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Coating Technology to Improve the Performance of Resistance Welding Electrodes for Zn-Mg-Al Alloying Coated Steel Sheets

SangHoon Yoon[1,†] and Gyuyeol Bae[2]

[1] *Automotive Steel Surface Research Group, POSCO Technical Research Laboratories, Korea*
[2] *Welding & Joining Research Group, POSCO Technical Research Laboratories, Korea*
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PosMAC (POSCO Magnesium Aluminum alloy Coating product) is a ternary alloy-coated steel (Zn-3%Mg-2.5%Al) developed by POSCO utilizing proprietary technology to achieve high corrosion resistance. However, the weldability of PosMAC is lower than that of standard steel sheets due to reactions between Cu-based electrodes and the coated layer during resistance welding. This interaction leads to the formation and growth of CuZn compounds, which causes uneven wear on the electrodes and shortens their lifespan. In this study, we produced the coating using the High Velocity Oxygen Fuel (HVOF) process with various types of WC-based powders. We evaluated both coated and uncoated electrodes by measuring fracture strength at 100 spot points after spot welding. Additionally, we assessed the final coating electrode through projection resistance welding at a dual fan component manufacturer. The HVOF-sprayed WC-12Co coating demonstrated promising results in both spot and projection resistance welding tests. Notably, in projection welding tests with the coated electrode, its lifespan was found to be ten times longer than that of the commercially available uncoated electrode.

Keywords: *Coated steel sheet, HVOF coating, Projection welding, Spot welding, WC-based powder*

1. Introduction

The concept of manufacturing corrosion-resistant alloyed coated steel plates by adding Mg and Al to molten Zn has been reported since the early 1960s [1]. The commercialization of high-corrosion alloyed coating products gained momentum after the development of commercial products in the 2000s [2]. The application of Zn-Mg-Al alloyed coatings initially focused on construction materials.

The demand for corrosion-resistant steels has been steadily increasing in various industries such as automotive, construction, and infrastructure. POSCO has successfully developed PosMAC steel sheet, a ternary alloy coated steel that offers excellent corrosion resistance. POSCO has produced PosMAC3.0 coated steel in Korea since 2012 [3,4]. It is ideal for various applications such as supporting solar power panels, cooling towers, sandwich panels, and roof walls. However, there is a challenge with the weldability of Zn-Mg-Al alloyed coating sheets, including PosMAC steel sheets. The interaction between a copper-based electrode and the plating layer during resistance welding processes leads to reduced weldability due to the formation of the CuZn compound. This results in welding defects and a decreased electrode lifetime.

Spot and projection welding are indeed commonly used electric resistance welding processes. They both utilize the principle of generating heat through resistance to electric current to create welds between metal pieces. In spot welding, two or more metal sheets are placed together, and an electric current is applied at specific points to generate heat and create a bond. Projection welding, on the other hand, involves welding metal parts that have raised features (projections, embossments, or intersections on the welds) designed to concentrate the heat and force of the welding process. Both spot and projection welding are widely used in various industries due to their efficiency and reliability in creating strong and durable welds [5-7]. Zn-Mg-Al alloy-coated steel sheets have excellent corrosion resistance advantages. However, compared to conventional galvanized steel sheets (GI), the melting point of the coating is lower, and in resistance welding processes, problems such as alloying of the electrode surface, electrode

†Corresponding author: sam314@posco.com

degradation, and surface cracking occur due to the high heat generated between the coated steel surface and copper-based electrodes [8]. As a result, the electrode lifetime is significantly reduced, and it is difficult to ensure weld joints of good quality. In order to improve quality issues caused by wear and electrode degradation due to alloying, in resistance welding processes with coated steel sheets, the electrode is managed by reducing the dressing frequency compared to general steel materials or by reducing the replacement cycle. Companies like Valio have implemented projection welding for automobile motor parts by initially performing projection welding on cold-rolled sheets (CR), followed by plating to enhance corrosion resistance. To improve productivity and reduce costs, there is interest in utilizing high-corrosion-resistant PosMAC steel sheets for projection welding without the need for an additional plating process. However, the electrode lifetime varies depending on the type of material used. Generally, CR can last for 5000 runs, GI for 1000 runs, and PosMAC for only 300-500 runs. In actuality, when performing projection welding using PosMAC plated steel plates, the spot welding score was only about 10% compared to when using conventional cold-rolled steel plates. If the weldability was not improved, there were limitations to using PosMAC, which has excellent corrosion resistance.

The primary objective of this research is to extend the lifetime of welding electrodes by applying coating technology to create a barrier layer that inhibits reactions between the plated steel surface and copper-based electrodes during welding. Thermal spray coating, particularly the High-Velocity Oxygen Fuel (HVOF) process, is employed to enhance properties such as heat resistance, wear resistance, and corrosion resistance [9-11]. The HVOF process uses high-temperature flames and high-velocity gas to apply coatings, making it suitable for materials like carbides and cermets. This method involves using fuels such as propane, propylene, hydrogen, acetylene, and liquid fuels like kerosene, which react with oxygen to generate a flame with temperatures ranging from 2,700 to 3,000 ºC. The gas velocity is accelerated to about 2,000 m/sec (Mach 4) during the coating process. Although the lower temperature of the heat source generally prevents the use of materials like ceramics, HVOF exhibits excellent performance in coating layers formed by materials such as carbides or those with relatively low melting points due to the high-speed flame.

