Evaluation of Surface Crack in Resistance Spot Welds of Zn-Coated Steel

Young Gon Kim1,* , In Ju Kim1, Ji Sun Kim1, Youn Il Chung2 and Du Youl Choi2

1Green Manufacturing Process Technology Center, KITECH, Gwangju, 500-460, Korea
2Product Application Center, POSCO, Incheon, 408-840, Korea

The development of the automotive industry is now focused not only on improving basic vehicle performance but also on reducing weight and enhancing safety and durability. Various automotive high-strength steels are being developed, and Zn-coated steels are being manufactured to prevent corrosion of the external white vehicle body. The most commonly used welding method in the car body assembly process is resistance spot welding (RSW), which has been extensively studied worldwide. In this process, the work piece is basically heated according to the contact resistivity of the interface between the electrode and the material as well as the bulk resistivity of the material itself. At this point, if the metal is Zn, which has a lower melting point than the Fe base metal on the surface, it is mainly melted in the temperature range of 400–900°C. It becomes easy to penetrate the grain boundary of the HAZ during welding. Also, the tensile stress in such a state decreases the ductility of the grain boundary and causes liquid metal embrittlement (LME).

Cu5Zn8, an intermetallic compound, can be formed from the reaction of the alloy with the Cu material electrode in the expulsion current range at a high temperature. Its formation is likely to be facilitated by LME or a surface crack.

In this study, the fatigue characteristics of a tensile shear specimen during spot welding was investigated with the welding parameters that influence the surface crack of welds on Zn-coated steel. Finally, a controlled spot welding condition was suggested to prevent surface cracks.


Keywords: spot welding, zinc-coated steel, expulsion, surface crack, liquid metal embrittlement

1. Introduction

The automotive industry recently started to require lighter weight, enhanced crash safety and durability in vehicles in addition to fundamentally good performance in relation to regulations and fuel efficiency. Therefore, car makers are increasingly using various advanced high-strength steels (AHSS) to reduce the body-in-white (BIW) weight of vehicles. Moreover, galvanized and Galva-annealed steels are being used in vehicles to prevent external corrosion of the automotive body.1) The most commonly used welding method in the car body assembly process is resistance spot welding, which is now being extensively studied worldwide for use with high-strength steels or Zn-coated steels.2–5) Around 3,000 resistance spot welds are used in a BIW per car. In particular, the welding conditions of Zn-coated steel such as weld current and force are higher than those of cold-rolled steels. As a result, it was found that the optimum welding current range is narrow and the number of spot welds is reduced by the welding electrode that is influenced by the zinc.6,7)

Resistance spot welding is basically performed by the interfacial contact resistance between the electrode and the material and based on their specific resistance. During welding, a nugget is formed from the metal that is melted by the heat-resistant part. In this case, a metal with a lower melting point, such as zinc, is easy to penetrate in a liquid state to reach the grain boundary of the HAZ because it melts mainly in the temperature range of 400–900°C on the surface of the material. By the end of the welding process, liquid metal embrittlement (LME) would have occurred when the ductility of the grain boundary is reduced by tensile stress.8) A brittle Cu5Zn8 intermetallic compound is also created by the reaction of the Cu electrode and the material at the high-temperature expulsion current range, which makes LME or surface cracking very easy to promote.9–11)

In this study, the surface cracking of spot welds on automotive galvanized steel and its factors were analyzed, and the tensile shear fatigue properties of spot weld specimens were investigated to determine the conditions of those with significant surface cracks and of those without defects. The pre-current method was then investigated by preheating for a short time before nugget formation and removal of the molten zinc layer to prevent surface cracking of the welds based on the weld schedule.

2. Experimental Procedure

In this study, 1.6 mm-thick GA TRIP (Transformation-Induced Plasticity) steel plates were used. The microstructure had ferrite, bainite, martensite and a small amount of residual austenite, and the tensile strength of the base metal was 590 MPa.

