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Effects of surface thermal spray coating on mechanical properties of STD11 steel

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Abstract

This study aimed to increase wear resistance by forming a thermal spray coating layer on the steel surface using a high-hardness coating material. After quenching at 1030°C and low-temperature tempering at 170°C on the existing STD11 steel, HVOF thermal spray of WC-12Co powder, surface fusing treatment using 60W-40Ni self-fluxing alloy powder, and arc wire thermal spray using Fe-29%Cr wire were performed to form a high-hardness coating layer on the surface of the STD11 steel. The surface of the manufactured sample was measured five times using a Vickers hardness (HV) tester, and the HVOF thermal spray was measured to be HRC70.6, the fusing thermal spray HRC64.2, and the arc wire thermal spray HRC62.9. The cross-section of each thermal spray coating layer was analyzed by SEM-EDX (Scanning Electron Microscopy-Energy Dispersive X-ray Analysis).

Keywords: 60W-40Ni powder, Arc wire thermal spray, Fusing treatment, HVOF thermal spray, STD11 steel, WC-12Co powder.

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1. Introduction

Thermal spray is a process in which powder or wire coating material is melted and propelled, and particles flying with thermal energy and velocity collide with the surface of the base material, forming a coating with strong adhesion to the base material and dense cohesion between particles. Fundamentally, there are problems such as porosity, mechanical bonding, and serious surface brittleness due to combustion products. The usual characteristics of thermal spray coating vary depending on the method, but unlike other surface treatment technologies, coating is possible without restrictions on the material of the base material, the size, and the shape of the base material. In addition, there is no thermal deformation of the base material during coating, the coating thickness can be easily controlled, the coating speed is very fast, the durability is superior to other surface treatments with the same hardness, and various coating materials are available. However, there are various process variables in the thermal spray method, and these process variables have a great influence on the determination of the characteristics of the coating. Thus, in order to obtain a high-quality coating, it is necessary to objectively analyze the effect of process variables on the coating result, and the optimal thermal process must be designed based on the results of this analysis to ensure consistent quality [1-6]. However, in most industrial sites, the most important thermal spray process conditions that affect the characteristics of the coating layer are determined based on the experience and trial and error of field workers, rather than through quantitative analysis of the factors affecting the performance of thermal spray. As a result, the quality of the coating is inconsistent, leading to frequent defects and claims from clients, as well as numerous issues related to durability and productivity, such as low reliability of the coated products. An important advantage of thermal spray is that the hardness of the coating layer is high, providing excellent wear resistance, but a significant disadvantage is its low adhesion strength, making the coating layer prone to peeling off easily under strong impact wear. Even in the thermal spray coating of WC-Co (tungsten carbide-cobalt) alloy powder using the most widely used high-velocity oxygen fuel spray (HVOF), exposure to high-temperature flames causes a serious decrease in hardness due to accelerated decarburization and phase decomposition, which can rapidly weaken impact wear resistance. To improve wear resistance, carbide particles are re-precipitated through heat treatment at 600°C after thermal spraying, which also increases the bonding strength between WC particles and the matrix, and significantly reduces micropores. Additionally, unlike the method of spraying WC-Co alloy powder onto metal surfaces, Gostol in Slovenia directly processes non-metallic WC and manufactures it into market-ready products. Although the productivity and economy of these products are significantly lower, their service life is increased by 8 to 16 times compared to that of tool steel [7-10].

As described above, since the economical, productive, and simple thermal spray method can be considered to have greater advantages in terms of high hardness and high wear resistance despite the disadvantages of thermal spray, such as peeling and brittleness of the coating layer, it is necessary to develop steel by thermal spray coating. Thus, in this development technology, the existing STD11 steel was treated with quenching and tempering, and then HVOF thermal spray of WC-12Co powder, surface fusing treatment using 60W-40Ni self-fluxing alloy powder, and arc wire thermal spray using Fe-29%Cr wire were performed to develop a wear-resistant steel with a high-hardness coating layer by thermal spray.

2. Materials and Methods

2.1. HVOF Thermal Spray Of WC-12Co Powder

2.1.1. Manufacture of 1 Mm Thermal Spray Layer

For the base material of the sample, STD11 steel rolled material for cold molding, which is an existing material, was used. The commercially available STD11 material was purchased, cut to the processing dimensions, and then milled into a blade shape. Figure 1 presents the processing process of the STD11 material used as the base material.