In this study, the selection of a coating material was based on its low reactivity with the Zn plating layer, similar to the sink roll barrel coating material used for Zn plating. The lifetime of both coated and uncoated welding electrodes was evaluated by measuring the fracture strength at every 100 spot points after spot welding. Finally, projection resistance welding using the optimized coated electrode was performed by a dual fan manufacturer to validate the effectiveness of the developed process. The thermal spray coating technology offers advantages such as minimal distortion of the material, fast formation speed of the coating layer, control over coating thickness, and a relatively simple process, making it a promising solution for improving the durability and performance of welding electrodes.

2. Experimental

The different cermet powders were used as feedstock. Five commercial spray cermet powders, viz. WC–12Co (Praxair 1342VF), WC-8Co-10Cu (Fusimi DTS-W529), MoB-45CoCr (Fusimi DTS B49), WC-10Ni (Praxair 1310VM), and WC-30WB-10Co (Amperit 538) were used in the current study. Feedstock was manufactured using an agglomerated and sintered method. Cu alloy and CuCrZr welding electrode were used as the substrate. Grit blasting was performed before the coating process to generate the desired surface roughness of the specimens. The thermal spray coating process is influenced by various process variables such as the temperature and velocity of the flame, fuel flow rate and spray distance, powder feed rate, and gun traverse speed. Therefore, it is necessary to determine the optimal coating process conditions according to the powder used, as the characteristics of the coating layer are greatly influenced by these variables.

HVOF spray coating was carried out using a commercially available HVOF (Praxair JP 5000) spray system. The equipment and the coating process are described elsewhere. Generally, the spray distance has a significant impact on the coating characteristics, so coating was performed at different spray distances. In most cases, the spray distance for HVOF thermal spray coating process ranges from 200 to 300 mm. In order to optimize the process conditions, experiments were carried out for two different spray distances of 230 mm and 280 mm. The gun scanned with a speed of 300 mm/s during coating experiments. The target for coating thickness is 50 micrometres of less. Table 1 summarizes the process parameters for HVOF spraying coating.

The cross-sectional microstructures of the coatings were observed using a field emission scanning electron microscope (FE-SEM, Gemini sem 500). Scanning electron microscopies (SEM, JEOL, JSM-6610) with back-scattered electron, as well as an energy dispersion X-ray spectroscopy (EDS, Oxford ultim max) were utilized to examine the microstructures and compositions of the coating. Also, the Vickers hardness of the coatings was measured using a micro-hardness tester under a load of 300 gf for 10 s. The mean hardness value from 10 readings was obtained for each sample.

In order to evaluate the lifetime of the coated and uncoated welding electrodes, spot welding tests were conducted using PosMAC3.0 (Zn-3wt%Mg-2.5wt%Al) coated steel sheets with DYNA spot welding test machine, as shown in Fig. 1. Fracture strength was measured at every 100 spot points after spot welding. The detailed spot welding conditions are listed in Table 2. The Vickers hardness of welding electrode was measured after 1,000 spot points using a micro-hardness tester under a load of 200 gf for 10 s. The mean hardness value from 5 readings was obtained for each sample.

Fig. 1. DYNA spot welding test machine

Projection resistance welding of the final coating electrode was carried out by a dual fan manufacturer. The projection welding conditions for the coated electrode are different from the conventional electrode conditions. The voltage for projection welding with the coated electrode is 235 kV, and the welding pressure is 1.8 kgf/cm^2. The fracture strength test was performed on the welded part after projection welding at every 200 spot points. Three out of the six welded parts were measured at 2, 4, and 8 o'clock. The required specification for welding strength is a minimum of 65 kg or above.

3. Results and Discussion

3.1 Optimization of the coating process

HVOF coatings were applied to various powders on Cu alloy substrates using the process variables listed in Table 1. Optimal conditions, including spray distance and pass number, were determined based on microstructure, coating thickness, and hardness. Figs. 2 and 3 show that WC-based HVOF coatings exhibit decarburization and carbide phase decomposition. Black areas within the coating layer, identified as oxides and pores, degrade the mechanical properties. Microstructural differences, such as porosity and oxidation, varied with spray distance for each powder, resulting in different hardness values (Table 3). WC-12Co and WC-30WB-10Co coatings, with denser microstructures, exhibited higher hardness. MoB-45CoCr

Table 1. HVOF spray process parameters

Conditions	H_2 flow (SCFH)	O_2 flow (SCFH)	Feed Rate (g/min)	Distance (mm)	Traversal speed (mm/s)
	1450	490	38	230, 280	300

Table 2. The conditions of spot welding

Conditions	Welding Force (kN)	Current (kA)	Welding Time (ms)	Holding Time (ms)	Comments
	2.6	10.5~11.5	270 (16 cycles)	40 (2 cycles)	AC

