Shear strength of CMT brazed lap joints between aluminum and zinc-coated steel

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1. Introduction

In vehicle body assembly, aluminum alloy is one of the most acceptable materials for weight reduction. However, how to join aluminum alloys and steels is an unsolved problem.

If fusion welding processes such as arc welding and resistance spot welding are employed to join aluminum alloys with steels, the brittle inter-metallic compounds (IMC) will be always produced at the interface of aluminum and steel. It was reported by Kreimeyer and Sepold (2002) that only if the thickness of inter-metallic compound layer between aluminum and steel is less than 10 μm, joining steel and aluminum dissimilar materials becomes possible. This report showed that the zinc coating on steel plays a very important role in joining the steel and aluminum dissimilar materials. From the above research results, researchers got a hint that, if the aluminum part is molten and spreads on the steel surface with zinc coating and if steel part is only fused little to avoid thick IMC layer formation, the welding and brazing process may be possible to join steel and aluminum.

The cold metal transfer (named as CMT), invented by Fronius company, is known as an innovated welding process based on short-circuiting transfer process with low heat input and no-sputter. It is suitable to join the very thin sheets which are widely used in the automobile bodies. Therefore welding and brazing process by CMT is a promising method to join steel and aluminum for vehicle body assembly. Up to now, studies were mainly focused on the arc characteristics by Feng et al. (2009) or Zhang et al. (2009) and CMT joining process by Pickin et al. (2011). Ahmad and Bakar (2011) investigated the effect of post-weld heat treatment on aluminum CMT joint strength. The strength and the failure modes of CMT brazed joints of dissimilar materials were not reported yet. Before the CMT joints are applied to automobile bodies, the joint strength must be confirmed firstly. In this study, both the strength and the failure modes of CMT brazed joints of aluminum alloy and steel were investigated by experiments in details. Then, a numerical model was developed for the estimation of the strength of CMT brazed lap joints of dissimilar materials. The influencing factors on the strength of CMT brazed joints were also discussed and validated in details.

2. Experimental measurement

2.1. Joint shape and dimensions

In order to measure the joint strength and to observe the failure modes, the aluminum alloy sheet (AA6061) with 2 mm thick and the low carbon steel whose thickness were 0.7 mm and 1.2 mm, were used in experiments. A welding wire ER4043, a kind of Al–Si alloys, was selected as the filled metal to join the aluminum sheet and the steel sheet.

The welding current, welding voltage and welding speed employed for brazing CMT lap joints of aluminum alloy sheet and steel sheets were 70 A, 11.5 V, 0.7 m/min, respectively. After brazing, the testing pieces were cut off from the brazed joints as shown in Fig. 1 in order to investigate the shear strength and failure modes. The shape and dimensions of the testing piece are shown in Fig. 1.
The overlap length between the aluminum sheet and the steel sheet was set to be 8 mm or 15 mm. The bonded line length was about 6 mm which was rarely affected by the overlap length.

2.2. Shear strength and failure modes

Various CMT lap joints were prepared for the observation of failure modes by changing the thickness of steel sheet and preset gap between aluminum and steel sheets. The experimental results under the shear loading are shown in Table 1. CMT brazed lap joints failed in the two modes. One was interface failure and another was fusion line failure. The interface failure occurred at the interface layer between aluminum and zinc-coated steel as shown in Fig. 2(a), whose load–displacement curve are shown in Fig. 2(b). The fusion line failure occurred at the boundary between the weld metal and base metal of aluminum side as shown in Fig. 3(a), whose load–displacement curve was shown in Fig. 3(b), different from that of interface failure.

As seen from Table 1, the effect of the thickness of the steel sheet on failure modes was significant. If the steel sheet was thin, such as the low carbon steel with 0.7 mm in thickness, the interface failure occurred. If the steel sheet was thicker (e.g. 1.2 mm), fusion line failure occurred. The reason to cause various failure modes is discussed detail in Section 5.

