Defects Modification of TiB$_2$–TiC Composite Phase Coating Resistance Spot Welding Electrode via Friction Stir Processing

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In this work, surface modification was carried out using friction stir processing (FSP) technique to investigate on the electro-spark deposited (ESD) TiB$_2$–TiC coated electrode caps for resistance spot welding. The morphology, microstructure, phase composition and resulting mechanical properties of the electrode were examined and characterized. The results showed that treatment with FSP significantly reduced the number of cracks formed on TiB$_2$–TiC coating and enhanced the interfacial binding force between the TiB$_2$–TiC coating and the substrate. The micro-hardness and bonding strength of the TiB$_2$–TiC coating were also improved and the heat affected zone (HAZ) of the substrate disappeared due to the influence of FSP. The improvement mechanism are attributed to a decrease in the number of coating cracks, improved delamination, and refined substrate grains size near the interface. [doi:10.2320/matertrans.M2013363]

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1. Introduction

The service life of electrode cap is commonly extended using the effective method of electro-spark deposition (ESD) on its surface. Previous work by Luo et al.$^1$ has demonstrated improved service life of spot welding electrodes by application of an ESD TiB$_2$/Ni surface coating. Additionally, Zou et al.$^{23}$ reported on the ESD of a multi-layer of Ni/(TiC particle reinforced Ni)/Ni composite coating onto the top surface of copper electrodes. As a result, the coated electrode exhibits an extended service life more than an uncoated electrode. However, due to the large difference in thermal expansion coefficients between the coating and substrate materials, the electrodes display several defects including cracks and poor adhesion; resulting in a negative impact on the lifespan of spot welding electrodes. In an attempt to reduce the electrode coating defects, Chen and Zhou$^5$ have applied post-laser treatment on the electrodes. However, due to the high energy density of the laser input, this process led to the consequent softening of the electrode substrate. This property severely limits the applicability of laser treatment for the reduction of coatings defects. To overcome this issue, FSP as an innovative promising post treatment of electrode coatings is presented. Our findings suggest that FSP not only eliminates or reduces the defects of the coating, but may also prevent the substrate from softening. FSP has two important characteristics: a low amount of heat generation, and formation of very fine grains in the stirred region. These features of FSP have been studied extensively and FSP itself has been reported as a surface treatment technique for various metallic materials. Bauri et al.$^5$ employed FSP to improve in situ the microstructural and properties of an Al–TiC composite using FSP technique. Famoush et al.$^5$ fabricated nano-hydroxyapatite coatings on the Ti–CaP nanocomposite surface layer by FSP and electrophoretic deposition. Grewal et al.$^5$ found that the friction stir processed (FSPed) hydroturbine steel (Fe–13Cr–4Ni, mass%) gave 2.6 times old improvement in micro-hardness and erosion rate as compared to unprocessed (unFSPed) steel samples. Morisada et al.$^7$ reported that the thermally sprayed cemented carbide (WC–Cr–Ni) layer was successfully modified by FSP to exhibit greater hardness and being crack-free. Mansoor and Ghosh$^{11}$ demonstrated the possibility of employing FSP to produce a high-strength Mg alloy with multiple overlapping passes to partial depth using FSP. Based on these studies, FSP may be an ideal choice for surface modification of coated electrodes.

In the present work, TiB$_2$–TiC composite phase coated electrodes were treated by FSP, to reduce or eliminate coating defects that are typically found in the unFSPed counterparts and the corresponding microstructure modification and resulting mechanical properties of the FSPed electrode were investigated.

2. Experimental Procedures

2.1 Preparation of TiB$_2$–TiC composite phase coating electrodes

Precipitation strengthened and cold formed B nose domed flat electrodes (Cu–1Cr–0.05Zr, mass%, domed-flat type (B-nose) electrodes, φ16 mm in diameter and 23 mm in length, flat top with 5 mm in diameter at top surface.) was selected to be used in this experiment. Before performing the coating process, the electrodes were cleaned in acetone using an ultra-sonic cleaning equipment. A specially sintered TiB$_2$–TiC (TiB$_2$–60TiC–5Ni, mass%) ceramic rod with 6 mm in diameter and 30 mm in length was used as anode for deposition via custom-made electro-spark deposition instrument, consisting of a handheld vibrator. The coating process was conducted in air, at room temperature, using an output voltage of 24 V, a capacitance of 2000 µF, for 2 min.