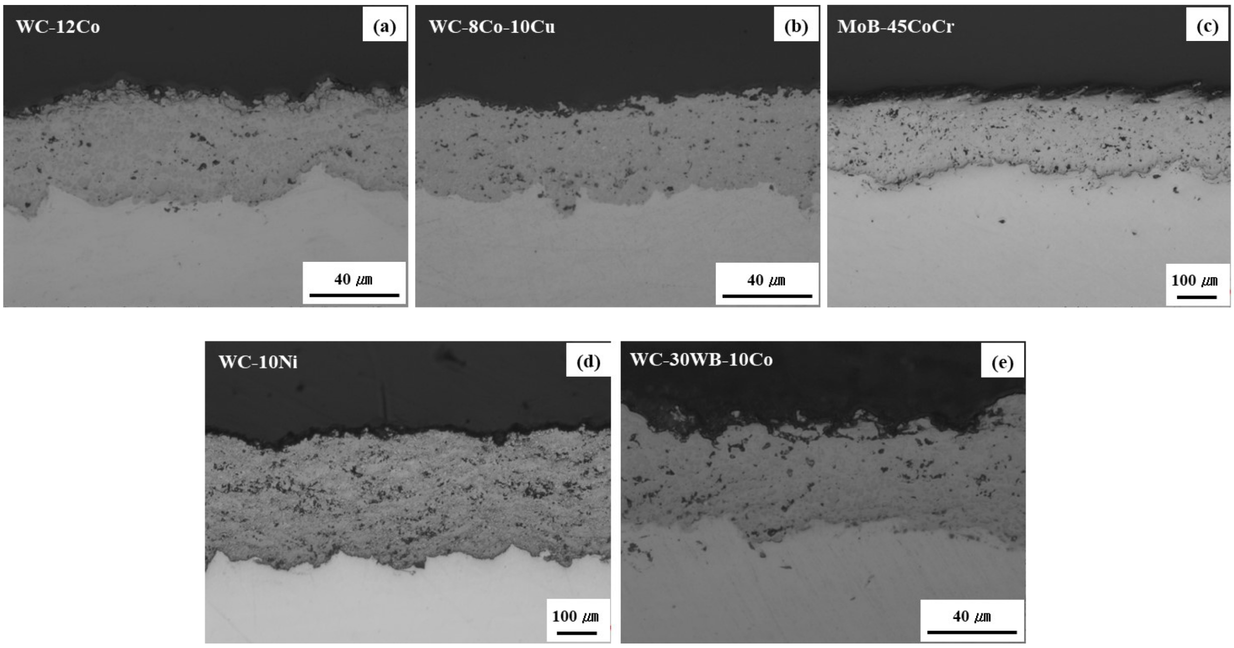

Fig. 2. Cross-sectional SEM micrographs (backscattered electrons imaging mode) with five types of powders coated under the condition of a 230 mm spraying distance. WC-12Co (a), WC-8Co-10Cu (b), MoB-45CoCr (c), WC-10Ni (d), WC-30WB-10Co (e)

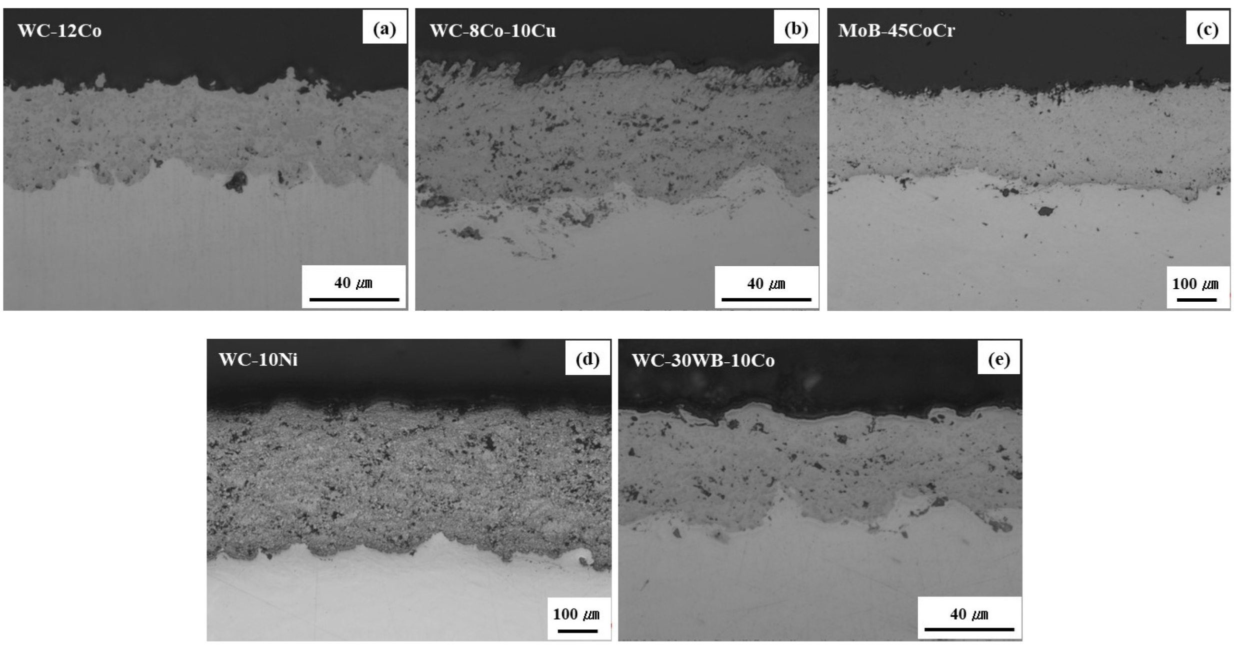

Fig. 3. Cross-sectional SEM micrographs (backscattered electrons imaging mode) with five types of powders coated under the condition of a 280 mm spraying distance. WC-12Co (a), WC-8Co-10Cu (b), MoB-45CoCr (c), WC-10Ni (d), WC-30WB-10Co (e)

