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Studies on Two Failure Modes and Shear Strength of Various CMT Brazed Lap Joints of Dissimilar Materials†

Jian LIN*, Ninshu MA, Yongping LEI* and Hidekazu MURAKAWA****
*** College of Materials Science and Engineering, Beijing University of Technology, Beijing 100124, P. R. China**
**** Joining and Welding Research Institute, Osaka University, Osaka 567-0047, Japan**

Abstract

Cold metal transfer (CMT) is a promising method to join steel/Al dissimilar materials together in vehicle body assembly. In this paper, shear strength and failure mode of CMT brazed lap joint of steel/Al dissimilar materials are investigated in detail by both experimental and numerical simulating method. Two failure modes, including interface fracture and fusion line fracture are found out. Failure mode transition and the factors influencing joint strength and failure mode are discussed in detail. Finally, a numerical model to estimate shear strength and failure mode of CMT brazed lap joint of dissimilar materials, is developed based on the failure criteria of interface layer and fusion line fracture. It is shown that the numerical model including interface layer and fusion line failure criteria can be used to predict shear strength and failure mode of CMT brazed lap joint of dissimilar materials. Steel sheet thickness and strength grade can have an obvious effect on joint strength of interface layer fracture because of stress concentration status variation at interface layer element. And joint strength of fusion line fracture can be improved by reducing micro defects in weld metal.

KEY WORDS: Cold metal transfer, Steel/Al dissimilar materials joint, Shear strength, Failure mode, Numerical model

1. Introduction

In vehicle body assembly, aluminum alloys have been proved to be the most acceptable material for weight reduction to save gap consumption. However, the study about how to join aluminum alloys to the traditional material such as low carbon steel or high strength steel is seldom.

Joining aluminum alloys with steels by fusion welding is always seen as difficult because the brittle inter-metallic compounds will come into being at the interface of aluminum and steel during fusion welding. However, when the thickness of inter-metallic compound layer between aluminum and steel is less than 10μm, it is possible for steel/Al dissimilar materials joint to be used in reality. And the zinc coating on steel is very important for steel/Al dissimilar materials joint formation [1]. Therefore, the welding/brazing process can be used to join steel/Al dissimilar materials together, in which the aluminum part is molten and spreads on the steel surface with zinc coating while steel part is fused little to avoid thick IMC layer formation.

Cold metal transfer (named as CMT) joining process is known as a modified metal inert gas welding process based on short-circuiting transfer process with low heat input and no-spatter [2], which is suitable to join the very thin sheets used widely in the automobile industry. Therefore CMT joining method can be considered to be used to join aluminum and steel with zinc coating together. Up to now, some studies for CMT joining process were mainly focused on the arc characteristics and welding process parameters [3, 4]. However the study on the fracture modes and estimation of strength of CMT brazed joint of dissimilar materials are few. Before the CMT joint is applied to automobile bodies, the strength and safety need to be clear firstly. In this study, the fracture modes and joint characteristic of CMT brazed joint of aluminum alloy and steel are investigated in details. And a numerical model to estimate the strength of CMT brazed lap joint of dissimilar materials is developed based on the results by experimental observation and numerical estimation. The influencing factors on CMT brazed joint strength are also discussed in detail.

2. Experimental observation of two failure modes of various CMT brazed lap joints

2.1 Joint shape and dimensions

A lap joint of aluminum alloy and a steel sheet with zinc coating was brazed as by CMT process. The aluminum alloy sheet with 2mm thick is AA6061 and the steel sheet is selected as low carbon steel and DP600 steel, whose thickness is from 0.7mm to 1.2mm. Aluminum wire ER4043, a kind of Al-Si alloy was used as the filled metal. The overlap length was set to 8mm and 15mm, respectively in the making the specimens.

After brazing, the testing pieces are cut off from the brazed joint to investigate the shear strength and fracture modes. The shape and dimension of the testing piece is shown in Fig. 1. The bonded line length measured is about 6mm which was almost the same for both of the overlap length.

