Effect of Adhesive Characteristics on the Weld Quality in Weld Bonding Multiple Steel Sheets

Guidelines are presented for weld bonding multiple stacks of steel sheets for vehicle manufacturing

BY Y. S. ZHANG, J. SHEN, Y. Y. ZHAO, PEI-CHUNG WANG, AND B. CARLSON

ABSTRACT

The use of weld bonding (i.e., a combination of resistance spot welding and adhesive bonding) as a structural fastener is increasing in the automotive industry. However, a series of issues needs to be addressed such as the influence of adhesive characteristics (e.g., adhesive properties and bondline thickness) in the weld-bonding application to enhance the knowledge of this technology and reinforce its use. As part of the development and implementation of weld bonding, the present study was undertaken to experimentally evaluate the effects of the adhesive characteristics on the weld quality of weld-bonded multiple steel sheets.

The weld quality in terms of the weld size, weld expulsion, and weld strength in weld bonding multiple stacks of steel sheets composed of 0.8-mm-thick SAE1004, 1.4-mm-thick DP600, and 1.8-mm-thick DP780 with different epoxy adhesives (i.e., A2 and A1) and bondline thicknesses (0.2~1.4 mm) are investigated in this study. It was found that while the viscosity of the adhesive significantly affects the static contact and dynamic resistances between the steel sheets, the uncured adhesive bondline thickness has little impact upon the contact and dynamic resistances. Consequently, the weld size and weld expulsion in weld-bonding multiple steel sheets increased with an increase in viscosity of the adhesive and exhibited little effect by the bondline thickness. The lap-shear strength of weld-bonded multiple steel sheets was increased significantly by the presence of the cured adhesive but was not affected by the applied, uncured adhesive bondline thickness. Finally, the placement of an adhesive between the thin external and thicker middle sheet to improve the weld size and penetration into the thin external sheet could be a feasible solution to resolve undersized welds in the resistance welding of multiple steel sheets. This study provides guidelines to the application of adhesive in weld bonding multiple stacks of steel sheets for vehicle manufacturing.

KEYWORDS

Weld Bonding
Multiple Steel Sheets
Weld Quality
Bondline Thickness

Introduction

In mass producing automotive lightweight body frames, the application of hybrid joining techniques is increasing in importance. The weld bonding process, shown in Fig. 1 as a combination of resistance spot welding (RSW) and adhesive bonding, provides a more desirable joint performance compared to either RSW or adhesive bonding alone (Refs. 1–3). It not only improves the crashworthiness, stiffness, fatigue behavior, and corrosion resistance (Refs. 4, 5), but also potentially enables a reduction in the number of welds in vehicle structures. Therefore, the technology is state of the art in many branches of joining metal sheets, especially for newly developed advanced high-strength steels (AHSS).

However, a series of issues needs to be addressed such as the influence of adhesive property and location in weld bonding multiple metal sheets to enhance the knowledge of this technology and reinforce its use. The variety of adhesive strengths and moduli leads to potentially different bonding conditions, changes the contact state of the steel sheets after being squeezed out by the electrode force, and consequently influences the weld quality in weld bonding steel sheets. Many studies concerning weld bonding two steel sheets have shown that the adhesive increased the weld size and strength in the weld-bonded joints compared to resistance spot welds under the same welding parameters (Refs. 6–8). Furthermore, the effect of the adhesive on the weld size is closely related to the increase of the contact resistance between the steel sheets, which influences the current density pattern and temperature field via the joule heating effect (Refs. 9–12). The temperature field then influences the mechanical pressure distribution through thermal deformation of the workpieces. Therefore, the formation of the weld is indeed dependent upon the contact phenomena at the faying interfaces. In weld bonding multiple stacks of steel sheets, the contact states between the steel sheets are more complex than for the traditional two-sheet stackup. Therefore, it is essential that an understanding of the effect of adhesive characteristics on weld bonding multiple-sheet stackups of steel sheets be obtained.