Figure 1.
Processing sequence of STD11 rolled steel.

After the machining was completed, the sample was heated under the following conditions. The material was first preheated at 600°C for 50 minutes in a vacuum heat treatment furnace, then preheated at 850°C for 2 hours, and finally heated at 1030°C for 2 hours for austenitization. After austenitization, nitrogen gas was injected to suppress the growth of carbides and create a martensitic matrix, then rapidly cooled. Tempering was performed immediately after heat treatment, with the sample maintained at 170°C for 4 hours before air cooling.

Figure 2.
Vacuum heat treatment furnace and controller.

WC-12Co powder with a particle size of 30~60 μm was melted at 2700°C on the base material (STD11), which had undergone quenching and tempering processes, and sprayed at a speed of 700 m/sec under pressure with fuel y (LPG) and liquid oxygen to form a 1 mm thermal spray coating layer. The sample was air-cooled without external cooling equipment. HVOF thermal spray equipment was used for all operations.

2.1.2. Manufacture of 300 μm Thermal Spray Layer

STD11 steel rolled material manufactured in the same manner as above was used as the test sample base material. WC-12Co powder with a particle size of 15~45 μm was melted at 2760°C on the base material (STD11) that had undergone heat treatment, and sprayed at a speed of 700 m/sec under pressure along with fuel (LPG) and oxygen to form a 300 μm~350 μm coating layer. The sample was air-cooled without external cooling equipment. Thermal spray was performed using a high-velocity oxygen fuel spray equipment (HVOF system, DJ2700). Figure 3 presents the configuration of the HVOF thermal spray equipment, and Figure 4 presents the schematic of the growth of the layer treated with HVOF thermal spray. Also, Figure 5 presents the shape of the sample that was heat-treated after thermal spray.

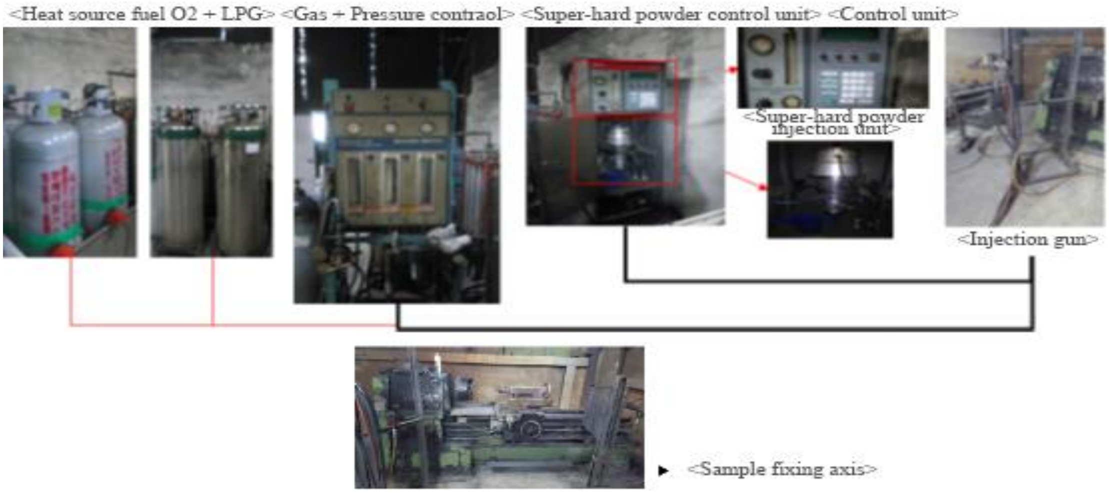

Figure 3.
Configuration of HVOF spray system.

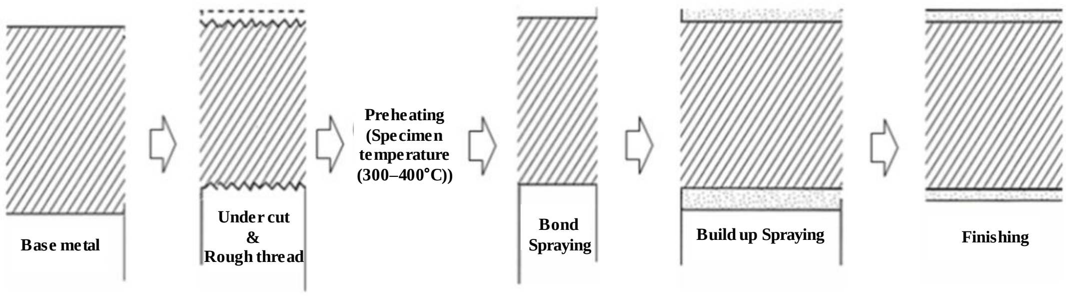

Figure 4.
Schematic of high velocity spray coating.