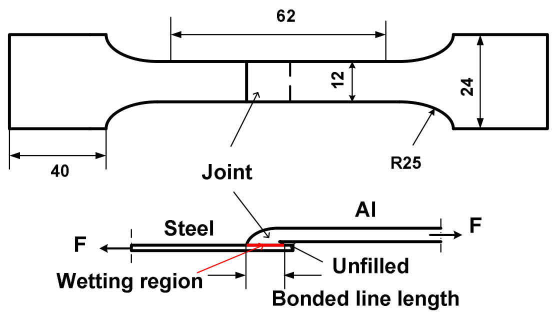


Fig. 1 Shape and dimension of sample for lap-shear test

2.2 Measurement of micro hardness

The photograph of cross section of the brazed joint is shown in Fig. 2. During brazing, the aluminum alloy sheet is molted by the fusion filling wire while the steel part was not molted. In order to make sure the changes of mechanical properties of aluminum alloy after brazing, the micro hardness in the cross section of the aluminum part, including the weld metal and base metal, was measured as shown in Fig. 2.

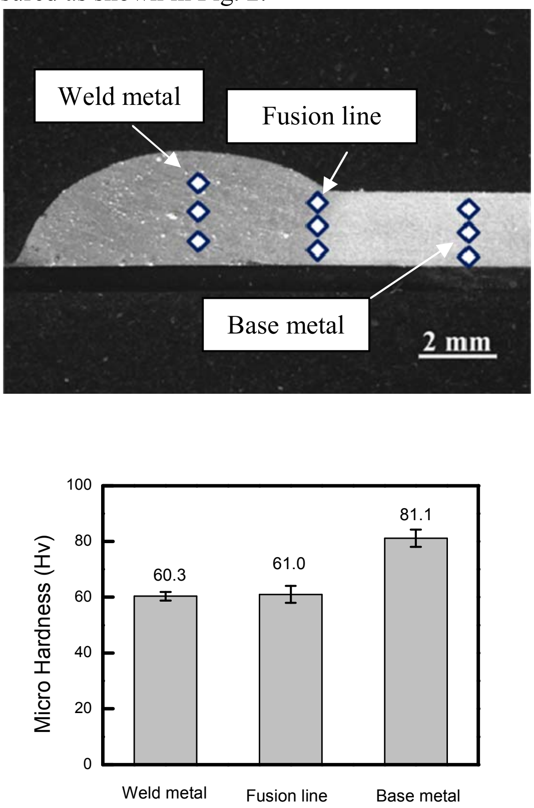


Fig. 2 Micro hardness in weld metal, fusion line and base metal of aluminum alloy

Fig. 2 shows the measured micro hardness in the weld metal, fusion line and base metal of aluminum sheet. The hardness in the weld metal and fusion line is almost the same and its magnitude is about 75% of base aluminum sheet. The lower hardness in the weld metal and fusion line means that the tensile strength and yield limit will be lower than the base metal as well. It should be considered in the FEM model to estimate the strength of CMT brazed joint.

2.3 Micro observation of joining section

After brazed, there are some micro defects such as porosity and un-fusion in cross section of the joint as shown in Fig. 3. The micro defects exist mainly in the fused aluminum side and can be accepted for products because they are very difficult to avoid by CMT brazing process. However, the effects on the joint strength have to be investigated by experimental measurement and FEM simulation.

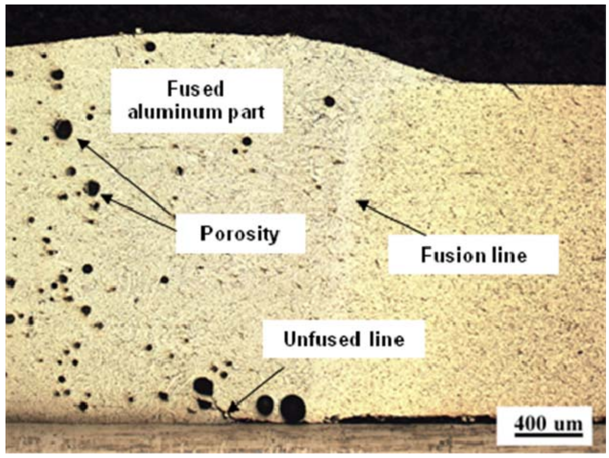


Fig. 3 Micro defects in cross section after brazing

2.4 Observation of two failure modes for various lap joints

During CMT brazing, the effects of steel sheet thickness, steel strength grade (including low carbon and DP600 steel) and preset gap on joint strength and failure mode are considered. And for the different cases, the shear loading test results show that CMT brazed lap joint fails in the two fracture modes. One is interface fracture mode and another is fusion line fracture mode.