The present study was undertaken to...
experimentally evaluate the effect of the adhesive characteristics on the weld quality in weld bonding multiple stacks of steel sheets. There are three main parts in this study; the first presents the experimental procedure, including material, experimental setup, sample fabrication, weld expulsion and weld nugget size measurements, plus mechanical test. In the following section, the static contact resistance during the squeeze cycle and dynamic resistance during the weld cycle were measured and analyzed to investigate the weld formation mechanism in weld bonding multiple steel sheets. Finally, the effects of adhesive type and bondline thickness on the weld quality in terms of the weld expulsion, weld size, and joint strength were experimentally studied. This study provides valuable guidelines to the application of adhesive in weld bonding multiple stacks of steel sheets for vehicle manufacturing.

**Experimental Procedure**

**Materials**

To investigate weld bonding multiple stacks of steel sheets, 0.8-mm-thick hot-dipped galvanized (HDG) low-carbon steel SAE1004, 1.4-mm-thick (HDG) DP600, and 1.8-mm-thick (HDG) DP780 steels were used in this study. All steel sheets had a coating thickness of 60 g/m². The chemical composition and mechanical properties of these steels were measured and listed in Table 1. Two one-component hot-cured epoxy resin-based adhesives (i.e., A1 and A2) were used in this study. Per the manufacturer’s data sheet, Table 2 lists the material properties of A1 and A2 adhesives.

**Sample Fabrication**

In this study, the weld-bonding process was realized through use of a servo gun welding system having a medium-frequency direct current (MFDC) welding machine. The multiple stacks of three steel sheets was composed of 0.8-mm-thick SAE1004 as top sheet, 1.4-mm-thick DP600 as middle sheet, and 1.8-mm-thick DP780 as bottom sheet (Fig. 2A). The adhesive bead (i.e., A1 or A2) was manually applied onto the steel sheets by a glue gun and then the steel sheets with adhesive were stacked together prior to resistance welding. The welding current is applied through the adhesive and steels to get a final weld-bonded joint. A Class II copper alloy with chromium and zirconium electrode (Cr: >0.4%, Zr: 0.3–0.15) was used in the experiment, and the welding parameters are listed in Table 3 (Ref. 13). To show the weld nugget formation, various welding times were used and metallographic cross-section examinations of the weld-bonded joints were performed to measure the weld nugget sizes. To ensure that the contact resistance measurement was consistent, a set of steel shims were used in this study to maintain a consistent bondline thickness. Figure 2B shows the bondline thickness maintained by the steel shims that were removed prior to welding.

**Measurement of Contact Resistance**

To investigate the adhesive’s effect on the contact resistance between the steel sheets, both static contact resistance (Ref. 12) and dynamic resistance (Refs. 14–17) have been measured in this study. The measurement principle, presented in Fig. 3A, is based upon RM, which is the total resistance between two fixtures. These fixtures are installed 40 mm from the centerline of the electrode and enables RM (where RM = 2R S + R C ) to be directly measured by the system. When a controlled current is passed through the electrodes, the voltage between the fixtures, i.e., contacts shown as arrows in Fig. 3A,

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Al</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE1004</td>
<td>0.037</td>
<td>0.21</td>
<td>0.01</td>
<td>0.02</td>
<td>0.018</td>
<td>0.04</td>
<td>152</td>
<td>278</td>
<td>66</td>
</tr>
<tr>
<td>DP600</td>
<td>0.08</td>
<td>1.74</td>
<td>0.012</td>
<td>0.003</td>
<td>0.016</td>
<td>0.041</td>
<td>316</td>
<td>607</td>
<td>29</td>
</tr>
<tr>
<td>DP780</td>
<td>0.15</td>
<td>1.80</td>
<td>0.004</td>
<td>0.016</td>
<td>0.010</td>
<td>0.048</td>
<td>508</td>
<td>834</td>
<td>26</td>
</tr>
</tbody>
</table>
can be measured and is denoted by $R_M$. However, this also represents the voltage across the top sheet through the adhesive and to the bottom sheet.

