stop. Ideally, the water wall tube furnace uses a material that has resistance to erosion, abrasion, and high oxidation. However, such materials usually alloy steel that not economically feasible.

One of the solutions to increase the resistance to erosion, abrasion, and high-temperature oxidation is by coating. Some materials based on ceramic materials can be used as a coating on the steel substrates [4-7]. High-Velocity Oxygen Fuel (HVOF) is one of the coating methods that can be used. The working system of HVOF starts from the movement of the heated particles, which are pushed and accelerated by the flow of pressurized gas, then projected onto the surface of the substrate to be coated. A result of the collision at high speed causes a bond between the particles and the surface of the material and forms a lamellar layer structure [8-10].

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Nickel-based coatings such as Ni-Cr-B-Si are widely used in components that require erosion resistance and oxidation resistance or corrosion resistance at high temperatures. Nickel-based powders are mostly an alloy of Ni-B-Si, plus the addition of other alloying elements. Boron (B) has the effect of lowering the melting point of Ni. Silicon (Si) is added to improve self-fluxing properties, which are very useful during the coating process when the cooling process of the layers and layers hardens. The addition of chromium (Cr) to the alloy will increase the oxidation resistance and corrosion resistance at high temperatures and increase the hardness of the coating with the formation of a hard phase. While the addition of carbides will form carbides that have a high hardness value, with a high hardness value, the erosion resistance of the coating will be increase [11,12]. The composite of materials with based NiCrBSi has been studied previously [13,14] and shows potential to be applied for tubing other components.

In the present work, the addition of SiC in NiCrBSi-SiC is studied. The amount of SiC is varied between 0 to 40% and pre-mixed before the coating process. The potential advantage of NiCrBSi-SiC is the hardness caused by SiC particles but also high thermal conductivity compared with other ceramics-based materials.

2. MATERIALS AND METHODS

2.1 Material

The sample used as a substrate is low carbon steel with a sample size of 50x50x3 mm. Before the coating process, the substrate was cleaned properly with sandblasting method until it looked shiny. The sandblasting was done using alumina particles with the nozzle distance to the specimen was 170 mm and an angle of 45 degrees. The alumina used was grid 1.2 mm. The NiCrBSi powder product used was trademark Diamalloy 2001 with the following chemical composition certificate is shown in Table 1.

Table 1: Chemical Composition of NiCrBSi Powder

Alloying Elements	Percentage (wt. %)
Ni	Balance
Cr	17
B	3.5
Si	4
C	1

In the present work, NiCrBSi was mixed with various percentages of SiC, from 0 to 40%, as shown in Table 2. Before the coating, each powder was pre-mixed using a V-Blend machine. The stirring time for one mixture was 8 hours so that the NiCrBSi and SiC powders were evenly mixed before used in the coating process.

Table 2: Variations in the Percentage of NiCrBSi-SiC Powder

Variations	Percentage (wt. %)	
	NiCrBSiC	SiC
X	100	0
A	80	20
B	70	30
C	60	40

2.2 Coating Process with HVOF Method

The coating process was done in the following stages; the steel specimens to be coated was put on the stand and firmly attached. Then the sample thickness was measured with a micrometer to determine the initial thickness of the sample before the coating process and to determine the thickness of the coating later on. The pre-mixed coating powder that has been blended into the powder feeder, the ratio is adjusted to the surface area of the material. The parameters of the HVOF equipment were set based on best practice on the control console [15] with the following parameters.

- Oxygen flow rate: 270 slpm
- Combustion gas flow rate: 60 slpm
- Nitrogen gas pressure 6 kg/cm^2

- Oxygen pressure: 9 kg/cm^2
- Combustion gas pressure: 6.5 kg/cm^2
- Powder feed rate: 55 g / min

During the process, the material temperature is maintained between 150℃-200 ℃. The process can be continued again as long as the material temperature is below 150 ℃. After the desired thickness was reached, a fusing process was performed to minimize the porosity [16]. After the coating process was finished, the sample was cooled to room temperature, and the thickness of the material and the coating were measured.