The interface fracture occurs at the interface layer between aluminum and zinc coating steel as shown in Fig. 4. And the fusion line fracture occurs at the boundary between the weld metal and aluminum base metal as shown in Fig. 5.

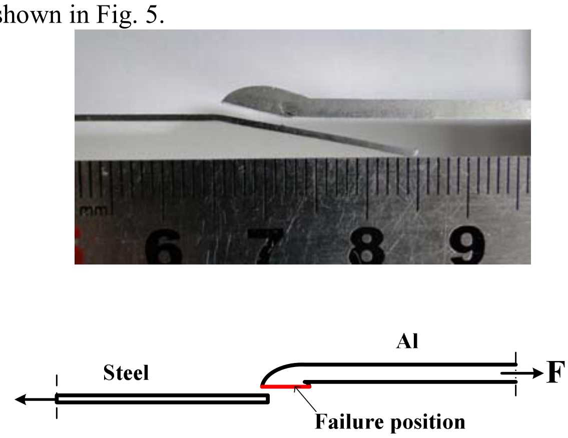
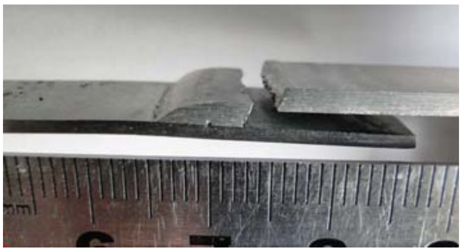


Fig. 4 Interface fracture mode of CMT brazed lap joint:



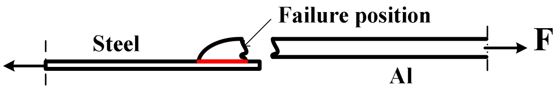
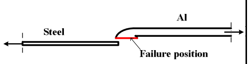
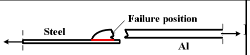


Fig. 5 Fusion line fracture mode of CMT brazed lap joint

For the different cases, the effect of steel sheet thickness and steel strength grade on joint failure mode is observed and shown in Table 1. And overlap and preset gap have no obvious effect on the failure mode.

Tab. 1 Effect of steel sheet thickness and strength grade on CMT joint failure mode

Case	Steel strength grade	Thickness (mm)	Failure mode	Joint strength (kN)
1	Low carbon steel (270MPa)	0.7	 interface fracture	2.1
2		1.2	 fusion line fracture	>2.5
3	DP600 (590MPa)	1.0		
4		1.2		

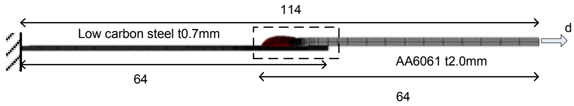
Seen from Table. 1, when the steel sheet is thin and weak, such as low carbon steel with 0.7mm thickness, interface fracture occurs. And when the steel sheet is thicker (e.g. 1.2mm) and stronger (e.g. DP600 steel), fusion line fracture will occur.

The above experimental observation gave us hint that the influence of the existence of porosity and decrease of micro hardness in weld metal must be considered if numerical simulation for the estimation of joint strength and fracture modes is to be conducted.