Furthermore, the contacts are sufficiently far from the electrodes to avoid shunting of the current. Since $R_S$ is the bulk resistivity of the steel sheets from the contact region to the fixture, and is a known constant value at ambient temperatures than $R_C$, the static contact resistance between the steel sheets can be calculated using the following relationship: $R_M = 2R_S + R_C$. Figure 3B is a schematic of the measurement method where $R_1$ is the dynamic resistance between the top and middle sheets, and $R_2$ is the dynamic resistance between the middle and bottom sheets. Measurements of dynamic resistance appear to be one of the most widely accepted procedures to assess weld quality. To directly inspect the heat to generate the nugget, tip voltage and current measurements at the secondary side of the transformer are used to calculate dynamic resistance. A Miyachi Weld Checker, including the toroidal coil and voltage detection cord, were used to directly measure the tip voltage and welding current in secondary circuit. The resistance can be calculated accurately using the current, where $\frac{di}{dt} = 0$, and the voltage at that moment. Five replicates were performed for each type of weld bonding, and the average dynamic resistances were reported. A detailed description can be found in Ref. 14.

Measurement of Weld Expulsion

One attribute of weld quality in resistance spot welding is the amount of weld expulsion. Although weld expulsion is an important indicator of weld quality, there are few references regarding quantification or measurement of weld expulsion. To generate weld expulsion, the process parameters listed in Table 3 were kept unchanged except that the welding current was increased to 10.0 kA and the bondline thickness was fixed at 0.4 mm. Five replicates were performed, and the weld spatter was collected and weighed.

To capture the weld expulsion in this study, the welding process was conducted in a 1-m³ box made of transparent resin; refer to Fig. 4A. The weld spatter material was collected using a magnet shown in Fig. 4B. To separate the collected spatter from the magnet more easily, the magnet was...

| Table 2 — Material Properties for A1 and A2 Adhesives |
|-------------|-------------|-------------|-------------|-------------|-------------|
| Adhesive    | Specific Gravity | Viscosity @50°C (Pa·s) | Tensile Strength (MPa) | Elongation at Break (%) |
| A1          | 1.03         | 20–40       | 37           | 6.2          |
| A2          | 1.05–1.20    | 30–50       | > 30         | > 10         |

| Table 3 — Welding Parameters |
|-------------|-------------|-------------|-------------|-------------|-------------|
| Cap (Class II) | Electrode Force (kN) | Welding Current (kA) | Squeezing Time (ms) | Welding Hold Time (ms) |
| 5.0         | 5.5         | 8.5         | 200         | 420         | 100         |
wrapped in a clean paper. Using this magnet to scan everywhere within the box, the spatter would jump onto the paper due to the magnetic force. To generate the weld expulsion, the welding current was increased to 10.0 kA while other parameters were kept constant as shown in Table 3.

Weld Characterization

Because of the complexity of the joint stackup, the traditional weld dimension (diameter in the center of the weld) cannot clearly characterize the quality and shape of the weld in weld bonding three sheets. Hence, a new weld configuration with a typical dimensional parameter for joints having multiple sheets is presented in Fig. 2. There are two critical dimensions of the weld — weld sizes \( d \) and \( D \). Weld size \( d \) can represent the joint quality between the top and middle sheets. Weld size \( D \) represents the connection between the middle and bottom sheets. These two weld sizes can be measured from the micrographs of the joint cross section, which is prepared for measurement using Nital 4% etch applied after mechanical grinding and polishing. Five replicates were prepared for the metallographic tests. The thicknesses of the top and middle sheets are 0.8 and 1.4 mm, respectively, the minimum dimension for weld size \( d \) is set at 4.0 mm (Ref. 13). Furthermore, the desired minimum weld size \( D \) is 5.0 mm.