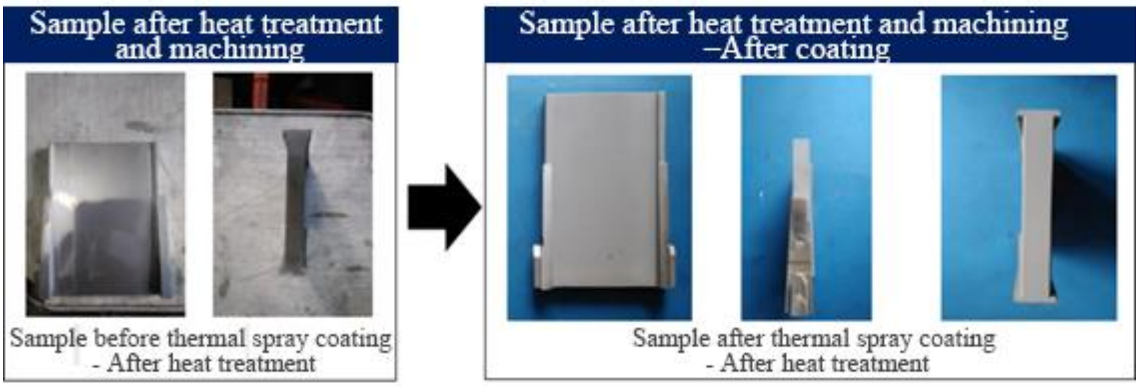

Figure 5.
Sample shape before and after heat treatment of HVOF spray coating of WC-12Co powder.

2.1.3. Method of Cutting Samples and Fabricating Test Samples

Test samples were manufactured for tissue observation and hardness measurement. First, to minimize the peeling of the surface coating during cutting of the STD11 steel treated with surface thermal spray, water jet cutting (Tops, SJA-T300) was performed. After cutting the central part of the sample, each sample was cut into a size of 20 mm×10 mm. In particular, for polishing the sample, a metal guide was installed to prevent the loss of the coating layer, and after mounting, #1000 to #2000 sandpaper was used sequentially for careful polishing to prepare test samples for tissue observation and hardness measurement. SEM photography was performed to observe the thickness of the cross-section of the spray coating layer and its bonding with the base material, and the hardness of the remaining samples was measured using a Vickers hardness (HV) tester. Figure 6 presents the process of cutting the STD11 steel treated with surface spray and manufacturing the test samples.

Figure 6.
Cutting of surface-spray coated STD11 steel and tissue observation, and the process of fabricating test samples for hardness measurement.

2.2. Fusing Thermal Spray of 60W-40Ni Powder

For the test sample base material, STD11 steel, which was processed and heat-treated in the same way as HVOF thermal spray, was used, and for the fusing thermal spray material, 60W-40Ni powder was used. The 60W-40Ni powder was melted at 2700°C and sprayed at a speed of 150 m/sec onto the STD11 steel base material to form a coating film. That is, the fusing method of melting the surface with the flame of the applied torch after thermal spraying was used, so that the base material and the alloy could form a stronger bond. Figure 7 presents the form of fusing thermal spraying.

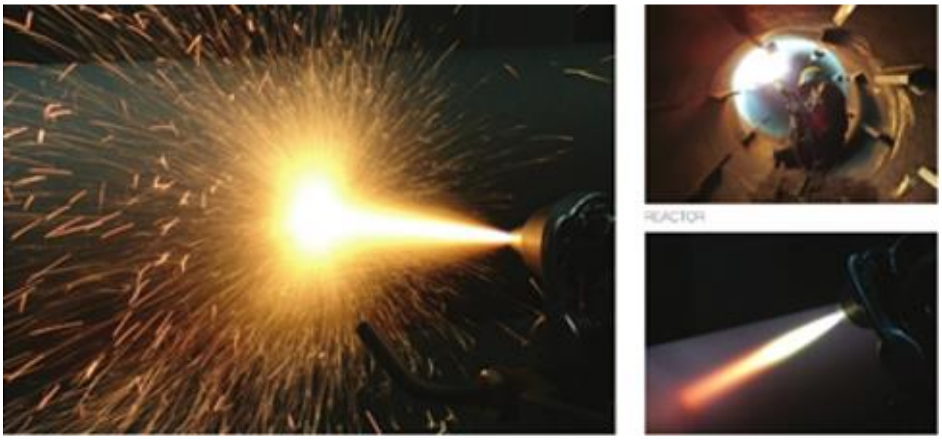

Figure 7.
Fusing thermal spray.