2.3 Characterization

Several testing was conducted to evaluate the coating results and to study the effect of silica fraction on the hardness, microstructure, and thermal oxidation properties. Microstructure examination was done on the cross-section of the specimen using an optical microscope to observe the microstructure, porosity, and interface between the substrate and the coating. Before the examination, the sample was polished and ground. The sample was then evaluated by hardness testing to determine and compare the substrate material's hardness value and the coating layer. The equipment used in this test is the Vickers hardness tester. During the test, the loading used in this test was 0.5 kg.

The thermal oxidation test determines the weight gain in the specimen during working conditions, which happens because of a reaction between the specimen surface and oxygen at high temperatures [17]. The thermal oxidation test is carried out by inserting the specimen into the furnace, then heating it at a temperature of 900 ℃ and holding it for 1 hour, then cooling it in the furnace, and measuring and recording the added weight.

3. RESULTS AND DISCUSSIONS

3.1 Macro and Microstructure

Figure 1 to Figure 4 shows the cross-sectional microstructure of the deposited coating. In Figure 1, the microstructure is presented at 50 to 500 magnification to give detail overview and length scale of the coating microstructure. It can be seen in the figure the substrate and coated material. The coating thickness measured by optical microscopy of each specimen averaged 250-300 μm. In higher magnification, it can be seen that the coated composite consists of a layered structure as the result of a step-by-step deposition process during the HVOF. In general, samples X, A, B, C have low porosity. Some porosity in the form of dots with black color is present in some parts, but generally, the coating layer has a dense microstructure. A good interfacial contact at the boundary between the substrate and the coating layer with no cracks can be observed.

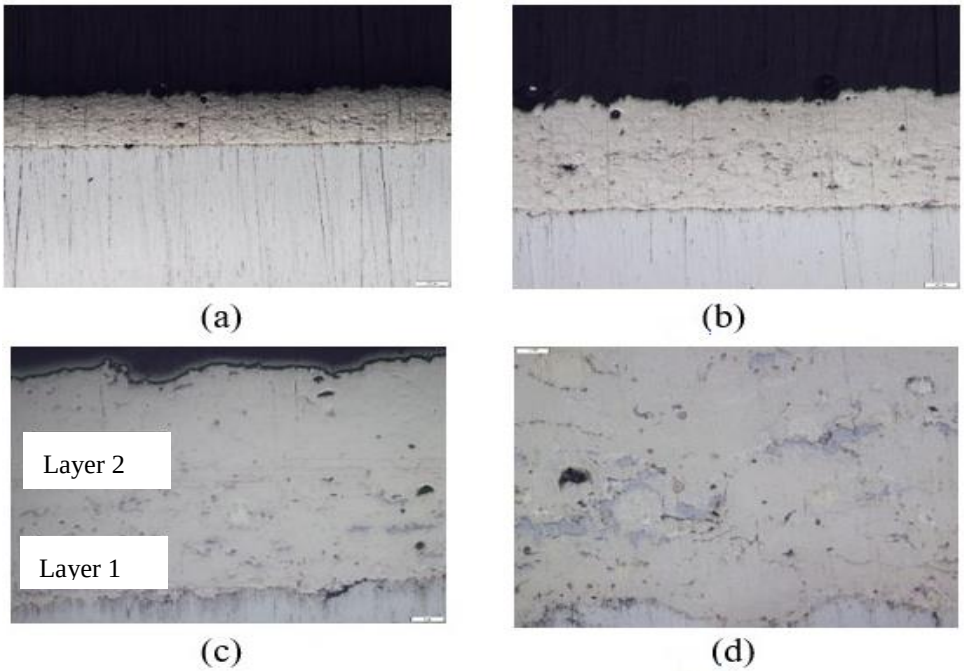

Figure 1: Microstructure of sample X (100% CrBSi) containing information about the thickness and microstructure of coating at several magnification; a) 50, (b) 100 X (c) 200 X (d) 500 X.