Mechanical Test

Beside the weld nugget size, weld strength is also an important indicator of weld quality. Since the sheet combination used in this study involves three steel sheets, there are two welds at two faying interfaces. To simplify the mechanical test specimen grip design, we measured only the strength of the weld between the middle and bottom sheets. Figure 5A shows a schematic of the specimen configuration and gripping arrangement. To minimize bending stresses inherent in the testing of lap shear specimens, filler plates used to accommodate the sample offset as can be seen in Fig. 5B were attached to both ends of the sample using masking tape. Lap-shear tests were performed at a crosshead speed of 5 mm/min with a SUNS universal testing machine. Five replicates were tested in this study.

Results

Static Resistance during Squeeze Cycle

Figure 6A and B present the effect of the adhesive on the static contact resistance between the following: A — 0.8-mm-thick SAE1004 and 1.4-mm-thick DP600; B — 1.4-mm-thick DP600 and 1.8-mm-thick DP780 steel.
For those situations without adhesive, the static contact resistance for both configurations is fairly stable below a value of 2.0 mΩ for the range of applied electrode forces, 0.5–6.0 kN. However, the static contact resistance between the middle and bottom sheets, i.e., 1.4-mm DP600/1.8-mm DP780, does rise slightly for electrode forces below 2.0 kN whereas the same resistance for the top and middle sheets, i.e., 0.8-mm SAE1004/1.4-mm DP600, does not. The application of adhesive increases the contact resistance for all levels of electrode force but significantly more so for adhesive A2 than adhesive A1 at lower levels of electrode force. In particular, the contact resistance for the middle and bottom sheets, i.e., 1.4-mm DP600/1.8-mm DP780 interface, rise significantly below electrode levels of 3.0 and 4.0 kN for adhesives A1 and A2, respectively.

### Table 4 — Adhesive Combinations with A1 and A2

<table>
<thead>
<tr>
<th>Adhesive Combinations</th>
<th>Adhesive Applied at the Interface between Top and Middle Sheets</th>
<th>Adhesive Applied at the Interface between Middle and Bottom Sheets</th>
</tr>
</thead>
<tbody>
<tr>
<td>No adhesive</td>
<td>No adhesive</td>
<td>No adhesive</td>
</tr>
<tr>
<td>No adhesive + A1</td>
<td>No adhesive</td>
<td>A1</td>
</tr>
<tr>
<td>No adhesive + A2</td>
<td>No adhesive</td>
<td>A2</td>
</tr>
<tr>
<td>A1 + No adhesive</td>
<td>A1</td>
<td>No adhesive</td>
</tr>
<tr>
<td>A1 + A1</td>
<td>A1</td>
<td>A1</td>
</tr>
<tr>
<td>A1 + A2</td>
<td>A1</td>
<td>A2</td>
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<tr>
<td>A2 + No adhesive</td>
<td>A2</td>
<td>No adhesive</td>
</tr>
<tr>
<td>A2 + A1</td>
<td>A2</td>
<td>A1</td>
</tr>
<tr>
<td>A2 + A2</td>
<td>A2</td>
<td>A2</td>
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</tbody>
</table>

**Effect of Bondline Thickness on Static Contact Resistance**

Beside the effect of the adhesive, the uncured bondline thickness between the substrates is another variable that may af-
WELDING RESEARCH

It can be seen from the results that the dynamic resistances at faying interfaces between the top and middle sheets (i.e., 0.8-mm-thick SAE1004 and 1.4-mm-thick DP600) and the middle and bottom sheets (i.e., 1.4-mm-thick DP600 and 1.8-mm-thick DP780) are higher than that without adhesive during the first and second stages of the weld-bonding process. Adhesive A2 exhibited the greatest dynamic resistance followed by adhesive A1 and finally steel without adhesive for any welding time in the period between 50 and 150 msec. The dynamic resistance for all conditions eventually leveled out to approximately the same value at a welding time of 300 msec. No significant effect of the applied bondline thickness on the dynamic resistance between the multiple steel sheets can be made (refer to the results presented in Fig. 9).