2.3. Electric arc Wire Thermal Spray of Fe-29Cr

For the test sample base material, STD11, which was processed and heat-treated in the same manner as above, was used. A wire thermal spray method using an electric arc heat source was employed, and Fe-29%Cr wire was used as the spraying material. The Fe-29Cr wire was continuously melted at a temperature of 4100°C on the base material, and at the same time, the droplets were finely divided using compressed air and sprayed at a speed of 150 m/s to form a coating film approximately 2 mm thick.

3. Results and Discussion

3.1. HVOF thermal spray of WC-12Co powder

3.1.2. Vickers Hardness (HV) Measurement and Observation of Coating Layer Cross-Section

Figure 8 presents the Vickers hardness (Hv) measurement method for the surface of the STD11 steel treated with thermal stray, and Table 1 presents the hardness measurement results of the thermally sprayed sample with a coating layer thickness of approximately 300 μm. The Vickers hardness measurement load was 50 g.f., and the magnification was 400 times. The HRC hardness was expressed as a converted value after measuring the Vickers hardness value. Since there was a deviation in the Hv hardness value as presented in Table 1, the coating layer was heat-treated in an oxidizing atmosphere at approximately 600°C for a certain time to precipitate carbides by recovering the decarburized layer on the surface of the thermally sprayed layer. However, the hardness value was similar to that of the sample that was not heat-treated after thermal spraying, with almost no difference. Therefore, the degree of decarburization was thought to be not significant.

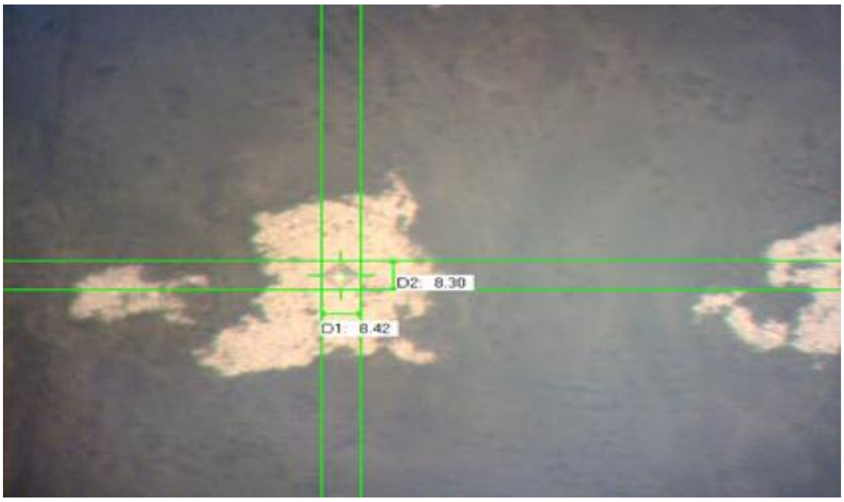

Figure 8.
Vickers hardness measurement of the surface of the thermal sprayed STD11.

Table 1.
Hardness measurement results of HVOF sprayed test sample with a 300 μm coating layer thickness.

Number of measurements	D1	D2	Hardness value (HV)	Converted value (HRC)
1	8.29	8.44	$1325.08HV_{0.05}$	HRC73.0
2	8.99	8.99	$1147.24HV_{0.05}$	HRC70.9
3	8.56	8.44	$1283.32HV_{0.05}$	HRC72.5
4	9.55	9.69	$1001.90HV_{0.05}$	HRC68.9
5	9.41	8.72	$1128.33HV_{0.05}$	HRC70.6

Figure 9 presents the cross-sectional SEM image of a sample coated with HVOF with a 300 μm thermal spray layer thickness. The coating layer thickness was slightly less than 300 μm. This was because there was a slight loss of the coating layer during emery grinding, even though a guide was installed while mounting the sample. The bond between the coating layer and the base material was judged to be sound, and the cross-section of the coating layer was confirmed to be generally uniform without any large pores or defects inside.