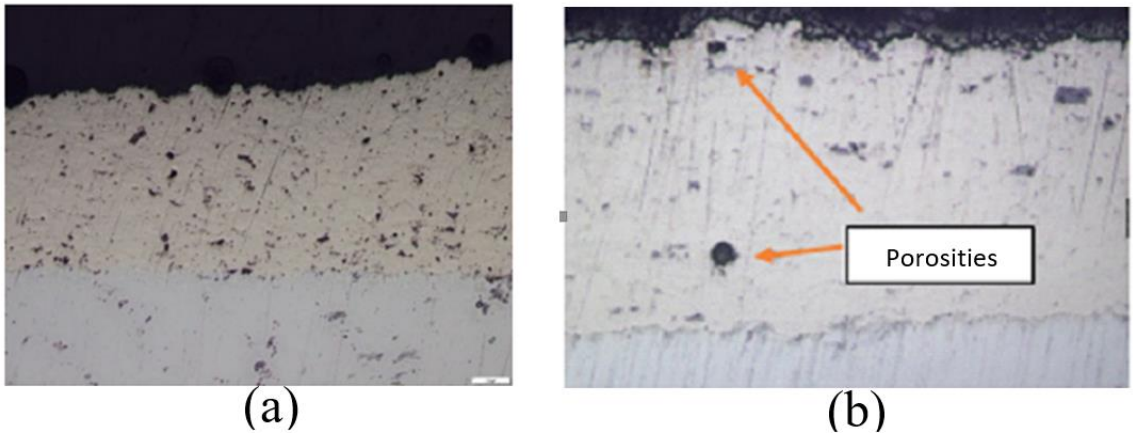

Figure 2 : Microstructure of Specimen A (80 % NiCrBSi-20% SiC) at: (a) 100 X, (b) 200 X.

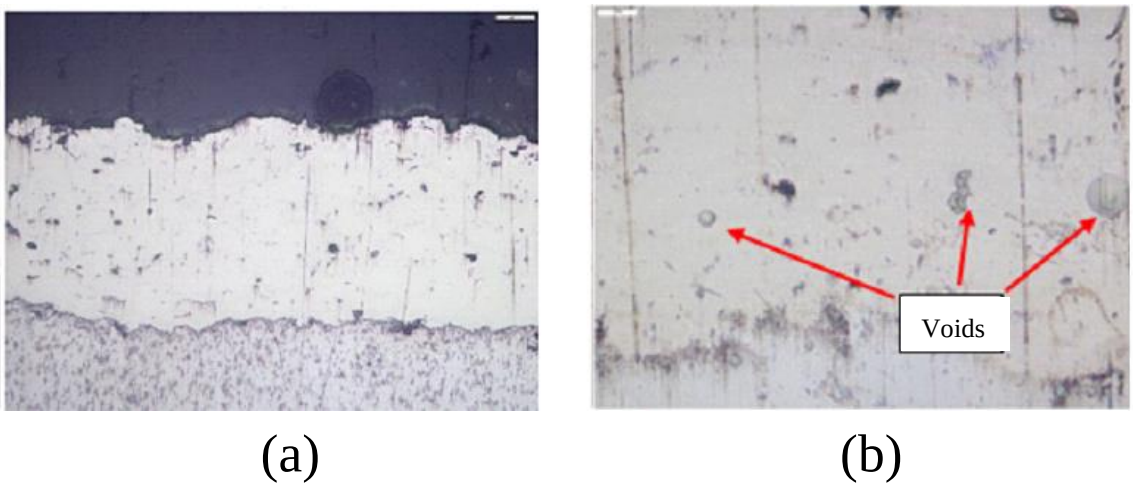

Figure 3: Microstructure of specimen B (70% NiCrBSi-30% SiC) at: a) 200X, (b) 500 X.