Dynamic Resistance during Weld Cycle

To investigate the effect of the adhesive on the dynamic resistance during the weld cycle, weld bonding multiple steel sheets (i.e., 0.8-mm-thick SAE1004, 1.4-mm-thick DP600 and 1.8-mm-thick DP780 steel) with A1 and A2 adhesives was conducted with the welding parameters listed in Table 3, and the results shown in Fig. 8. It can be seen from the results that the dynamic resistances at faying interfaces between the top and middle sheets (i.e., 0.8-mm-thick SAE1004 and 1.4-mm-thick DP600) and the middle and bottom sheets also included in Fig. 10C. Two general observations can be made — longer welding times resulted in increased weld nugget diameters, and the presence of adhesive, either A1 or A2, resulted in greater weld nugget diameters, d and D in reference to Fig. 2A, compared to the same stackup without adhesive for a given weld schedule. Furthermore, the results show that the weld bonding nugget diameter with A2 adhesive was consistently larger than that with the A1 adhesive.

To thoroughly assess the effect of the adhesive on the weld bond in weld bonding, tests with various adhesive combinations shown in Table 4 were also conducted. Five replicates were tested for each adhesive combination using the welding parameters listed in Table 3, and the results are presented in Fig. 11. The presence of the adhesive between the workpieces regardless of the bondline thickness in the range that was studied increased both weld sizes d and D. However, the extent of that increase in weld size varies widely for different adhesive types and combinations.

Tests were also conducted to study the effect of the bondline thickness of A2 adhesive on the weld size in weld bonding multiple stacks of steel sheets. Figure 12 presents the test results that show the adhesive bondline thickness had no statistical effect upon the weld sizes d and D in weld bonding multiple steel sheets in this study. These results are consistent with the measurements of the static and dynamic resistances shown in Figs. 7 and 9.

Weld Expulsion

Since weld expulsion is an important weld quality attribute, the effect of the adhesive combinations shown in Table 4 on the weld expulsion was investigated in this study. The weld spatter results for various combinations of weld bonding with adhesives A1 and A2 are presented in Fig. 13. As would be expected, the amount of weld spatter increased with the presence of the adhesive where A2 generated a greater amount as compared to A1. As shown in Fig. 14, as the bondline thickness increased from 0.2 to 1.2 mm, the weld spatter decreased from 1.30 to 0.88 g. Figure 15 shows the SEM photos of the broken faying interface with various adhesive bondline thicknesses.

Weld Strength

To assess the effect of adhesive combination on the weld strength of weld-bonded multiple steel sheets, lap-shear tests were performed prior to the adhesive curing. Figure 16 has the test results. As shown, the presence of the uncured adhesive significantly improved the force displacement of weld-bonded multiple steel
sheets. Tests were also performed to measure the effect of the adhesive bondline thickness on the strength of weld-bonded multiple steel sheets, and the results are shown in Fig. 17. The uncured adhesive bondline thickness had no significant effect upon the strength of weld-bonded multiple steel sheets.

**Discussion**

**Static Contact Resistance**

The static contact resistances shown in Fig. 6A and B between the middle and bottom sheets, i.e., 1.4-mm DP600/1.8-mm DP780, are greater than the resistance for the top and middle sheets, i.e., 0.8-mm SAE1004/1.4-mm DP600 for a given electrode force. This is attributed to the fact that the thinner and less-stiff top sheet deforms upon application of the electrode force and thereby wraps around the electrode tip to a greater extent than the thicker and stiffer bottom sheet. This creates a greater interfacial area and hence, increases the static contact resistance for a given applied electrode force.

