Electrode Degradation in Resistance Spot Welding of Magnesium Alloy

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Mechanism of electrode degradation in resistance spot welding (RSW) of magnesium alloy has been investigated using scanning electron microscopy (SEM) and energy-dispersive spectrum (EDS). The results show that electrode degradation experienced mainly four basic steps (i.e. magnesium alloy pickup, electrode alloying with magnesium, electrode tip face pitting, and cavitation). Magnesium alloy pickup began from the first weld as tiny drops of molten magnesium alloy were transferred from the sheet surface to the electrode tip face. A complex alloy layer (Cu2Mg and CuMg2) was formed by the molten magnesium alloy reacting with the electrode. Electrode pitting occurred by brittle fracture of alloyed region formed on the electrode tip face resulting in material removal from the electrode tip face. Once the electrode pitting started, large cavities formed by combining smaller pits. Therefore, it is favorable to periodic cleaning of the electrode tip face for extending electrode life and obtaining well appearance of joint surface.

KEY WORDS: resistance spot welding; magnesium alloy; electrode degradation; microstructure.

| Table 1. Chemical composition of magnesium alloy (wt%). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Al   | Zn   | Si   | Fe   | Cu   | Mn   | Ni   | Mg   |
| 2.90 | 0.837| 0.067| 0.0045| 0.005| 0.431| 0.0013| balance |

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8 cycle welding time, 23 kA welding current and 2.5 kN electrode force. After welding, the electrode tip faces were cleaned in an acetone bath, followed by metallographic examination. Then the electrode was sectioned through the center normal to the plane of electrode tip face. The cross-sections were ground, polished and cleaned in an acetone bath for metallographic examination. The microstructure of the electrode was examined using scanning electron microscopy (SEM; Model JSM-5310, Japan) equipped with energy-dispersive spectrum (EDS; Model Link-Isis, Britain).

3. Results and Discussion

Figure 3 shows optical photographs of electrode tip faces after making 25 welds. It can be seen that there are a lot of large cavities existing on the electrode tip faces. The cavities distribute in the form of network which had electrode tip faces damaged (i.e., electrode degradation). Besides, the electrode degradation was more serious on the top electrode than on the bottom electrode, which is consistent with the polarity effect since top and bottom electrodes remain positive and negative, respectively, during welding operation. According to the Peltier effect, the heat generation was higher on the top electrode tip face than on the bottom electrode tip face, which would speed up the electrode degradation at the top junction. The following discussion will concentrate on the behavior of the top electrode.

It can be seen from Fig. 4 that melting and pitting are very obviously on the electrode tip face. Large amounts of Mg element were found on the electrode tip face by EDS analysis. In this investigation, the pickup of magnesium alloy by the electrodes even started at the first weld. Prior to starting welding, the electrode tip faces were clean and without visual blemishes. However, the current constrictions during welding, created by the fractures of the surface oxides, would result in a very high current density and hence local magnesium alloy melting. This molten magnesium alloy would wet better on the electrode tip face than on the magnesium alloy sheet surface covered by magnesium oxide, which resulted in magnesium alloy pickup on the electrode tip face. Afterward, the Mg content of the tip face varied as the electrode pitted and refilled/recoated with fresh magnesium alloy.

Figure 5 shows one of the local, alloyed regions in the cross section of the electrode after making 25 welds. The EDS analysis was performed to estimate compositions of possible Cu–Mg phases (Table 2) as compared to those of the equilibrium Cu–Mg phases (Table 3). Solidification
structure is clearly shown in Fig. 6, which may be the eutectic with Cu₃Mg and CuMg₂ (point 1 in Fig. 5). The solidification structure further confirmed that melting occurred during welding. Another alloy layer, possibly Cu₃Mg, was also observed between the possible eutectic layer and electrode base metal (point 2 in Fig. 5). Once the melted magnesium alloy was picked up on the electrode tip face, the electrode base metal would react with the magnesium alloy. Diffusion rate of Cu in melted magnesium alloy is quicker than that of Mg in solid state electrode. Consequently, low melting point eutectic liquid might form on the electrode tip face. During sequent cooling, when temperature of liquid reached to 552°C, the eutectic reaction might proceed as follows:

\[
L \rightarrow Cu_3Mg + CuMg_2 \quad \text{..........................(1)}
\]

At the end of cooling, the eutectic with Cu₃Mg and CuMg₂ was leaved on the electrode tip face. This Cu–Mg mixture would further increase the local resistivity and heat generation, thus increasing local melting around the alloyed regions on the electrode tip face. Therefore, Mg content increased on the electrode tip face with the number of welds increasing in order to increasing contact resistance between electrode and sheet, which resulted in higher temperature on the electrode tip face during the following welding operation. Under the conditions of high temperature and pressure, Cu₃Mg layer would form through element solid diffusion between the CuMg₂ phase and electrode base metal. As a result, Mg content decreased as far from the electrode tip face. Distance of Mg element diffusion in the electrode base metal reached to about 62 µm according to 0.91 wt% Mg content by EDS analysis at point 7 in Fig. 5. EDS area analysis of electrode cross-section is shown in Fig. 7. The results demonstrate further that the Cu–Mg mixture existed on the electrode tip face and Mg diffusion occurred in electrode base metal.

As is well known, electrode pitting is a result of material removal from the electrode tip face. In this investigation,

Table 2. Chemical composition estimated using EDS.