Table 3. The average Vickers hardness of the coatings at each spraying distance

Spray distance	WC-12Co (#1)	WC-8Co-10Cu (#2)	MoB-45CoCr (#3)	WC-10Ni (#4)	WC-30WB-10Co (#5)
230 mm	1129 Hv	987 Hv	1169 Hv	1247 Hv	1287 Hv
280 mm	1311 Hv	942 Hv	1192 Hv	1153 Hv	1442 Hv

and WC-10Ni powders showed high deposition efficiency under the same conditions. Based on each powder's characteristics and a coating thickness criterion of below 50 micrometers, the optimal process conditions are: WC-12Co: 280 mm, 3 passes; WC-8Co-10Cu: 230 mm, 3 passes; MoB-45CoCr: 280 mm, 2 passes; WC-10Ni: 230 mm, 3 passes; WC-30WB-10Co: 280 mm, 3 passes.

3.2 The evaluation of spot welding with coated electrodes

Coating was applied to the spot welding electrodes (CuCrZr) based on the derived optimal process conditions for each powder. Spot welding tests was conducted using PosMAC3.0 coated steel plates based on the conditions listed in Table 2. After coating the spot welding electrodes, the fracture strength was measured at 100 spot points for both the coated and uncoated electrodes. The welding current for the uncoated and coated electrodes was varied from 10.5 to 11.5 for the test, and the spot welding was conducted using the most ideal conditions for each electrode based on the test results. As seen in the results in Table 4, the #3 (MoB-CoCr) coated electrode showed the worst weldability compared to the uncoated electrode. For the #3 coated electrode, coating delamination and excessive sparking were observed during the welding test. As a result, the experiment was not continued beyond 400 cycles. Except for the #1 (WC-12Co) coated electrode, a decrease in fracture strength was observed as the number of spots increased for both the uncoated electrode and all the coated electrodes. The #1 (WC-12Co) coated electrode maintained the initial fracture strength even after 1000 spot welds. In conclusion, WC-12Co HVOF coating showed the most excellent fracture strength characteristics for the welded joint.

After conducting a spot welding test with 1000 spot points, the cross-sectional microstructure of the surfaces of the uncoated and coated electrodes was observed. Fig. 4 shows the cross-sectional microstructure of the uncoated electrode. As observed in Fig. 4a, a white arrow indicates the presence of a thick reaction layer and fractures on the surface of the electrode. In other words, the electrode suffered degradation due to welding. Electrode degradation is a common problem that can occur in resistance welding processes. It is caused by a combination of factors such as the high heat generated during welding, chemical reactions between the electrode and the workpiece, and mechanical wear. The EDS analysis results of the reaction layer in Fig. 4b confirmed the presence of plated components of Zn, Mg, Al, and Fe within the Cu-based electrode. It was evident that a reaction layer formed between the Cu-based electrode and the plating layer and the Fe-based material, particularly the formation of CuZn intermetallic compound. As the welding continued, the formed CuZn intermetallic compound layer fractured, causing an increase in the surface area of the welding electrode and a decrease in weldability. Fig. 5 shows the cross-sectional microstructure of the most ideal #1 (WC-12Co) coated electrode. As seen in Fig. 5b, the localized EDS analysis results confirmed the embedding of Fe and the plated layer, but overall, the formation of the reaction

Table 4. The fracture strength of the coated and uncoated electrodes at every 100 spot points

Coating Materials	Current (kA)	Tensile Failure Load (kN)									
		100	200	300	400	500	600	700	800	900	1000
Uncoated	11.2	10.5 10.6	10.3 10.4	9.7 10.6	9.3 9.4	9.8 10.9	10.3 9.8	10.0 10.4	10.3 10.8	9.9 10.9	8.6 8.0
#1	11.2	10.6 10.4	10.3 10.4	10.4 10.1	10.4 10.2	10.4 10.5	10.5 10.4	10.3 10.1	10.5 10.1	10.3 10.2	9.8 10.2
#2	11.5	10.0 9.9	10.2 9.9	10.3 10.0	9.5 10.2	10.1 9.8	10.0 10.1	9.8 9.7	10.1 4.9	7.2 9.0	10.3 9.0
#3	10.5	10.3 10.2	10.0 9.9	9.7 8.0	9.6 9.4						
#4	11.2	10.0 10.3	10.1 -	10.3 10.1	10.2 10.4	10.0 10.2	10.7 10.3	10.5 9.0	9.2 9.2	6.6 9.2	6.6 8.8
#5	11.5	10.0 10.5	9.9 9.9	10.1 10.2	10.2 9.9	9.6 9.9	10.0 10.0	3.6 10.0	6.9 10.0	8.5 9.4	7.9 8.0