To evaluate the weldability of the GA 590TRIP, spot welding was performed using a 60 Hz single-phase AC welding machine. The diameter of the electrode tip was 8 mm, and a dome-radius-type Cu–Cr material was used. Figure 1 shows the basic welding condition of the ISO18278 standard. To investigate the surface cracking tendency of spot welds, major welding factors were considered such as the force, current, welding time and holding time, as shown in Table 1. The influence of the electrode tip shape was also investigated.

Figure 2 shows the method of observation of the surface cracks in the spot welds. A stereo microscope was used to inspect the weld defects and then the surface crack, which was shown in the vertical direction by cutting the crack. The cross-sections of the spot welds were also inspected. For the optical microscopic observations, they were polished and etched with a 4% Nital water solution. FE-SEM (JEOL,
6700F) and EDS analysis were carried out to determine the cause of the surface crack. Also, a fatigue test of the welds was conducted with a maximum load of 2 tons on a high-cycle fatigue testing machine using a tensile shear specimen, as shown in Fig. 3. The test conditions were a frequency of 21 Hz and a stress ratio of 0.1.

3. Results and Discussions

3.1 Effect of welding conditions

The main welding parameters were tested using a DOE experiment (a statistical technique) to determine the key factors of surface cracks. Visual inspection of the test conditions clearly showed that at the lowest force of 4.0 kN, significant surface cracks occurred. Other welding parameters were also tested through visual inspection after they were estimated using techniques based on statistical analysis. Table 1 shows the experiment conditions for observation of the surface cracks.

Figure 4 shows the results of the main analysis of such factors. The X axis represents the experiment conditions of each variable, and the Y axis, the qualitative ratio of the surface cracking to the welding condition. This means that the higher the value was, the higher the occurrence of the cracking was.

Surface cracking of spot welds significantly occurs if the force is low, the weld current is high and the welding time is increased. The holding time, which closely related to the weld solidification during the cooling process, has less effect than the other factors. However, the increase in holding time tends to slightly decrease surface cracking. Even so, the correlation between the crack depth and the heat input requires further investigation. On the other hand, the dome-radius-type and flat-type electrode tips are compared in Fig. 5. Under the same welding conditions, the cross-section of the flat-type tended to slightly decrease with a significant
defect in the number of surface cracks, and the concave depth of the welds was shallower than in the dome-radius type. The higher the heat input current range of the conditions, e.g., expulsion, the more surface cracks could be seen as not completely removed regardless of the electrode tip shape.

3.2 Occurrence of surface cracking

Cracks were formed on the welded surface at the higher welding current of 12.0 kA beyond the expulsion current of 10.4 kA. The cross-sections of the welds were analyzed in detail. It was observed using an optical microscope that the cracks progressed in the top and bottom concaves of the welding centers (a) and (b) areas) and near the end of the inclined region (c) from the inside, as shown in Fig. 6. In particular, the crack at the middle of the concave advanced to the center of the thickest area along the grain boundaries near the surface. Therefore, the occurrence of surface cracks is considered to follow the mechanisms in resistance spot welding. First, the molten zinc is relatively easy to penetrate in a liquid state along the grain boundaries of the HAZ from the surface at a high temperature during thermal expansion and contraction in welding. In other words, the tensile stress caused by thermal expansion and contraction leads to a surface crack. On the other hand, the surface crack is suppressed if there is compressive stress. The location of the crack is a deformed concave, which is mainly caused by the electrode force after the welding. This is considered to be associated with the deformation.

Figure 7 shows the results of the representative FE-SEM observation and EDS analysis in the case in which a significant surface crack occurred in the lower part of the cross-section, as shown in Fig. 6. The enlarged surface cracks that were observed via FE-SEM showed many precipitates around them. The EDS analysis confirmed that
this was a brittle Cu_5Zn_8 (r-brass, Zn/Cu = 1.6) of the intermetallic compound, which had a Vickers hardness of about 360–430 Hv.2,11)

The surface crack is closely related to the welding heat input. It is assumed that excessive heat input is likely to promote more cracks due to the LME phenomenon and the formation of brittle intermetallic compounds.

3.3 Results of the fatigue test of the welds

High-cycle fatigue tests in the tensile shear mode were conducted to compare the good condition of no cracks at the welding current of 8.4 kA and the significant cracks that occurred at 12.0 kA. The welding conditions for each load in the fatigue life results are shown in Fig. 8.