2.3. Micro observation of joint section

After brazed, there were some micro defects such as porosity and unfused root in cross section of the joint as shown in Fig. 4(a). The formation process of the porosity and unfused root needs to be investigated in the future and it may have some relation with the molten metal flow in the gap between steel sheet and aluminum sheet.

If the strength of CMT joints is higher than traditional spot welds or satisfies the designed strength, the micro defects existing in the CMT joints can be accepted for products because they were very difficult to be avoided in the CMT brazing. However, their effects on the joint strength must be investigated by both experimental
measurement and numerical simulation. The appearance of the interface layer between steel and aluminum are shown in Fig. 4(b). It could be seen that there was an inter-metallic compound (IMC) layer between steel and aluminum.

2.4. Measurement of micro hardness

The photograph of cross section on the aluminum side of the CMT lap joint are shown in Fig. 5. There existed three zones on the aluminum side which were fusion zone (weld metal), base metal and fusion line between them. In order to investigate the changes of mechanical properties of the CMT lap joint, the micro hardness at the locations of weld metal, fusion line and base metal of aluminum side, shown in Fig. 5(a), was measured. Fig. 5(b) shows the measured micro Vickers hardness in the weld metal, fusion line and base metal of aluminum side. The Vickers hardness in both the weld metal and the fusion line was almost the same and its magnitude was about 75% of base metal of the aluminum sheet. The lower hardness in the weld metal and fusion line indicated that the tensile strength and the yield limit were lower than the base metal as well. It should be considered in the numerical model to estimate the strength of the CMT brazed joints.

3. Numerical modeling

3.1. Finite element (FE) mesh

Based on the measured shape and dimensions of the CMT brazed lap joints of aluminum alloy and steel, a finite element (FE) model was created as shown in Fig. 6 using eight node isotropic solid elements. The minimum size of solid mesh is 0.13 mm at the aluminum side near the fusion line. The thickness of interface layer is about 0.05 mm. A commercial software ABAQUS explicit developed by Simulia (2009) was employed for the computation.

3.2. Material model for base metals

In the numerical simulation, an elastic–plastic material model was used for base metals of the CMT joint. The stress–strain curves for the base metals of low carbon steel with zinc coating and aluminum alloy 6061 are shown in Fig. 7. In order to verify the established FE model, another steel material DP600 was selected and its stress–strain curve is also shown in Fig. 7.

The Young modulus is 210 GPa for steels and 70 GPa for aluminum alloy AA6061, respectively. The poisons ratio is assumed to be 0.33 for all the materials.

3.3. Material model for weld metal

Since porosities were exiting at the weld zone of aluminum side after brazing, the macro Young’s modulus of the weld metal aluminum may be lower than that of the aluminum sheet. Here an
equivalent macro Young's modulus for the weld metal $E_{\text{weld}}$ defined by following equation was used in the simulation.

$$E_{\text{weld}} = E_{\text{base}} (1 - \alpha)$$  \hspace{1cm} (1)

where $E_{\text{base}}$ is the Young's modulus of the base metal AA6061 and $\alpha$ is the porosity ratio at the weld zone. The Young's modulus is about 70 GPa for base metal. The measured porosity ratio at the weld zone is about 3–5%. The equivalent Young's modulus is about 66.5–67.9 GPa.

The micro hardness of weld metal was only 75% of that of base metal at aluminum sheet. Since the strength is proportional to the hardness, it was assumed that the yield stress and tensile strength of weld metal were about 75% of those of the base metal.