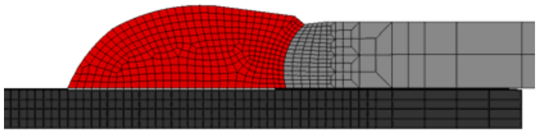
3. FEM modeling for two failure modes and shear strength

3.1 FEM mesh

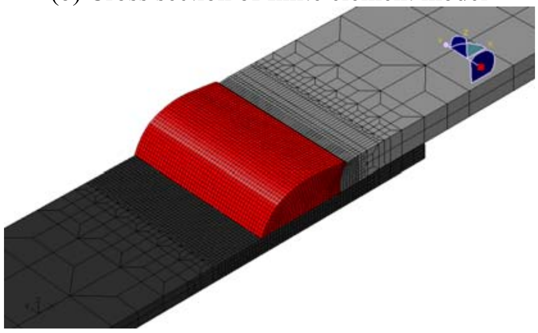
Based on the measured shape and dimensions of real CMT brazed lap joint of aluminum alloy and steel, the finite element model was created as shown in Fig.6 using eight node isotropic solid elements. The minimum size of solid mesh is 0.13mm at the aluminum side near the fusion line and the total element count is 35676. The thickness of interface layer is assumed to be 0.05mm. Commercial FEM code ABAQUS explicit was employed for the computation [5].



(a) Shape and dimension of finite element model



(b) Cross section of finite element model



(c) Total FE model

Fig. 6 FE mesh of CMT dissimilar materials brazed joint (Al to steel)

3.2 Material model for mild steel and aluminum alloy

In this finite element model, low carbon and DP600 steel with zinc coating and aluminum alloy 6061 are set as elastic-plastic materials. Their stress-strain curves are shown in Fig. 8. Their Young modules are 210GPa for low carbon and DP600 steel and 70GPa for aluminum alloy AA6061, respectively. The passion ratio is assumed to be 0.33 for all materials.

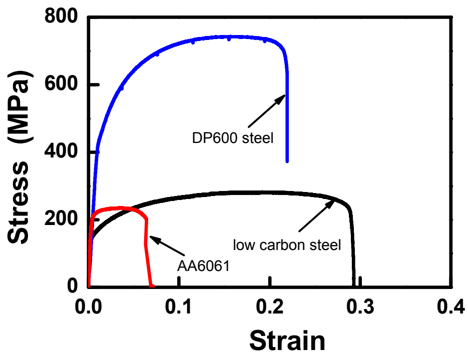


Fig. 7 Stress-strain relations of low carbon and DP600 steel and AA6061

3.3 Material model for weld metal

Since there is some porosity at the weld zone of aluminum part after brazing, which may influence the macro Young's module of the molten aluminum used in simulation. According to the analysis before, the macro

Young's module of the molten aluminum E_{weld} is set as

$$E_{weld} = E_{base}(1-\alpha) \quad (1)$$

where, E_{base} is the Young's module of the base metal AA6061 and α is the porosity ratio at the weld zone. The Young's module is about 70GPa for base metal. The measured porosity ratio at the weld zone is about 3%~5%. The Young's module is about 66.5GPa～67.9GPa.

The micro hardness of weld metal is only 75% of that of base metal at aluminum part after brazing, which can influence the final tensile strength of the weld metal. According to the analysis before, the yield stress and tensile strength for weld metal can be computed and its values are about 80% of those of the base metal, which was used in this computation.

3.4 Material model for interface layer and failure criteria

In order to predict the fracture of interface layer between steel and aluminum alloy, the failure criterion needs to be determined for the material of interface layer. According to the analysis before, the Young's module of interface layer material is assumed to be 70GPa which is the same as AA6061. The material of interface layer is assumed to be ideal elastic plastic as shown in Fig.9 [6].

The fracture criteria of interface layer material between steel and aluminum alloy can be express by following two equations,

$$\frac{\sigma_1}{\sigma_1^f} \geq 1.0 \quad (2)$$

$$\frac{Q_e}{Q_e^f} \geq 1.0 \quad (3)$$

Where, σ_1^f and Q_e^f are the fracture stress and fracture energy of material of interface layer, respectively. σ_1 is maximal principal stress at interface layer calculated by the FE model and Q_e is the deformation energy of the interface element, calculated by the following equation,