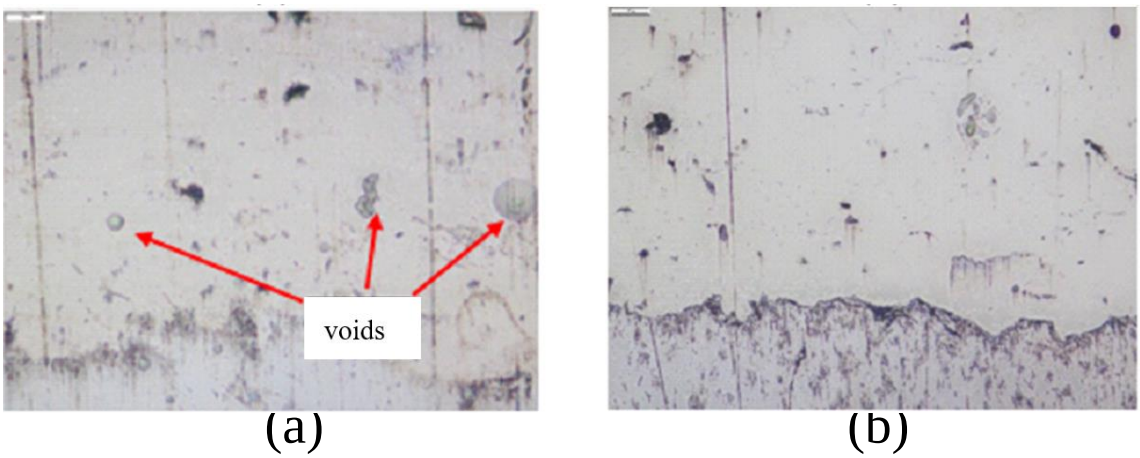

Figure 4: Microstructure of Specimen A (60 % NiCrBSi-40% SiC) at: (a) 200X, (b) 500 X.

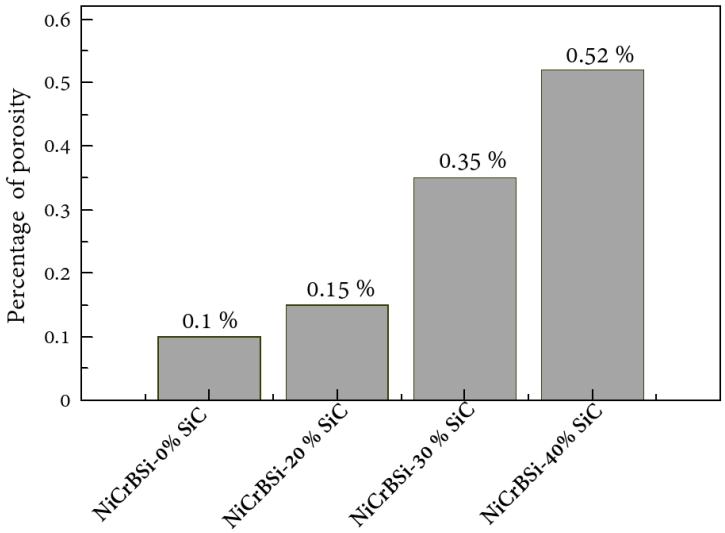

Figure 5: The effect of SiC fraction on amount of porosities.

The microstructure of the coating layers of specimen X, A, B, C is dominated by the Ni matrices microstructure, characterized by light gray in the microstructure image. The microstructure with dark gray color is C, Cr, and Ni (CrB_2, Cr_3Ni_2Si). The microstructure with black color is the combination of Cr and C (Cr_7C_3) [18]. In the coating process with the HVOF method, a mixture of NiCrBSi and SiC powders decomposes due to high temperatures, then forms a new phase during the fusing process. The microstructure of the coating layer in the area close to the boundary was dominated by Ni and Cr. In contrast, the areas that approach the surface are Si and C. This shows that the SiC powder did not melt completely during the coating process; this could happen because of a possible difference in particle size between NiCrBSi (-45 + 15μm) and SiC (40 + 50 μm) [18] [19].

Porosity was calculated using a grid mapping method according to ASTM B276 [20]. The photo results from an optical microscope with the same magnification for all specimens were given a grid, then the area of porosity was calculated, then compared with the area of the coating. The data obtained shows that the porosity of specimen X has a porosity of 0.1%, specimen A has a porosity of 0.15%, specimen B has a porosity of 0.33%, and specimen C has a porosity of 0.52%.

3.2 Hardness

The hardness testing results on the substrate cross-section, interfaces, and coating parts can be seen in Table 3 and plotted in Figure 6.

Table 3: Hardness data at different indentation points along the substrate to the coating.