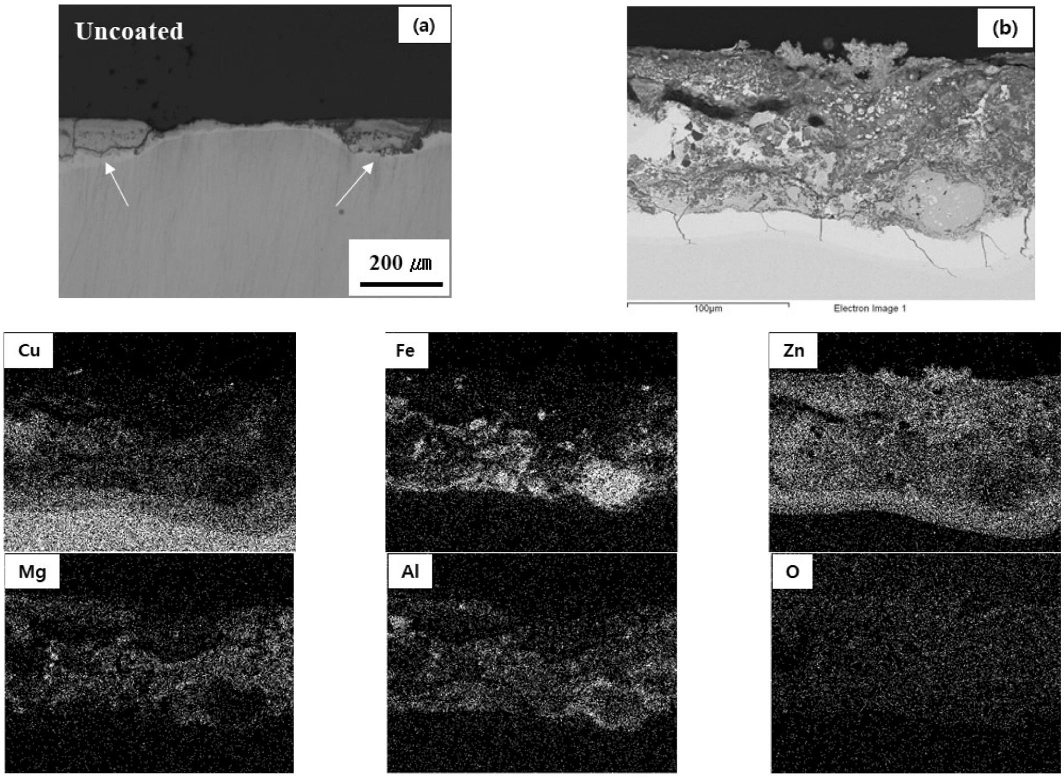

Fig. 4. Cross-sectional SEM micrographs (backscattered electrons imaging mode) and EDS analysis of uncoated welding electrode after 1000 spot points

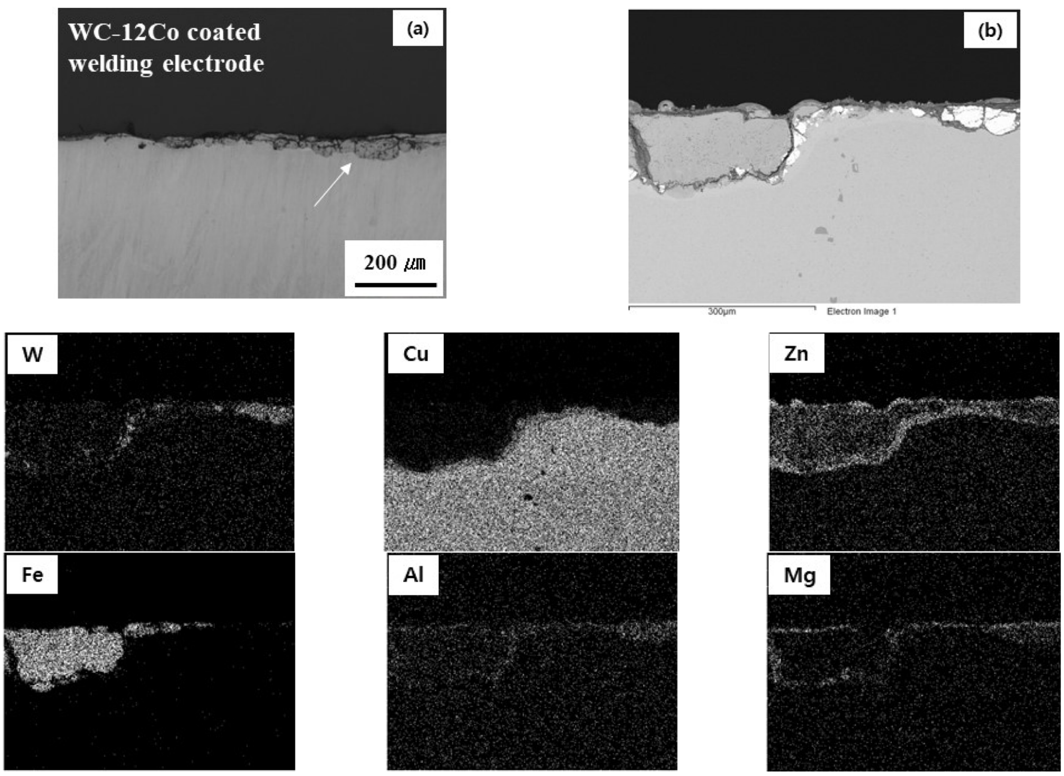

Fig. 5. Cross-sectional SEM micrographs (backscattered electrons imaging mode) and EDS analysis of WC-12Co coated welding electrode after 1000 spot points