$$Q_e = \int_e \sigma \cdot d\varepsilon \cdot dV_e \quad (4)$$

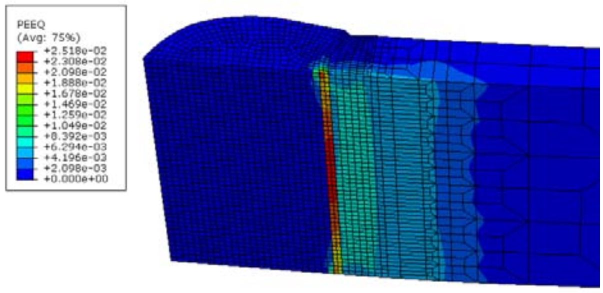
When both of the maximal principal stress and deformation energy of the interface element reach the fracture criteria, the interface layer elements will be deleted and the stress on deleted interface elements will reduced to zero immediately.

The fracture stress and fracture energy here are set as 200MPa and 10MPa (=200MPa*0.05), respectively, from the computing results before.

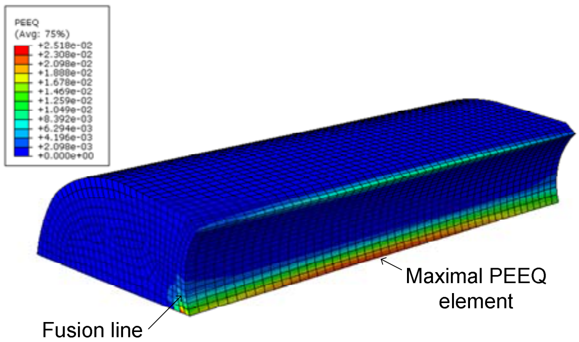
3.5 Practical criteria for fusion line failure considering micro fusion defects

Relating to the fracture criterion for the fracture mode on the fusion line, the equivalent plastic strain (recorded as PEEQ) $\bar{\varepsilon}^p$ was used. If the equivalent plastic strain $\bar{\varepsilon}^p$ in welded metal computed by FEM reaches the given criterion value ε^f of weld metal and fusion line, the fracture will start. The load when the fracture started is considered as the shear strength for fusion line fracture mode.

Since fusion line fracture mode occurs when the steel thickness is increased to 1.2mm in experiment, the PEEQ and applied load analysis are carried out in the model of 1.2mm low carbon steel + 2mm aluminum alloy. The computed equivalent plastic strain (PEEQ) distribution at aluminum part is shown in Fig. 8. It can be seen that there is a large PEEQ value distributing at the aluminum local region near the fusion line (the local mesh size is 0.13mm). That means it is easy for aluminum material to begin to fail at this region, similar to the experimental phenomenon of fusion line fracture mode.



(a) PEEQ distribution at aluminum part



(b) PEEQ distribution near fusion line (some elements removed)

Fig. 8 Equivalent plastic strain (PEEQ) distribution at aluminum part

After brazing, the molten aluminum alloy at weld zone is weaker than the base metal because

a. the tensile strength is weaker, from the results of micro hardness shown in Fig. 2;

b. There is a unfused line near the weld toe, which can cause crack initiation at the local region and reduce the strength of the weld metal, shown in Fig. 3.

Therefore, concluded from the statistical experimental results of a number of samples, the CMT joint strength can be influenced by the unfused line length at the weld toe of aluminum part (caused by the different preset gap between steel and aluminum sheets). Thus the failure criterion $PEEQ_c$ of aluminum part near the weld toe should be able to reflect the effect of the unfused line length at the weld toe.

In this study, the micro defects at weld metal, including porosity and unfused line, will not be involved in the FE model. The failure criterion $PEEQ_c$ of the weld metal is directly determined by the lap-shear test of the CMT joint.

The relationship between the failure criterion $PEEQ_c$ of the failure element at aluminum part near the weld toe and the unfused line length is shown in Fig. 9. Seen from Fig. 9, with the unfused line length at the weld toe increasing, the failure criterion $PEEQ_c$ decreases obviously. That means that it is suitable for the equivalent plastic strain (PEEQ) near the weld toe to be set as the failure criterion of aluminum part.