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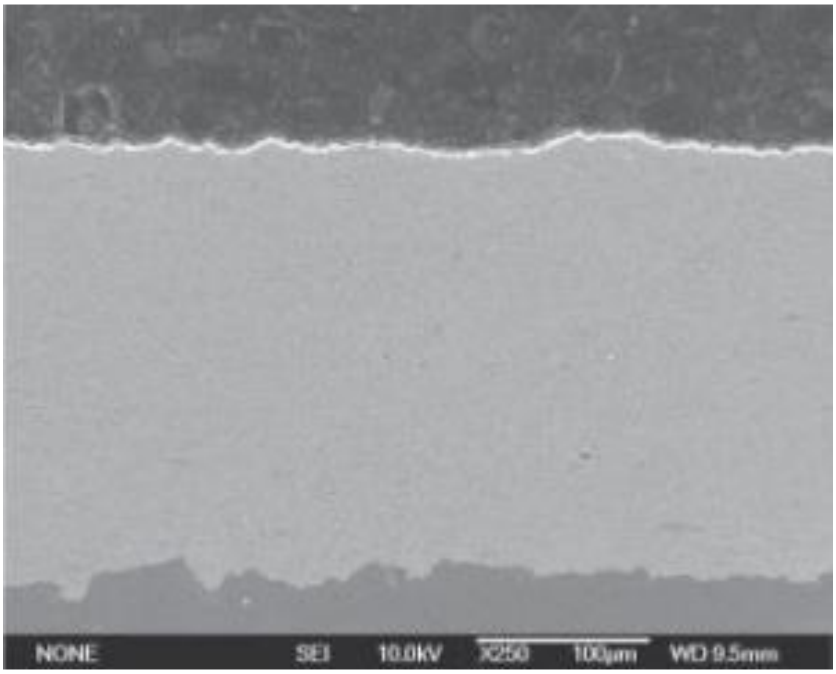

Figure 9.
Cross-sectional SEM image of the sample treated with thermal spray coating.

3.2. Fusing Thermal Spray of 60W-40Ni Powder

3.2.1. Hardness Measurement

The hardness of the sample treated with fusing thermal spray was measured using a Rockwell hardness tester after cutting. Table 2 presents the hardness measurement results of the surface of the test sample base material treated with fusion thermal spray.

Table 2.
Hardness measurement results of the sample treated with fusing thermal spray.

Number of measurements	Measurement value
1	HRC64.2
2	HRC63.5
3	HRC64.0
4	HRC63.8
5	HRC64.0

3.2.2. Cross-Sectional Structure

Figure 10 presents the optical microscope structure of the cross-section of the fusing layer, and Figure 11 presents the SEM-EDX analysis result of the cross-sectional layer. The thickness of the fusing layer is approximately 1.7~2 mm. In the cross-sectional structure, there are solidification shrinkage pores in several places, and the surface is also uneven. Additionally, in the SEM structure, there are many weak square crystal compounds due to W, so it can be predicted that the coating layer is brittle.

Figure 10.
Optical microscopic structure of the cross-section of fusing layer (×200, Nital etching).