As for the fatigue test, the load was in the range of 3.7–4.1 kN. The test was stopped when there was a +0.3 mm displacement. According to the test results for the same load, the fatigue life at 12.0 kA was longer than that at 8.4 kA. In addition, Fig. 9 shows the observed cross-sectional pictures of the welds for each current condition in the fatigue test at the load of 3.9 kN. The fatigue fracture located mainly on the outer nugget surface was propagated at the end of the concave side, starting from the part where stress was concentrated at the interface of the material. Eventually, it was thought that the fatigue life of the welds had little effect on the surface crack but increased the diameter to that of the nugget.

3.4 Reduction of surface cracks

As mentioned in Section 3.1, various factors that influenced the surface crack were evaluated. The causes and improvements of the surface crack during the welding process are as follows.

(1) Excessive welding current (Increase in current density) \rightarrow Adoption of the appropriate welding current
(2) Increase in welding time (Lengthening of the current flow) \rightarrow Reduction in welding time
(3) Lower electrode force (Increase in contact resistance) \rightarrow Increase in electrode force
(4) Smaller electrode tip diameter (Concentrated current density) \rightarrow Need for the appropriate electrode tip diameter
(5) Insufficient electrode alignment (Concentrated current density) \rightarrow Good electrode alignment

As the above discussion is related to heat input, the use of the passive reduction method for proper maintenance is suggested. Thus, an applied pre-current pattern was actively investigated to reduce surface crack while changing the welding condition over the range of the expulsion current.

The significant crack was caused by the higher welding current, such as at the expulsion current, and in turn caused the deformation of the concave and the melting of the Zn layer. However, it can be used in the pre-current method due to its preheating effect. The basic concept is to flow the pre-current for a short time before the second current (the primary current), as shown in the schematic in Fig. 10. This means that the method is intended primarily to melt the Zn layer and facilitate its removal before nugget formation.

In this study, three types of improvement methods were investigated: (1) the application of a multi-pulse after the pre-current (second current +2.0 kA); (2) the application of a multi-pulse after the pre-current (second current –2.0 kA); and (3) the application of a single pulse without cooling the multi-pulse after the pre-current (second current –2.0 kA). In these methods, the pre-current requires three cycles at the current of 10 kA to melt the Zn layer and a cooling time of 6 cycles to facilitate the removal of the layer, as shown by the simulation analysis of the spot welding process.
These results showed that Method (1) had no effect on the reduction of significant surface cracks and on the phenomenon of severe copper adhesion to the surface during welding. This is attributed to the very high pre-current. As for Method (2), the surface crack was not clearly seen in the visual inspection, but its micro-cracks were observed at the inclined parts of the concave in the cross-section. Method (3) is considered the best method because the crack did not appear and was not visible in the cross-sectional inspection.

Figure 11 shows the typical changes in the cross-sections with the changes in the welding method for each pre-current. The results showed that application of the pre-current pattern with short cycles and a relatively low current compared to the second current was helpful in the proactive melting and removal of Zn. Also, the use of single pulse is suggested by eliminating the cooling time of the multi-pulse after the pre-current was applied to reduce thermal shock during welding and shorten the process time.

4. Conclusion

In this study, the fatigue properties and the effect of welding parameters on high-strength Zn-coated steel were investigated in relation to surface cracks. The test results for reducing the surface cracks are summarized as follows.

1. The surface crack on welds is closely related to the welding heat input, and occurs easily with a lower electrode force and a higher welding current and longer period.

2. The FE-SEM observation and EDS analysis of the welds showed that the propagation of the surface crack was caused by the LME phenomenon that penetrated the grain boundary of the HAZ through the molten Zn and the brittle intermetallic compound Cu5Zn8 that formed by alloying with the Cu electrode.

3. The fatigue life of the welds hardly influenced the surface crack and did so only in proportion to the increase in the nugget diameter.

4. The pre-current method that was conducted before the second current can apparently reduce the surface crack on the welds even under expulsion current conditions.

REFERENCES