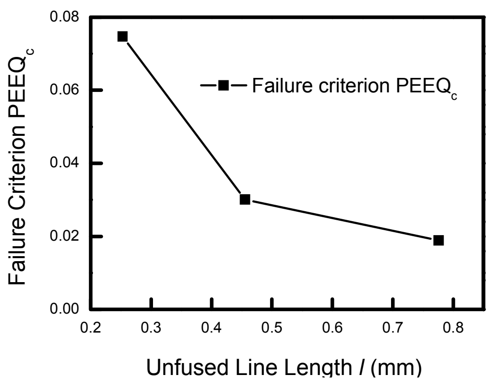


Fig. 9 Relationship between failure criterion $PEEQ_c$ and unfused line length at the weld toe of aluminum part

According to the failure criteria of different joint failure mode, the finite element analysis can be carried out in the following procedures as shown in Fig.10 to predict the strength and failure mode of CMT dissimilar materials brazed joint.

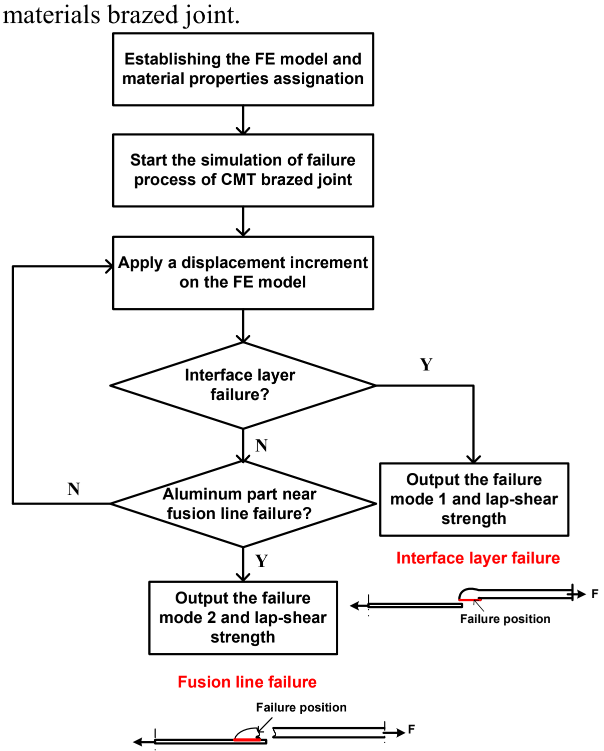


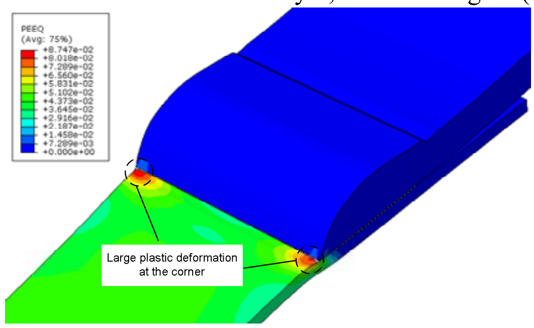
Fig. 10 FE analysis route of failure process of CMT dissimilar materials brazed joint under lap-shear loading

4. Discussion of two failure modes at various CMT brazed lap joints

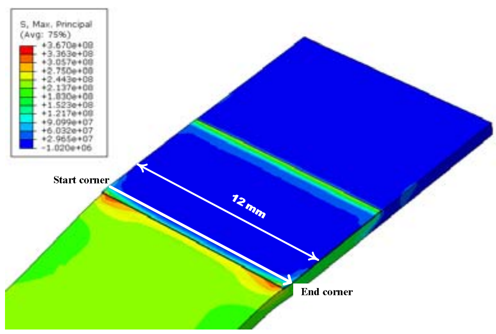
4.1 Joint failure and stress concentration

As mention above, there are two failure modes for CMT dissimilar materials brazed joint under lap-shear load in this study. Suppose that the thickness of the aluminum sheet is fixed as 2mm. When low carbon steel sheet is 0.7mm thick, interface layer failure occurs while fusion line failure for 1.2mm thick low carbon steel sheet and 1.0mm & 1.2mm thick DP600 steel, shown in Table 1. And the joint of fusion line fracture is stronger than that of interface fracture. Based on stress distribution analysis, the failure mode of steel/Al dissimilar materials CMT brazed joint can be discussed.