POSITION IN-DENTATION	MICROHARDNESS (HV)			
	X	A	B	C
	100% NiCrBSi	NiCrBSi-20% SiC	NiCrBSi-30% SiC	NiCrBSi-40% SiC
1	139	139	139	139
2	148	148	148	148
3	197	271	197	269
4	421	695	649	677
5	600	675	702	753
6	590	753	727	668
7	773	692	711	672

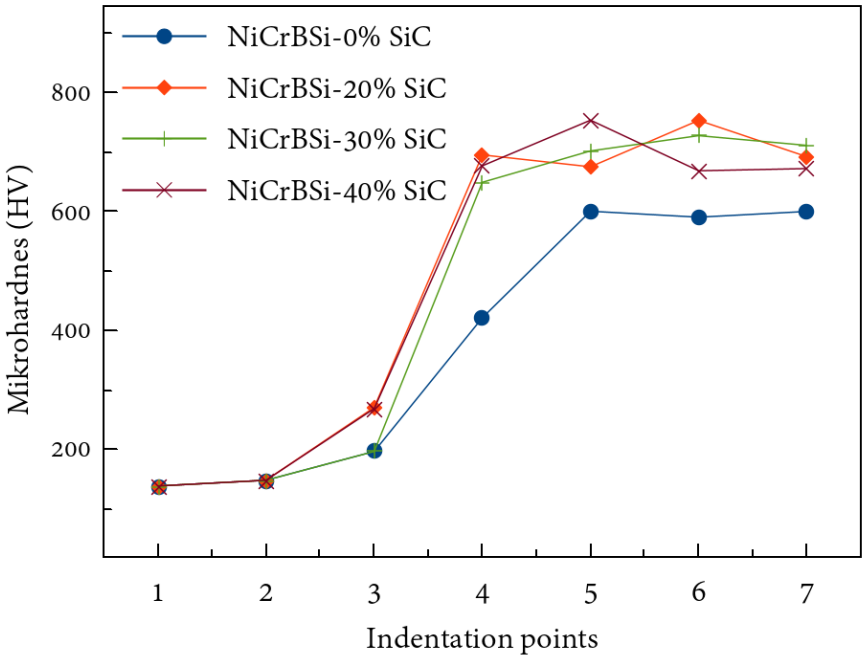

Figure 6: Hardness value is taken from the substrate (started at point 1) to the coating.

The hardness value data of the specimens are shown in Figure 6, which shows the hardness value of the substrate and coating layer on the cross-sectional profile. The graph shows hardness as a function of indentation points. From Figure 6, it can be seen that each specimen has a significant increase in hardness starting from the substrate boundary to the coating layer. The hardness on the substrate is between 138-148 Hv. At the boundary between the substrate and the coating layer, the hardness is between 196-270 Hv.

In the coating layer show an increased value for all specimen in average above 500 Hv. In specimen A the hardness value are between 675-753 Hv. The highest hardness value in specimen A occurs at the 6th indentation position. This can happen because the indentation position is right on the carbide section. In specimen B, the hardness value is rather constant between 701-711 Hv. In specimen C the hardness value is 676-753 Hv. The highest hardness value occurs at the 5th indentation position with a hardness value of 753 Hv. It can happen because specimen C has a higher percentage of SiC is 40%, so the distribution of carbide is more even. In general the high hardness of coating is because of chromium carbide (Cr_3C_2) region which has a higher hardness value.

Nickel-based coatings are widely used in applications requiring erosion resistance and oxidation resistance. The NiCrBSi-SiC powder consists mostly of Ni and alloy composition of Cr, B and Si. Each alloy has an influence on the resulting coating layer. Ni (nickel) as a base has good wear resistance and oxidation resistance properties. B (boron) has the effect of reducing the melting point of Ni (nickel) during the coating process. Si (silicon) enhances the self-fluxing properties of the mixture. Cr (chromium) has a hard phase which increases the hardness value of the coating and corrosion resistance. C (carbon) will form carbides which increase the hardness value of the coating layer [17].

The addition of silicon carbide (SiC) will produce carbides with high hardness values so that it will increase the wear resistance of the coating [19]. With the addition of a higher percentage of SiC, more carbide phases should be formed. It will produce a layer that has a high hardness value. The alloy of Cr and C will form chromium carbide (Cr_3C_2) so that it can produce a layer with a high hardness value.