The static contact resistances between the steel sheets with adhesive A1 were smaller than that with adhesive A2 during the squeeze stage. This difference is attributed to the fact that the viscosity of A1 is less than that of A2 (refer to Table 2), which translates to the adhesive A1 being spread thinner upon application of the electrode force and thereby posing a lower static resistance. Subsequently, following this logic, one can observe that without any adhesive the static resistance value is lowest. It can also be observed from Fig. 6 that there is a drop in contact resistance with increasing electrode force and that there is a knee in the data above which the resistance becomes increasingly independent of electrode force. This knee for the contact resistances between the top and middle steels with adhesive occurs at approximately 1 and 3 kN for adhesives A1 and A2, respectively, while it occurs at higher values, 2.5 and 4 kN for adhesives A1 and A2, respectively, for the contact resistance between the middle and bottom sheets with adhesive. The greater force levels to achieve a lower contact resistance is attributed to a greater stiffness of the joint between the middle and bottom sheets, which in turn is a result of greater sheet thicknesses and strengths as compared to the top and middle sheet combination.

**Effect of Bondline Thickness on Static Contact Resistance**

As shown in Fig. 7A, the effect of the bondline thickness on the static contact resistance is insignificant between the top and middle steel sheets at low electrode force. As the electrode force increases, the bondline thickness has no influence for an electrode force up to approximately 3 kN. This is likely due to the fact that the excessive adhesive, regardless of the bondline thicknesses in this study, was squeezed out of the steel sheets by the large electrode force. The results shown in Figs. 6 and 7 suggest that the contact resistance between the substrates with adhesive is primarily influenced by the adhesive properties and electrode force in weld bonding. Therefore, the bondline thickness had little effect on the contact resistance between the steel sheets under industrially relevant electrode force levels. Similar results were observed in Fig. 7B about the contact resistance between the middle and bottom sheets except that a larger electrode force is required to squeeze out the adhesive between the workpieces, which is attributed to the middle and bottom sheets having greater thickness and able to carry a greater load than the thinner top and middle sheets.

Finally, there is a significant increase of resistance with decreasing adhesive bondline thickness at the lowest electrode force levels. The reason for this is unclear and will require further study. However, the electrode force levels at this level are not industrially relevant.
Dynamic Resistance during Weld Cycle

The initial increase in dynamic resistance during the first stage in weld bonding compared to that without adhesive is attributed mainly to the influence of the adhesive on the static contact resistance between the substrates. However, as the temperature of the substrates increased, i.e., 50 to 200 or 300 ms in reference to Fig. 8A and B, respectively, this effect was diminished by the thermal degradation and decomposition of the adhesive.

The joule heat generation during the first stage enhanced the increase of the bulk resistivity of the steel sheets as the temperature increased (Ref. 15). Therefore, the total dynamic resistance of the weld bonded steel sheets during the second stage was greater than that without adhesive. The dynamic resistance of the joint with A1 adhesive was located in between that with A2 adhesive and without adhesive in Fig. 8. This was a result of less joule heat generation at the faying interfaces for the joint made with A1 because of the smaller contact resistance between the substrates as compared to that with the A2 adhesive.

Finally, the dynamic resistances shown in Fig. 8 also indicate that there is a major difference in the time to initiate a weld nugget between resistance spot welding and weld bonding. The details of the weld initiation and growth in weld bonding are discussed later.

The effect of the applied bondline thickness on the dynamic resistance is insignificant. This is likely attributed to the adhesive being squeezed out of the faying interfaces under the applied electrode force, and the variation in the amount of adhesive remaining as a function of applied bondline thickness is insignificant to generate any sizable differences in joule heating or other effect. Therefore, it can be concluded that the bondline thickness has little effect upon the weld formation and size in weld bonding multiple steel sheets.

Weld Size

The results in Figs. 10A–C and 11A, B exhibit a greater weld bonding nugget size with the A2 adhesive as compared to the A1 adhesive. Since the A2 adhesive is as-
associated with a greater static and dynamic contact resistance compared to the adhesive A1 (refer to Figs. 6 and 8), it is hypothesized that the greater resistance results in more joule heat generation, which assists the weld nugget initiation and growth of the molten weld nugget during welding that would increase the final weld sizes (i.e., d and D). Furthermore, the weld sizes d and D with either A1 or A2 adhesive were larger than the joints made without adhesive. A similar argument can be made for the presence of adhesive having greater levels of resistance as compared to joints without adhesive leading to greater weld nugget sizes, d and D.