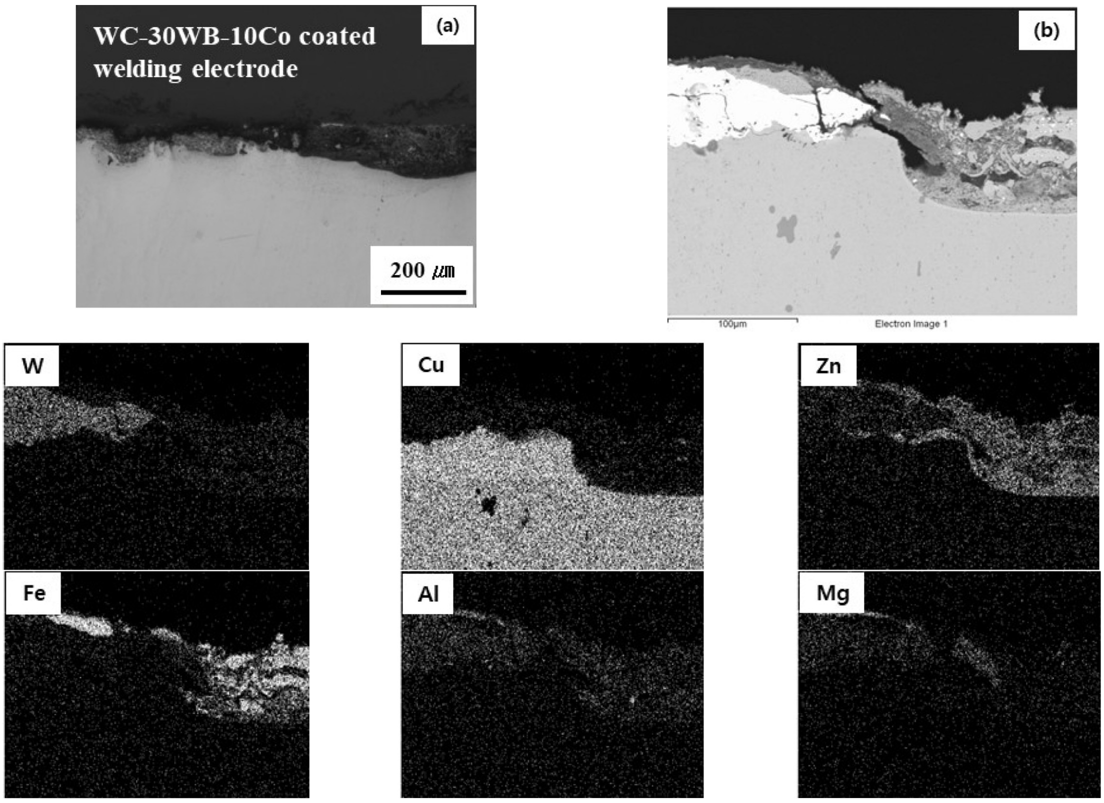

Fig. 6. Cross-sectional SEM micrographs (backscattered electrons imaging mode) and EDS analysis of WC-30WB-10Co coated welding electrode after 1000 spot points

Table 5. The Vickers hardness of the welding electrode before and after spot welding (at 1000 spot points)

Hardness (Hv 0.2)	Initial Welding Electrode	Welding Electrode after Spot Welding Test		
		Uncoated	WC-12Co Coated (#1)	WC-30WB-10Co (#5)
1	167	118	147	151
2	153	101	132	139
3	156	92	120	118
4	165	103	107	127
5	156	106	103	145
Ave.	159	104	122	136

layer was significantly reduced compared to the uncoated electrode, and partial remnants of the WC-based coating layer could be observed. Fig. 6 shows the cross-sectional microstructure of the #5 (WC-30WB-10Co) coated electrode. For the #5 coated electrode, parts with remaining WC (WB) layers could be observed, but a thick reaction layer and severe wear were evident. Based on the overall results, it can be concluded that coating can improve electrode lifetime, but maintaining a uniform coating layer on the electrode surface ultimately determines the welding characteristics and lifetime.

After a spot welding test with 1000 spot points, the Vickers hardness was measured for the uncoated electrode and the #1 and #5 coated electrodes. As seen in the results in Table 5, after the welding experiment, both the uncoated and coated electrodes exhibited lower hardness compared to the initial hardness of the electrodes. This is because the temperature on the electrode surface increases during welding, and as the number of welding cycles increases, the electrode deteriorates due to the heat. Particularly, it can be observed that the hardness of the uncoated electrode decreases more significantly compared to the coated electrodes under the same conditions. It is considered that the degradation mechanism of the welding electrode is the formation and growth of the CuZn compound and the occurrence of inhomogeneous wear, leading to a reduced electrode lifetime [12].