3.4. Failure criteria for interface layer

The material of interface layer was assumed to be ideal elastic plastic material. The Young's modulus of interface layer was assumed to be 70 GPa which is the same as that of AA6061. In order to predict the strength of interface layer between steel and aluminum alloy, the following two failure criteria of interface layer were proposed.

$$\frac{\sigma_1}{\sigma_1^f} \geq 1.0$$  \hspace{1cm} (2)

$$\frac{Q_e}{Q_e^f} \geq 1.0$$  \hspace{1cm} (3)

where $\sigma_1^f$ and $Q_e^f$ are the stress criterion and energy criterion for interface layer, respectively. $\sigma_1$ is the maximal principal stress at interface layer computed by finite element method (FEM) and $Q_e$ is the deformation energy of the interface element, calculated by the following equation,

$$Q_e = \int_{\epsilon} \sigma \cdot d\epsilon \cdot dV_e$$  \hspace{1cm} (4)

If both the maximal principal stress and deformation energy of the interface elements reach the failure criteria, the interface layer elements will be deleted and the stress on the deleted interface elements will reduced to zero immediately. At that time, the applied peak load on the model is recorded as the predicted shear strength.

![Stress–strain curves of low carbon, DP600 steel and AA6061.](image)
of the CMT joint. Therefore, the failure stress criterion and energy criterion should be identified before numerical prediction.

### 3.5. Practical criteria for fusion line failure

Relating to the failure occurring on the fusion line, the equivalent plastic strain \( \varepsilon_p \) was used as a failure criterion. If the equivalent plastic strain \( \varepsilon_p \) in weld metal computed by FEM reaches the critical value \( \varepsilon_f \), the fracture will occur. The load at the fracture starting time is considered as the shear strength.

Since fusion line failure occurred if the thickness of low carbon steel sheet was thicker than 1.2 mm in experiment, the FE model of low carbon steel with 1.2 mm thickness and aluminum alloy with 2 mm thickness were used in the simulation. The distribution of computed equivalent plastic strain \( \varepsilon_p \) at aluminum side is shown in Fig. 8. It can be seen that there is a large plastic strain \( \varepsilon_p \) produced at the local region near the fusion line of aluminum side. This means that the aluminum alloy is easy to fail at this region, which agreed with the experimental phenomenon of fusion line failure mode.

### 3.6. Identification of interface failure criterion

In order to identify the criterion values for interface failure, series FEM simulation was performed and the relative shear strength difference between simulation and measurement was compared by changing the values of stress criterion from small value to large value. The relative error of shear strength (named as \( E_r \) shortly) between FEM simulation and experiment is defined by following equation,

\[
E_r = \frac{P_{\text{fem}} - P_{\text{exp}}}{P_{\text{exp}}} \tag{5}
\]

where \( P_{\text{fem}} \) and \( P_{\text{exp}} \) are the shear strength obtained by FEM simulation and by experiment respectively.

The relationship between the relative error of shear strength and assumed value of stress criterion shown in Fig. 9 can be obtained.

It can be found that zero value of the relative error of shear strength is corresponding to the stress criterion value with about 200 MPa, which should be the failure value of stress criterion.

Referring the uniform elongation strain (5%) of aluminum sheet shown in Fig. 7, the maximum strain at the interface layer can be assumed to be about 5%. Therefore, the failure value of energy criterion can be calculated by multiplying failure stress (200 MPa) and the maximum strain (5%), which is 10.0 MPa for interface failure.

### 3.7. Identification of fusion line failure criterion

In the same way described in Section 3.6, the value of strain criterion for fusion line failure can also be identified using the FE model of CMT joint with 1.2 mm low carbon steel and 2 mm AA6061.

A number of experimental results showed that the failure strain \( \varepsilon_f \) on the fusion line of CMT joints was strongly influenced by the length of the unfused root at aluminum side. Fig. 10 shows the change of the failure strain \( \varepsilon_f \) which was identified based on the measured results with different lengths of the unfused root. The failure strain decreases obviously with the increase of unfused root length.

The effect of the unfused root on the failure can be reproduced by considering its local geometry into the FE models. However, the FE model with the local geometry of the unfused root for various CMT joints is quite difficult to be created and not practical for applications. For this reason, the failure strain criteria \( \varepsilon_f \) changing with the length of the unfused root were here employed based on engineering approach.