3.3 Thermal Oxidation

In the thermal oxidation testing, the data taken is the weight gain that occurs from each specimen in each cycle. With a variety of compositions as follows:

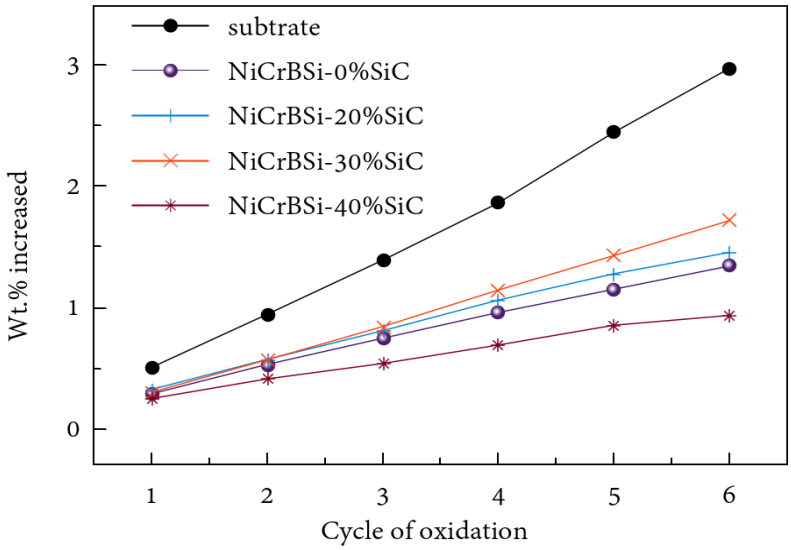

Figure 7: Thermal oxidation of sample as measured by weight gained during the cyclic measurement.

Figure 7 on the y-axis shows the percentage of weight gain, while on the x-axis is the number of cycles or thermal oxidation processes. The substrate was not coated on both surfaces. While specimens X, A, B, C were coated on one of their surfaces. From the data, it can be concluded that coating can reduce the rate of oxidation in the material.

The powder coating composition also has an impact on oxidation resistance. The nickel (Ni) matrix, which is the most of the coating layer, has a reasonably good oxidation resistance. Ni begins to be oxidized at a temperature of 500℃ [20]. Apart from increasing the hardness of the coating by forming a hard phase, the Cr composition is also able to increase the oxidation resistance and corrosion resistance at high temperatures. At high temperatures, Cr will react with O_2 to Cr_2O_3 in the surface area, then form a thin layer that will protect the coating layer from oxidation [1]. Boron (B) will also react with chromium (Cr) to become CrB which will increase oxidation resistance [18].

The addition of SiC will increase the oxidation temperature. Silicon has a high oxidation temperature of about 1080℃ [21]. In contrast, Ni will be oxidized at about 500℃ [20]. Silicon will also form a thin layer of SiO_2 which protects the coating from oxidation.

The addition of SiC was supposed to increase the oxidation resistance of the coating [20]. From the data obtained, the addition of SiC powder is proven to reduce the rate of oxidation. However, from the research data, it was obtained that specimen C, the percentage of SiC 40%, actually experienced a higher oxidation rate than specimen B with a percentage of SiC 30% and specimen A with a percentage of 20% SiC. This can be affected by porosity. In specimen C there is a porosity of 0.52%, specimen B has a porosity of 0.33%, and specimen A has a porosity of 0.15%. The porosity contained in the coating can be the value of hardness, wear-resistance, and oxidation resistance of the coating [9].

4. CONCLUSION

The effect of SiC amount in NiCrBSi-SiC HVOF-composite coating for boiler steel has been studied in detail. From the microstructural observation, HVOF coated layer is mostly dominated by NiCr matrices with some distribution SiC can be seen in some areas. In a specimen with 40% SiC, there is a porosity of 0.52%, specimen 30% SiC has a porosity of 0.33%, and specimen 20% SiC has a porosity of 0.15%. The bond between the layers and the substrate is suitable, and there is no porosity and cracks.

The addition of SiC was proven to increase the hardness of the coating when compared to the substrate, but the variation in the percentage of SiC in this study did not significantly affect the hardness. The hardness obtained was between 649-753 Hv. From the data from the thermal oxidation test results, it can be concluded that the addition of SiC powder has been proven to reduce the oxidation rate of the coating. But from the research data, it was obtained that specimens with 40% SiC actually experienced a higher oxidation rate when compared to a specimen with a percentage of SiC 30% and specimens with a percentage of 20% SiC. This can be influenced by the appearance of porosity because porosity reduces the hardness and oxidation resistance of the coating.

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