3.3 The evaluation of projection welding with coated electrodes

The evaluation of fracture strength conducted on spot welding electrodes has resulted in the identification of the best coating material and coating electrodes. Finally, the evaluation of projection welding was carried out on a dual fan component manufacturer's projection welding process. The target thickness of WC-12Co HVOF coating was 50 micrometers. As shown in Fig. 7, projection welding consists of top and bottom parts, each with six electrodes. Before coating, the electrodes were fixed on the jigs and masked to apply coating only to the welding electrodes. As shown in Fig. 8, the projection welding was performed using a projection welding machine designed for PosMAC material at an automotive parts supplier. Six parts were welded simultaneously. The

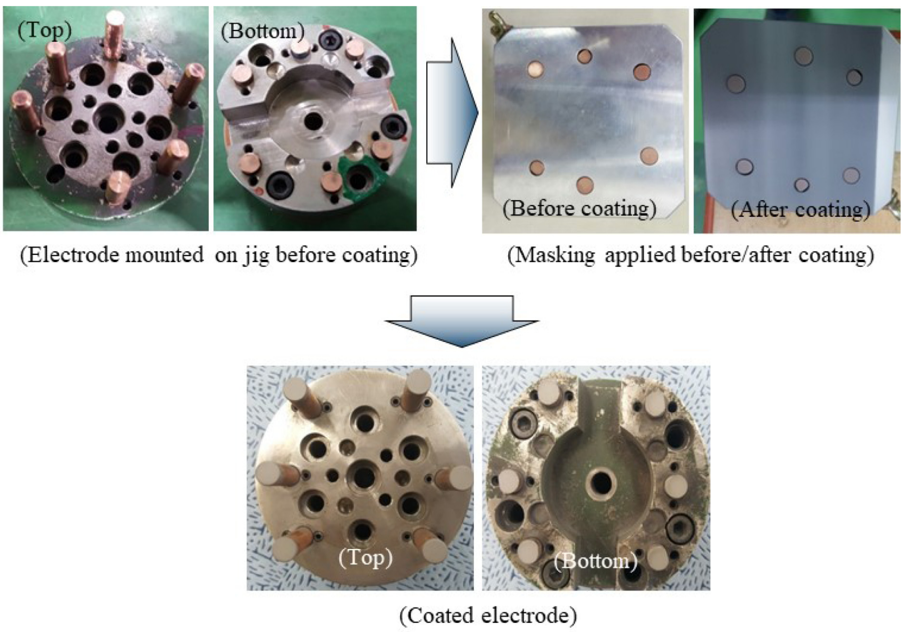

Fig. 7. Picture of the composition and coating of the projection welding electrode

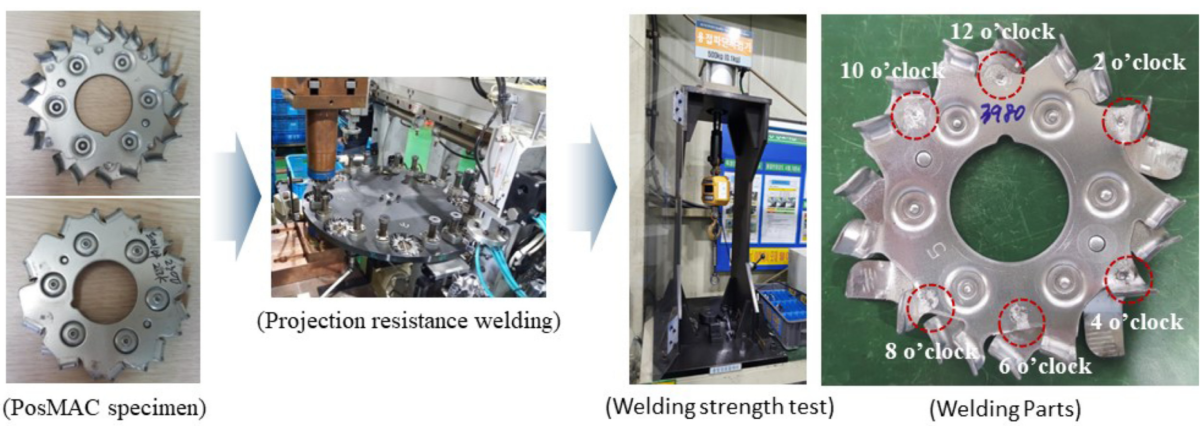

Fig. 8. Projection welding process and measurement of welding strength

Table 5. The fracture strength of welded part after welding

Spot Points	Fracture Load (kg)		
	2 o'clock	4 o'clock	8 o'clock
100	143 ↑ *	159 ↑	162 ↑
300	162 ↑	135	158 ↑
500	156 ↑	145	158 ↑
700	130 ↑	164 ↑	164 ↑
900	165 ↑	143	137 ↑
1000	167 ↑	153 ↑	155 ↑
1200	171 ↑	166 ↑	151 ↑
1400	166 ↑	158 ↑	164 ↑
1600	167 ↑	163 ↑	155 ↑
1800	172 ↑	159 ↑	166 ↑
2000	155 ↑	157 ↑	159 ↑
2200	168 ↑	160 ↑	165 ↑
2400	165 ↑	160	158 ↑
2600	169 ↑	43	95
2700	156 ↑	158 ↑	137
2800	166 ↑	153 ↑	156 ↑
2900	153 ↑	156 ↑	161 ↑
3100	164 ↑	134 ↑	150 ↑
3300	169 ↑	83	167 ↑
3500	163 ↑	156 ↑	163 ↑
3700	175 ↑	173 ↑	169 ↑
3900	157 ↑	164 ↑	155 ↑
3980	164 ↑	169 ↑	163 ↑