As shown in Fig. 11, the placement of the adhesive has a direct correlation to which weld nugget diameter attribute, d or D, will exhibit a statistical increase. The adhesive placed only between the top and middle steel sheets (A1 + No, A2 + No) increased the weld size d more than weld size D. Similarly, the placement of the adhesive between the middle and bottom steels (No + A1, No + A2) increased the weld size D more than weld size d. This is a function of the adhesive increasing the contact resistance resulting in relatively greater joule heating at that interface. These results agree well with the results on the static contact resistance and dynamic resistance shown in Figs. 6 and 8. Because the placement of the adhesive between the top and middle sheets generated a significantly greater weld size d, this could be a potential solution to resolve the issue of undersized weld nuggets as seen in Fig. 10C.

To summarize the effects of the adhesive and location on the weld sizes in weld bonding 0.8-mm-thick SAE1004, 1.4-mm-thick DP600, and 1.8-mm-thick DP780 steel, the empirical equations for the weld sizes d and D were derived based on the
test results, and are presented as follows:

\[
d = 4.90 \left( 1 + 0.0765X_1 + 0.0408X_2 + 0.0276X_1^2 + 0.0204X_2^2 - 0.0367X_1X_2 \right)
\]

with correlation coefficient \( R^2 = 0.9218 \)

\[
D = 6.87 \left( 1 + 0.0339X_1 + 0.1053X_2 - 0.0047X_1^2 - 0.0323X_2^2 - 0.0338X_1X_2 \right)
\]

with correlation coefficient \( R^2 = 0.9236 \)

where the values for \( X_1 \) and \( X_2 \) are described in Table 5. For example, if the adhesives A1 and A2 are placed at the interfaces between the middle and bottom sheets, and middle and bottom sheets, respectively, the weld size \( D \) is approximately 7.05 mm (i.e., \( X_1 = -1 \) and \( X_2 = 1 \)).

Weld Expulsion

Weld expulsion occurs when the pressure from the liquid molten pool against the solid containment equals or exceeds the applied electrode pressure. Since adhesive A2 generates a greater amount of joule heating followed by earlier weld nugget melt initiation and growth, compared to adhesive A1, it might be expected that there would be a corresponding greater molten pool pressure buildup as well. Therefore, the argument can be extended that a greater amount of weld spatter is to be anticipated with the presence of adhesive A2 compared to adhesive A1 or no adhesive at all. This line of reasoning is supported by the data presented in Fig. 13.

Experimental observations showed that most of the weld spatter erupted from the interfaces between the sheets instead of the sheet surface and that the adhesive surrounding the molten weld pool decomposed because of the elevated temperatures. Because of the relatively high current levels, weld spatter erupting at the faying interface was forced to pass through the remains of the adhesive layer. However, a small portion of the erupted liquid metal was retained by the remains of the adhesive layer and solidified in place as verified by experimental observations, refer to Fig. 18.

SEM and EDS analyses of the retained weld spatter particles from stackups using adhesives A1 and A2 are shown in Fig. 19A and B, respectively. Similarly, erupted weld spatter particles from weld bonding with adhesives A1 and A2 were analyzed, and the results are presented in Fig. 19C and D, respectively. For the purpose of the comparison, the weld spatter from resistance spot welding with no adhesive was also analyzed, and the result is
presented in Fig. 19E. It can be concluded from the EDS analyses that both the retained and erupted spatter produced from weld bonding multiple steel sheets contained silicon and calcium, which are inherent ingredients of the uncured adhesive and not the base metal. These results suggest that uncured adhesive in erupted weld spatter from weld bonding could potentially contaminate the tooling and fixturing.