### 3.8. Method for shear strength prediction

Based on the failure criteria of the two failure modes, the shear strength and failure modes of various CMT joints of dissimilar
materials can be predicted by FEM following the procedures shown in Fig. 11.

4. Prediction and validation results

Based on the failure criteria, the shear strength and failure modes of 0.7 mm and 1.2 mm low carbon steel and 2 mm AA6061 were computed. Their load–displacement curves are shown in Fig. 12. Compared with Figs. 2 and 3, the calculated load–displacement curves and failure modes agreed well with the experimental results.

In order to validate the established numerical model for shear strength prediction of CMT lap joint, the CMT brazed joints composed of 0.7 mm or 1.2 mm thick DP600 steel and 2 mm thick AA6061 were modeled and their shear strength and failure modes were predicted, shown in Fig. 13(a). The CMT brazed joint composed of 1.2 mm thick DP600 steel and 2 mm thick AA6061 was also manufactured and the shear test was performed. The load–displacement curve and failure mode observed in experiments are shown in Fig. 13(b). It can be seen that the predicted shear strength and failure modes of CMT brazed joints have a good agreement with the experimental results, which suggest that the established numerical model can be used to predict the shear strength and failure mode of steel-aluminum dissimilar materials CMT brazed joint with various thickness and materials.

The comparisons of shear strength and failure modes between FEM simulation and experimental results for various CMT brazed joints are all shown in Table 2.
Table 2
Computed and measured shear strength and failure modes for CMT brazed joints of dissimilar materials.

<table>
<thead>
<tr>
<th>Case</th>
<th>Steel strength grade</th>
<th>Thickness (mm)</th>
<th>Failure modes observed in experiments and predicted by FEM simulation</th>
<th>Shear strength (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FEM</td>
</tr>
<tr>
<td>1</td>
<td>Low carbon steel</td>
<td>0.7</td>
<td>interface failure</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>(270 MPa)</td>
<td>1.2</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>DP600 (600 MPa)</td>
<td>0.7</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1.2</td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>

5. Discussions

5.1. Failure modes and stress concentration

As mentioned in Section 2, two failure modes for CMT brazed lap joints of dissimilar materials under shear loading were observed in the experiments. If the thickness of the aluminum sheet was fixed as 2 mm, the interface failure occurred only if low carbon steel sheet was 0.7 mm thick (thin plate). The fusion line failure always occurred for 1.2 mm thick low carbon steel sheet, shown in Table 1. The shear strength of the CMT joint if the failure occurred on the fusion line, was higher than that if failure occurred at interface layer. The failure modes of CMT brazed joints of steel and aluminum dissimilar materials can be explained based on the computed results by the proposed numerical model.

If the low carbon steel sheet is thin such as 0.7 mm in thickness, the plastic deformation occurs firstly in steel sheet. As a result, the joint strength is determined by yield stress and cross sectional area of low carbon steel sheet. The cross sectional area of steel sheet becomes smaller with the increasing of the plastic deformation. However, the deformation at the interface layer is still very small due to the constraint of aluminum sheet with thicker thickness or higher yield limit. Then at the corner region between steel sheet and the interface layer, there will be a concentration in both the stress and the equivalent plastic strain $\varepsilon_p$ shown in Fig. 14(a).

Finally, a large stress concentration along all interface layer shown in Fig. 14(b) is produced. It can be understood that the crack started from corners of interface layer and then caused the failure of overall interface layer.

If the steel sheet becomes thicker (e.g. 1.2 mm thick) or stronger in the strength (DP600 steel is selected here), it is not easy to cause the large plastic deformation at the steel sheet under the same loading. In the other words, the deformation difference between aluminum sheet and steel sheet is small. Therefore the stress concentration near the corner of interface layer can be reduced. Thus the failure near the corner and the total interface layer is prevented.