<table>
<thead>
<tr>
<th>Location</th>
<th>Cu (wt%)</th>
<th>Mg (wt%)</th>
<th>Al (wt%)</th>
<th>Cr (wt%)</th>
<th>Possible phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.84</td>
<td>25.43</td>
<td>1.12</td>
<td>1.62</td>
<td>CuMg₂ and Cu₂Mg</td>
</tr>
<tr>
<td>2</td>
<td>85.64</td>
<td>14.08</td>
<td>—</td>
<td>—</td>
<td>CuMg</td>
</tr>
<tr>
<td>3</td>
<td>93.65</td>
<td>5.96</td>
<td>—</td>
<td>0.31</td>
<td>Cu₃Mg and Cu(Mg)</td>
</tr>
<tr>
<td>4</td>
<td>95.84</td>
<td>3.88</td>
<td>—</td>
<td>0.25</td>
<td>Cu(Mg)</td>
</tr>
<tr>
<td>5</td>
<td>97.25</td>
<td>2.53</td>
<td>—</td>
<td>—</td>
<td>Cu(Mg)</td>
</tr>
<tr>
<td>6</td>
<td>97.43</td>
<td>2.29</td>
<td>—</td>
<td>—</td>
<td>Cu(Mg)</td>
</tr>
<tr>
<td>7</td>
<td>98.89</td>
<td>0.91</td>
<td>—</td>
<td>—</td>
<td>Cu(Mg)</td>
</tr>
</tbody>
</table>

Table 3. Composition of major equilibrium phases in the Mg–Cu system.

<table>
<thead>
<tr>
<th>Equilibrium Phase</th>
<th>Cu (wt%)</th>
<th>Maximum Melting (or Transformation) Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg(Cu)</td>
<td>0 to 0.2</td>
<td>650</td>
</tr>
<tr>
<td>CuMg₂</td>
<td>56.5</td>
<td>568</td>
</tr>
<tr>
<td>Cu₃Mg</td>
<td>83.5 to 84</td>
<td>797</td>
</tr>
<tr>
<td>Cu(Mg)</td>
<td>98 to 100</td>
<td>1084.87</td>
</tr>
</tbody>
</table>

Fig. 7. Element distribution of electrode cross section after spot welding.
Electrode pitting occurred by brittle fracture of alloyed region formed on the electrode tip face resulting in material removal from the electrode tip face. In other words, the electrode pits formed as a result of the particles removed from the electrode tip face. Once Cu–Mg alloyed region formed, it would be affected by thermal and mechanical field during welding operation. Coefficient of thermal expansion of alloyed region is different from that of electrode base metal. Hence, volume expansion and shrinkage of alloyed region are not consistent with those of electrode base metal during heating and cooling. Besides, rates of heating and cooling were extremely fast during spot welding, which induced high level of stress at the interface between alloy layer and electrode base metal. As a result, cracks generated at the interface between alloy layer and electrode base metal, and then propagated into alloyed region resulting from its brittleness, as shown in Fig. 6. Pitting might form by the alloyed region broken away from the electrode tip face as electrode leaving sheet surface.

Initial pitting occurs generally on a ring near the periphery of the contact area because this is where the surface temperature would be the highest. The high temperature in this region would lead to the highest rate of magnesium alloy pickup and hence the highest rate of alloying as compared to the rest of the contact area. These pits soon formed a ring pattern around the contact area (Fig. 3(b)). Once the ring of pits was fully formed, it extended toward the center of the electrode tip face and subsequently formed large cavities by combining smaller pits. Melting point of magnesium alloy is lower than that of Zn-coated steels and aluminum alloy. However, welding current applied is higher during RSW of magnesium alloy than that of Zn-coated steels and aluminum alloy. Therefore, rate of magnesium alloy pickup on the electrode tip face is very fast, which results in short electrode life during RSW of magnesium alloy as compared to that of Zn-coated steels and aluminum alloy.

As is shown in Fig. 8, for the 25th weld, appearance of the joint surface corresponds to that of the electrode tip face (Fig. 3). Melting on the joint surface is also very obviously. There are a lot of protrusions and cavities observed on the joint surface at high magnification (Fig. 9). Besides, large amounts of Cu element were found by EDS analysis, which can reduce resistance to corrosion of the joint, as can be seen in Fig. 10. The results show that protrusions on the joint surface formed by obtaining material from electrode, whereas cavities formed by removing material from sheet. Periodic cleaning of the electrode tip face significantly extended electrode life, which resulted from limiting accumulation of Mg element on the electrode tip face and alloying with electrode, and hence the increase in contact resistance and heat generation. Consequently, well appearance of joint surface could be still obtained after a lot of welds under the condition of periodic cleaning of the electrode tip face. Therefore, it is favorable to periodic cleaning of the electrode tip face for extending electrode life and obtaining well appearance of joint surface.

4. Conclusions

(1) Electrode degradation experienced mainly four basic steps (i.e. magnesium alloy pickup, electrode alloying with magnesium, electrode tip face pitting, and cavitation) during resistance spot welded magnesium alloy. Periodic cleaning of the electrode tip face significantly extended
electrode life, which resulted from limiting accumulation of Mg element on the electrode tip face and alloying with electrode, and hence the increase in contact resistance and heat generation.

(2) Alloved region is composed of Cu₂Mg and CuMg₂ mixture, which results from the eutectic with Cu₂Mg and CuMg₂, and Cu₂Mg forming through element solid diffusion between the CuMg₂ phase and electrode base metal. As a result, Mg content decreased as far from the electrode tip face. Distance of Mg element diffusion in the electrode base metal reached to about 62 μm.

(3) Volume expansion and shrinkage of alloyed region (Cu₂Mg and CuMg₂) are not consistent with those of electrode base metal during heating and cooling due to different coefficient of thermal expansion of alloyed region and electrode base metal. Consequently, electrode pitting occurred by brittle fracture of alloyed region formed on the electrode tip face resulting in material removal from the electrode tip face.

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REFERENCES