2.2 FSP on TiB$_2$–TiC composite phase coated electrodes

Modification of the coated surface by FSP on the unFSPed electrodes was conducted using a general-purpose milling
machine. The FSP rotating tool was made of high-speed steel and was of a columnar shape (ϕ16 mm) in the absence of a probe. FSP was carried out under the following conditions: (a) rotation speed of FSP tool: 1200 min⁻¹, (b) hold time: 180 s, and (c) vertical pressure: 2000 N.

2.3 Evaluation of the unFSPed and the FSPed TiB₂–TiC layers

The microstructures of the coating surface and the corresponding cross-sections were observed using a scanning electron microscope (SEM). Phase identification was conducted with an X-ray diffractometer (XRD) with Cu Kα radiation operating at 40 kV and 40 mA. Mechanical behavior was characterized by measuring the micro-hardness and the bonding strength between the coating and substrate. The micro-hardness was measured using a HVX-1000 pyramidal diamond indenter of a Vickers hardness tester with a nominal load of 100 g applied for 20 s. The bonding strength was assessed using a universal testing machine with a loading rate of 500 N/min (according to the ASTM C-633 test method) with a sample size of ϕ40 mm in diameter and 50 mm in length. This experiment was conducted on 5 pairs of unFSPed and FSPed samples, with each pair forming a team, as such they were each, assigned a specific serial number (SN) Team 1, Team 2, Team 3, Team 4 and Team 5 respectively.

3. Results and Discussion

3.1 Microstructure

The surface and cross sectional SEM images of the unFSPed sample are shown in Fig. 1. The topography of the unFSPed electrode exhibited some splash features that are a common characteristic of ESD, particularly when the coating process is conducted in air for shielding, as in the present work. The occurrence of splashing is due to the formation of molten droplets that are accelerated by the plasma jet, striking the substrate surface at a high velocity. A high abundance of stress relief cracks are visible within the coating, as shown in Fig. 1(a). Notably, we also observed cracks in the cross-sectional layer, as shown in Fig. 1(b). Furthermore, Fig. 1(b) also reveals a few cracks or delamination, within the coating and at the substrate-coating interface. These cracks formed the basis of diffusion channels during the resistance spot-welding process, allowing the zinc metal (derived from the galvanized steel sheets) to penetrate through. Additionally, these cracks can also increase probability of an alloying reaction between the electrode substrate (Cu) and the coating of galvanized steel sheet (Zn), thus forming brittle brass alloy. Consequently, this alloying process accelerates the failure of the electrode.

Figure 2(a) shows the SEM images of the coating surface of the FSPed sample. It illustrates that the number of surface
cracks of the FSPed samples decreased significantly compared to their corresponding unFSPed samples. In addition, the cracks and the delamination within the layer, as shown in Fig. 2(b), have been improved and the coating layer became denser in contrast to in the unFSPed samples. The improvement of the FSPed sample may be attributed to the presence of interstitial gaps within the cracks and between the delamination and substrate, which may reduce under the influence of vertical pressure (produced in the early stage of FSP). In the later stage, the FSP produces intense plastic deformation, material mixing, and thermal exposure that causing the Ni binding material to diffuse into the cracks easily. Whereas, during the FSP process, the amount of Ni accumulated in the cracks results in the healing of the cracks, as a result of welding under the function of stirring and thermal exposure.