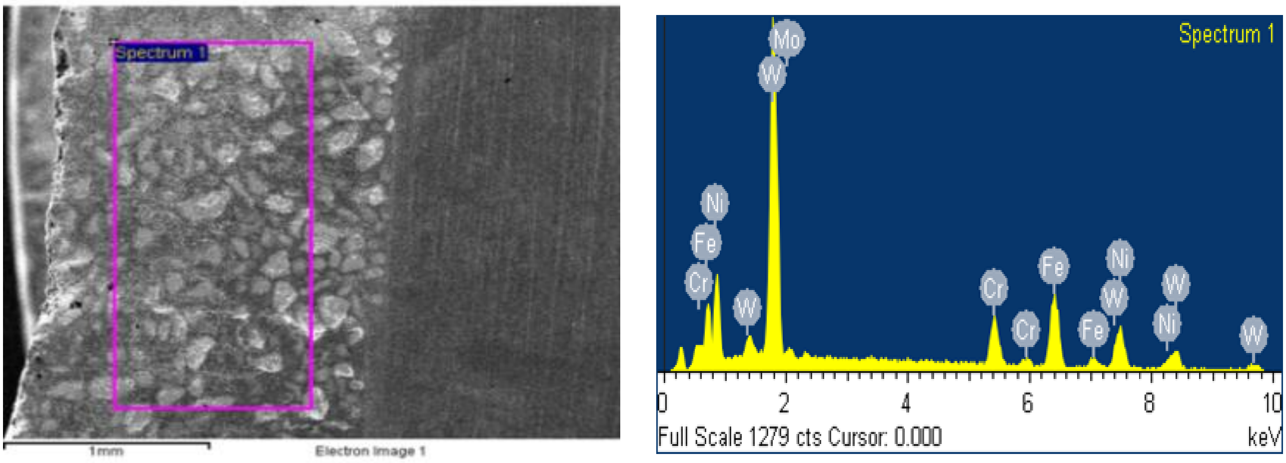

Figure 11.
SEM-EDX analysis of the cross-section of fusing layer.

3.3. Arc Wire Thermal Spray of Fe-29Cr

3.3.1. Hardness Measurement

The hardness of the sample treated with arc wire spray was measured using a Rockwell hardness tester after cutting. Table 3 presents the hardness measurement results of the sample treated with arc wire thermal spray.

Table 3.
Hardness measurement results of the sample treated with arc wire thermal spray.

Number of measurements	Measurement value
1	HRC63.6
2	HRC63.1
3	HRC62.8
4	HRC63.2
5	HRC62.9

3.3.2. Cross-Sectional Structure

Figure 12 presents the optical microscope structure of the cross-section of the arc wire thermal spray coating layer, showing a typical wave crest shape at low magnification. Figure 13 presents the SEM structure of the cross-section of the coating layer, showing the general shape of the sprayed layer, but the surface is uneven, and there are pores or solidification shrinkage pores in the structure.

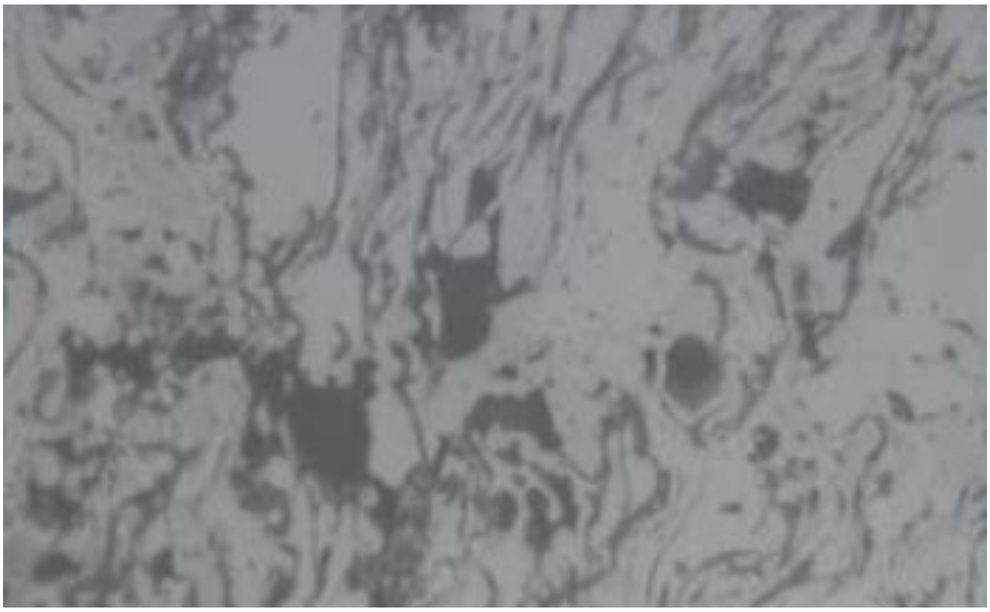

Figure 12.
Optical microscopic structure of the cross-section of arc wire thermal spray coating layer (×200, Nital etching).