* ↑ : Non-fractured welded part

projection welding conditions for the coated electrodes differ from those for conventional electrodes. After projection welding, the optimal welding conditions were obtained through the evaluation of welding strength. The derived welding conditions include a voltage of 235 kV for projection welding with the coated electrodes and a welding pressure of 1.8 kgf/cm^2. A fracture strength test was conducted on approximately 200 spot points after projection welding. As shown in Fig. 8, three out of the six welded parts were measured at 2, 4, and 8 o'clock positions. The required specification for welding strength is a minimum of 65 kg or above. Table 5 presents the results of evaluating the fracture strength of the welded areas after projection welding. As evident from the results, the fracture strength of the three evaluated parts (2 o'clock, 4 o'clock, and 8 o'clock directions) for approximately 4000 evaluations mostly exceeded the required spec of 65 kg and many welding areas did not experience fracture. Fig. 9 shows the evaluation of fracture strength for the three welded areas after 3980 welds, and all three areas exhibited high fracture strength without any occurrence of fracture. Even when examining the microstructure of the welded area, it can be seen that the welding between PosMAC materials has been perfectly ideal. As a result of the projection welding tests, the lifetime of the coated electrodes was more than ten times higher than that of

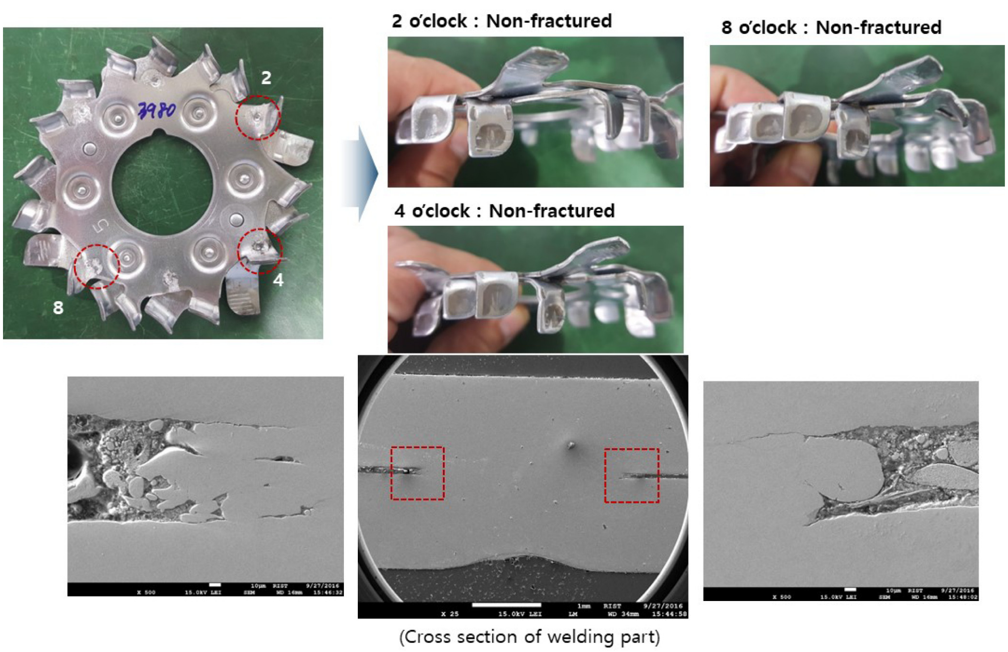

Fig. 9. Fracture strength test section and cross-sectional of SEM micrographs at 3980 spot point

the commercial uncoated electrodes. Furthermore, it was confirmed that the weldability of PosMAC material has significantly improved.

4. Conclusions

The identified degradation mechanism of welding electrodes in this study is as follows:

For conventional electrodes, the direct contact between the plating layer and the Cu electrode during welding results in the formation and growth of a reaction layer between the Zn plating layer and the Cu electrode. This leads to inhomogeneous wear and ultimately reduces the lifetime of the welding electrode.

On the other hand, for coated electrodes, there is a coating layer between the Zn plating layer and the Cu electrode during welding. This coating layer plays a crucial role in inhibiting the reaction between the Zn plating layer and the Cu electrode, which is a primary cause of electrode degradation. The presence of this coating layer significantly increases the wear resistance of the electrode. The coating layer acts as a barrier, preventing the formation and growth of CuZn intermetallic compounds, which are known to contribute to the rapid wear and degradation of welding electrodes. By mitigating this reaction, the coating layer helps maintain the integrity of the electrode surface, thereby reducing the occurrence of inhomogeneous wear patterns that typically lead to premature electrode failure. As a result, the lifetime of the welding electrode is significantly extended.

In conclusion, the HVOF sprayed WC-12Co coating has shown promising results in spot and projection resistance welding experiments. The evaluation results of the projection coated electrode (WC-12Co) prototype have demonstrated that the welding strength mostly satisfies the requirement specification for up to 4000 spot points. Moreover, when welding PosMAC (Zn-Mg-Al) coated steel plates, the lifetime of the coated electrode is more than 10 times higher than that of the commercial uncoated electrode.

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