When low carbon steel thickness is 0.7mm, steel sheet will enter its plastic stage before the interface layer fails because its yield limit is about 180MPa and the yield load for the steel sheet is 180MPa*12mm*0.7mm = 1.512kN < 2.1kN (fracture load for the joint). Therefore with the plastic deformation increasing in steel base metal, the cross section area of steel sheet will become smaller. However the cross section area of interface layer part changes less because there is less deformation at aluminum sheet (still in elastic stage). Then at the region near the interface layer corner, there will be a stress concentration to cause equivalent plastic strain (PEEQ) concentration because of cross section area variation, shown in Fig. 11(a). Therefore that will also cause stress concentration at the interface layer, shown in Fig. 11(b).



(a) Plastic deformation distribution at the steel sheet (0.7mm low carbon steel + 2mm AA6061)



(b) Stress concentration at the interface layer (0.7mm low carbon steel + 2mm AA6061) (aluminum sheet removed)

Fig. 11 Stress and plastic strain concentration at interface layer corner

In this way, it is easier for the interface layer element near the corner to failure. That will cause the total failure of the interface layer earlier. If the steel sheet becomes thicker (e.g. 1.2mm thick) or stronger (e.g. DP600), it is not easy to cause the large plastic deformation at the steel sheet under the same loading, which can decrease the stress concentration at the interface layer element near the corner. Thus the failure of the local element near the corner and the total interface layer will be pushed back. That means the interface layer can be strengthened with steel sheet's thickness or strength improving.

Fig. 12 shows the status of stress concentration at the line marked in Fig. 11(b) under the same applied load (1.8kN) for different steel thickness (0.7mm and 1.2mm) and strength grade (low carbon steel and DP600). For low carbon steel with thickness of 0.7mm, when applying 1.8kN on the lap joint, steel sheet has been entered its plastic stage. Then there is a stress concentration at the start and end corner of the marked line (shown in Fig. 11(b)), which is dangerous and can cause element failure at the corner earlier. But for low carbon steel with thickness of 1.2mm and DP600 steel with thickness of 0.7mm, steel sheet is still in its elastic stage when applying 1.8kN. Thus there is no stress concentration at the corner at that time, which can push the element failure back.

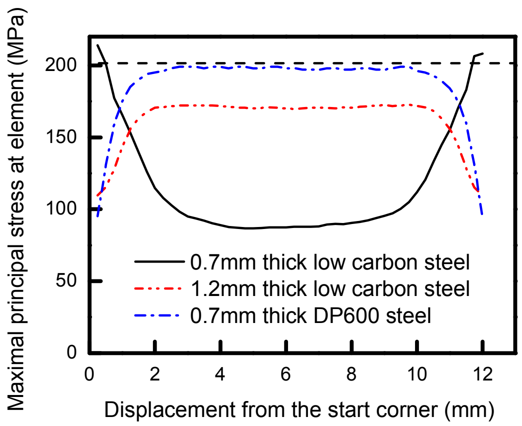


Fig. 12 Maximal principal stress distribution for different steel thickness and strength grade under the same load (1.8kN)

Therefore when steel thickness is increased from 0.7mm to 1.2mm or strength grade is improved from 270MPa to 590MPa, the interface layer is strengthened (the peak load for interface layer failure is higher). Thus before interface layer fails for 1.2mm thick low carbon and 0.7mm thick DP600 steel sheet, the applied load reaches the strength of fusion line at aluminum sheet to cause fusion line failure. That is why the failure mode and joint strengths transfer for different steel sheet thickness and strength grade.

4.2 General discussion of two failure modes at different joints

From the above analysis, for CMT dissimilar materials brazed joint (Al to steel joint), the transition of the two failure modes is the following:

a. When the steel sheet is thin and strength grade is low & the interface layer strength is lower than the molten aluminum's, interface layer fracture occurs;

b. When steel sheet becomes thicker or stronger & the interface layer is stronger than the molten aluminum near fusion line, failure mode will transfer to fusion line failure fracture.