Although the results shown in Figs. 7, 9, and 12 indicate that the bondline thickness exhibited little influence on the contact resistance and weld nugget size, there is a significant correlation to the amount of weld spatter. As shown in Fig. 14, as the bondline thickness increased from 0.2 to 1.2 mm, the weld spatter decreased from 1.30 to 0.88 g. This decrease is attributed to the fact that an elevated amount of weld spatter was retained by the increased bondline thickness. Figure 15 shows the SEM photos of the broken faying interface with various adhesive bondline thicknesses. As can be seen, the amount of retained weld spatter (in dark color) increased with increased adhesive bondline thickness.

In addition, although a reduction of the erupted spatter collected outside of the bondline was observed with thickening of the bondline, the amount of spatter with adhesive was still significantly higher than that without adhesive. This phenomenon also resulted from the growth in contact resistance and heat generation brought about by the adhesive layer. More metal was molten during welding and resulted in higher pressure from the liquid metal to the solid containment, thus weld expulsion would be easier to occur under the effect of the adhesive layer.

**Weld Strength**

The presence of the uncured adhesive significantly improved the force-displacement behavior of weld-bonded multiple steel sheets; refer to Fig. 16A and B. Since the tests were performed prior to adhesive curing, these results suggest that the increase of the force displacement is primarily attributed to the increased weld nugget size resulting from the extra joule heat introduced by the presence of the adhesive at the faying interfaces. This is supported by the good correlation coefficient, \( R^2 = 0.97287 \), of the peak load (as a measure of weld strength) vs. weld nugget size (D) data, refer to Fig. 20.

Tests to measure the effect of the adhesive bondline thickness on the strength of weld-bonded multiple steel sheets show (refer to Fig. 17A and B) that the uncured adhesive bondline thickness had no significant effect upon the strength of weld-bonded multiple steel sheets. This is consistent with the earlier data showing that the bondline thickness exhibited no significant relationship to static resistance or weld nugget size.

**Conclusions**

The measurements of the static and dynamic contact resistances, welding experiments, metallography analyses, and mechanical tests conducted on weld bonding multiple steel sheets (i.e., 0.8-mm-thick SAE1004, 1.4-mm-thick DP600, and 1.8-mm-thick DP780) with epoxy adhesives (i.e., A1 and A2) concluded the following:

1. The presence of adhesive between steel sheets during resistance spot welding results in a comparatively greater static and dynamic contact resistance leading to greater joule heating, earlier weld nugget melt initiation, and greater growth leading to a larger weld nugget diameter as compared to a joint without adhesive.
2. The viscosity of the adhesive significantly affects the static contact and dynamic resistances between the steel sheets. A more viscous adhesive requires a greater applied electrode force to squeeze out the adhesive from bondline and results in a relatively higher contact resistance.
3. The uncured adhesive bondline thickness in the range of 0.2–1.2 mm exhibits no statistical correlation to the contact and dynamic resistance.
4. The presence of adhesive is correlated to a relatively greater amount of weld spatter generation compared to a joint without adhesive. This is attributed to the elevated contact resistance resulting from the presence of the adhesive leading to relatively greater joule heating and a larger molten weld nugget pool, which in turn, leads to greater pressure buildup and resultant weld spatter.
5. Weld spatter from weld bonding has been found to be both retained within the bondline adhesive as well as erupted from the bondline, which poses a potential of contamination of the weld assembly fixtures.
6. The amount of erupted weld spatter collected outside of the weld coupon decreases with increasing bondline thickness in the range from 0.2 to 1.2 mm. This is attributed to a greater proportion of retained weld spatter being captured within the bondline thickness vs. having a greater proportion of the adhesive burning and thereby allowing the weld spatter to erupt from between the steel sheets.
7. The strength of weld-bonded multiple steel sheets was increased significantly by the presence of the adhesive but was not affected by the uncured adhesive bondline thickness.
8. The placement of the adhesive between the thin external and relatively thicker middle sheet to improve the weld size could be a feasible solution to resolve the issue of undersized welds in resistance welding of multiple steel sheets.

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References

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