Figure 3 shows the XRD patterns of the unFSPed and FSPed TiB2–TiC layers. It demonstrates that there is a slight difference in phase composition before and after FSP. We find that the layers consist mainly of TiB2, TiC, Cu, and a small amount of Ni. However, some impurity phases are observed in the XRD pattern of the unFSPed sample, such as titanium oxide, Ti–Ni, Cu–Ti and Cu–Ni intermetallic phases. The oxidation of the coating is produced due to the high amounts of heat generated during ESD in air, while intermetallic phases are the result of atomic diffusion. Interestingly, we find that the impurity phases disappeared in the FSPed sample as shown in Fig. 3. This may be due to poor adhesion of the impurity phases with the coating or substrate that leading to its removal during FSP. Figure 3 also illustrates that the heat generated by the FSP does not induce the formation of new phases. In the present work, it was determined that the temperature generated by FSP did not exceed the softening point (550°C) of the copper alloy substrate. The micro-hardness, as shown in Fig. 4, did not display any change between the unFSPed and FSPed samples, proving our hypothesis. Therefore, it is unlikely that the temperature generated in FSP would be high enough to oxidize the coating layer. Close examination of Fig. 3 reveals that the Cu peak intensity is increased by the FSP, meanwhile the Ni peak is slightly offset as shown on by the enlarged pattern areas. The former may be attributed to the thinning of the coating layer, which may have allowed the substrate derived-Cu to diffuse into the coating after FSP. The latter is presumably ascribed to the residual stress within Ni, generated by FSP.

3.2 Mechanical characterization

The mechanical behavior of the coatings was characterized by micro-hardness measurements between the coating and the adhesive strengths of the final substrates. Figure 4 shows the distribution of hardness from the top surface of the coating. Although the micro-hardness distribution of the samples has an identical trend before and after FSP, there are still few disparities present, as shown in Fig. 4. For example, the peak value of the coating hardness and the hardness value of the substrate above the matrix hardness line are observed to increase after FSP. Subsequently, the increase of coating hardness is due to the modification of cracks by FSP.

In order to determine the basis leading to the change in substrate hardness, we studied the SEM images of our samples at higher magnification, as shown on Fig. 5. Figure 5(a) reveals the magnified SEM cross section image of the unFSPed sample. A strip columnar grain zone approximately 10 µm wide is observed in the substrate near the interface. This type of microstructure is similar to the HAZ found in resistance spot welding process. As a matter of fact, ESD in principle was considered to be a micro-welding process as the literature3) reported the forming process of the HAZ. During the ESD process, a certain amount of heat is added to raise the temperature of the local spots on the electrode surface to its melting point. However, the heat energy did not raise the temperature of the substrate high enough to cause any significant melting or any substantial microstructural changes. Additionally, due to a much higher thermal sink in the substrate and the inherent characteristics of the spark pulses (the time between sparks is significantly long relative to the duration of the sparks), this allows the heat generated in the substrate to dissipate rapidly. Therefore, it causes a minor transitory melting of the substrate with the formation of only a very small HAZ adjacent to the surface. Figure 5(b) reveals the microstructure of the FSPed electrode. Here, the matrix grain size of the FSPed sample is considerably refined as compared with the unFSPed counter-
part. This is attributed FSP that generates significant frictional heating along with intense plastic deformation, causing the occurrence of dynamic recrystallization in the substrate near the coating. As a result, the hardness of the FSPed sample is increased according to the Hall–Petch equation, and simultaneously, the HAZ is found to disappear after FSP.

Figure 6 shows the bonding strength of the 5 teams of samples. It is found that the average bonding strength in the FSPed samples is about 6 times higher than that in the unFSPed samples. This indicates that FSP is able to either modify or remove the defects on unFSPed electrodes and improve the adhesion between the coating and substrate.

4. Conclusion

Our research findings demonstrate that the FSP process successfully reduces the cracks in the TiB₂–TiC coating and improves the interfacial adhesion between the TiB₂–TiC coating and substrate. The micro-hardness and bonding strength of the TiB₂–TiC coating are further enhanced, and HAZ of the substrate disappears as a result. The strengthening mechanism is attributed to a reduction in the number of cracks in coating, improved delamination, and the formation of refined substrate grains near the interface.

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