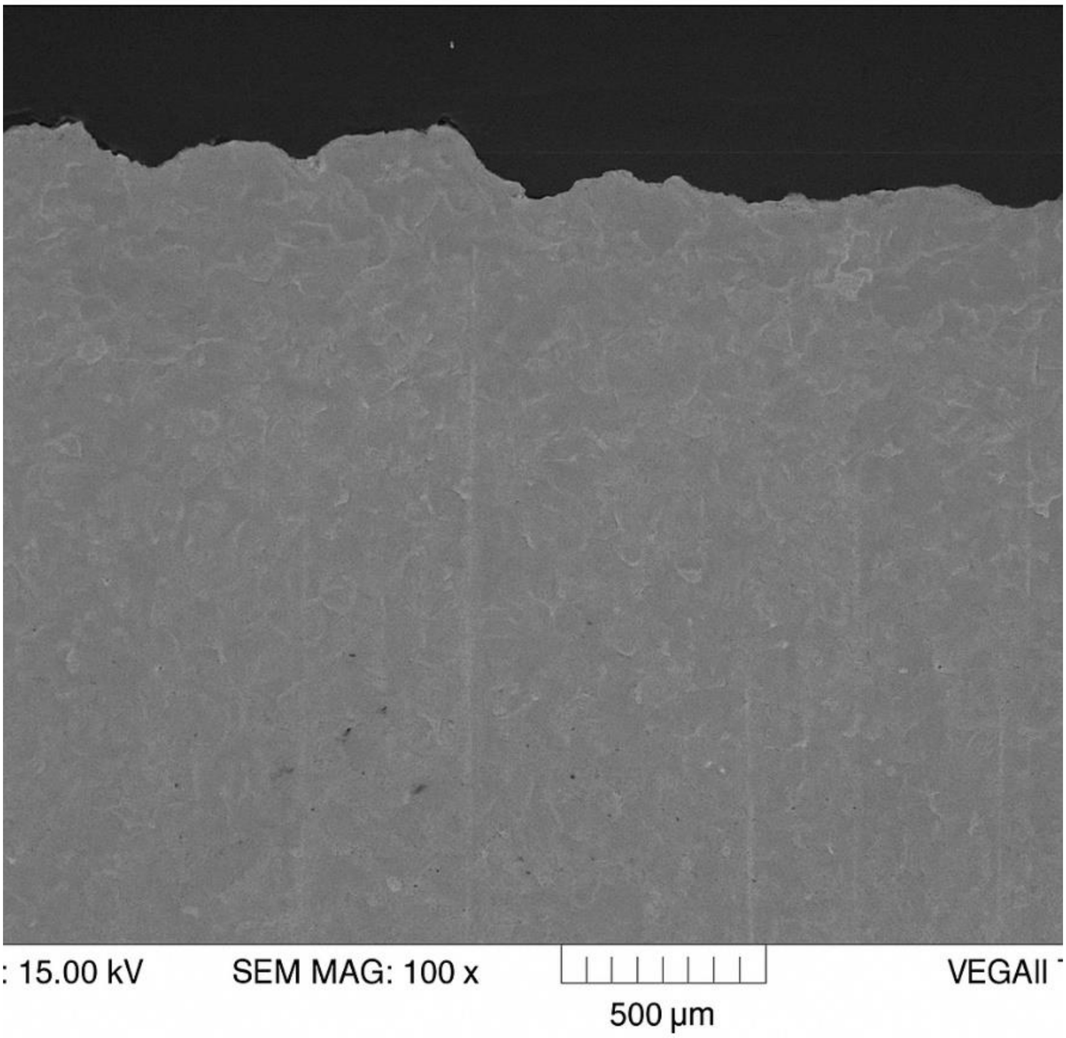

Figure 13.
SEM structure of the cross-section of arc wire thermal spray coating layer (×100).

4. Conclusions

STD11 steel was quenched at 1030°C and tempered at a low temperature, which is 170°C. Then, three methods were used to form a high-hardness coating layer on the surface of the steel: HVOF thermal spray of WC-12Co powder, surface fusing treatment using 60W-40Ni powder, and arc wire thermal spray using Fe-29%Cr wire. In addition to the durability of the existing heat-treated STD11 steel, a high-hardness spray coating layer was additionally formed, enabling the manufacture of steel with significantly increased overall durability. When HVOF thermal spray of WC-12Co powder was performed, a generally uniform film was formed without large pores or defects inside the coating layer. When surface fusing treatment was performed using 60W-40Ni powder, it was confirmed that there were solidification shrinkage pores in the structure, and the surface was also uneven. In the case of arc wire spray using Fe-29%Cr wire, it was also confirmed that the surface was uneven and there were pores or solidification shrinkage pores in the tissue. The hardness of each sample was measured five times, and the hardness values were HRC70.6, HRC64.0, and HRC62.9, respectively.

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