Fig. 15 shows the status of stress concentration at the line marked in Fig. 14(b) under the applied load 1.8 kN for different steel thickness (0.7 mm and 1.2 mm) and different strength grades (low carbon steel and DP600). For low carbon steel with thickness of 0.7 mm, steel sheet has been suffered a large plastic deformation. Then there is a stress concentration at both the start and end corners as marked in Fig. 14(a), which is dangerous and may cause failure at the corners earlier. But for low carbon steel with thickness of 1.2 mm and DP600 steel with thickness of 0.7 mm, steel sheet is still in the elastic deformation state if the applied load is 1.8 kN. Thus there is no stress concentration at the corners, which can prevent the failure at the interface layer.

Therefore if steel thickness is increased from 0.7 mm to 1.2 mm or strength grade is changed from 270 MPa (low carbon steel) to 600 MPa, the computed peak load of the interface failure is higher than that of fusion line failure. Thus before the failure at the interface layer, the applied loads in the cases of low carbon steel sheet
with the thickness of 1.2 mm and DP600 steel sheet with thickness of 0.7 mm, reach the strength of fusion line at aluminum sheet. This means that the fusion line failure occurred earlier. That is why the failure modes and joint strength will change with the thickness and strength grades of steel sheets.

5.2. Influencing factors of shear strength

With the aid of the FEM simulation on various CMT brazed joints of aluminum and steel dissimilar materials, the transition of the two failure modes can be concluded as follows:

(a) If the steel sheet is thin and strength grade is low, the strength of interface layer is lower than that of the weld metal aluminum and the failure occurs at the interface layer.
(b) If the steel sheet becomes thicker or higher in the strength, the interface layer is stronger than the weld metal aluminum near fusion line and failure mode will transfer to fusion line failure.

For interface failure, thickness and strength grade (especially yield limit) of steel sheets are the two important influencing factors on the strength for CMT brazed joints of dissimilar materials. The strength of CMT brazed joints increases with the increase of thickness and strength grade of steel sheets.

Some experiments by Yang et al. (2012) showed that the wettability of molten aluminum alloy on solid steel surface had some effect on the brazed length of interface layer and shear strength of CMT joint. If there is no zinc coating on the steel surface, the wettability becomes poor, then the molten aluminum could not spread on the steel surface during brazing. This led to the very short brazed length of the interface layer and the very low shear strength. If zinc coated steel was brazed with aluminum, the wettability was better. Therefore the brazed length of the interface layer was increased to about 6.0 mm and higher shear strength was obtained.

For fusion line failure, since the weld metal is weaker than the base metal of the aluminum sheet, any parameters that may improve the strength of weld metal can also improve the strength of CMT brazed joints. For example, if a preset gap between steel and aluminum sheet can be controlled before brazing, the melting metal can be increased by larger heat input for brazing in order to fill in the gap. Then the welding time staying at high temperature for the molten aluminum becomes longer and this may reduce the porosity ratio and the length of the unfused root. Thus the strength of CMT brazed joints of dissimilar materials may be improved with the increase of preset gap for fusion line failure.

Because the fusion line failure occurs on the aluminum sheet, thickness and strength grade of the aluminum sheet will have a large influence on the strength of CMT brazed joints. With the increase of thickness and strength grade of aluminum sheet, the strength of CMT brazed joints can also be improved.

6. Conclusions

Shear strength of CMT brazed joints are investigated by both experimental measurements and numerical modeling. Some important conclusions are listed as following:

(1) Higher shear strength and fusion line failure were observed in CMT brazed lap joint of aluminum alloy 6061 and zinc coated steels with high strength (DP600) or thick plate (1.2 mm). 
(2) Lower shear strength and interface failure were observed only if aluminum was brazed with low strength (270 MPa) and thin steel sheet (0.7 mm).
(3) The maximum principle stress and deformation energy were proposed as the criteria for the interface failure and plastic strain was proposed as a criterion for the fusion line failure.
(4) The two failure modes and shear strength were reproduced very well using proposed criteria for various CMT brazed lap joints of dissimilar materials under shear loading.

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