Thus the factors influencing the failure mode and joint strength of CMT dissimilar materials brazed joint can be discussed:

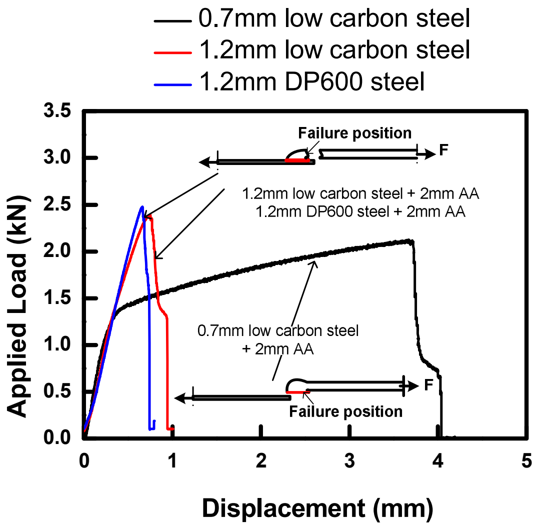
For interface fracture, steel sheet thickness and steel strength grade (especially yield limit) are the two influence factors for CMT dissimilar materials brazed joint strength: CMT brazed joint strength increases with steel sheet gage and strength grade increasing. The interface layer length might be an influence factor on CMT brazed joint strength. But it is not easy to be controlled during joint fabrication. In this study the interface layer lengths mostly drop into the range from 6mm to 6.5mm, which has no obvious effect on CMT joint strength.

For fusion line fracture, since the weld metal is weaker than the base metal for the aluminum part, the design and fabrication parameters that can improve the strength of weld metal can also improve the CMT brazed joint strength. For example, if there is a preset gap between steel and aluminum sheet before brazing, in order to fill in the gap, the melting metal and heat input will be larger during brazing. Then the welding time staying at high temperature for the molten aluminum is longer, which can reduce the porosity ratio and unfused line length near weld toe at the weld zone. Thus the CMT dissimilar materials brazed joint strength can be increased with preset gap increasing for fusion line fracture.

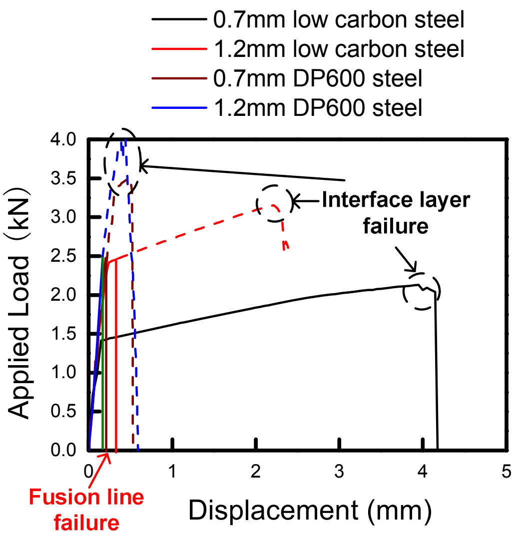
And because failure occurs at aluminum part for fusion line fracture, origin thickness and strength grade (especially the tensile strength) of the aluminum alloy sheet should be able to influence the CMT brazed joint strength: with the origin thickness and strength grade of aluminum sheet increasing, the CMT brazed joint of fusion line fracture should be able to be strengthened.

5. Validation of two failure modes and shear strength of CMT lap joints

Computing and experimental results are compared here to validate the established finite element model. The steel thickness is 0.7mm and 1.2mm and the steel strength grade is low carbon steel (270MPa) and DP600 (590MPa). The load-displacement curves and failure modes of experimental results are shown in Fig. 13(a). And the corresponding calculating results are shown in Fig. 13(b).



(a) Experimental results



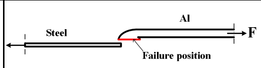
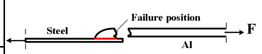
(b) Computing results

Fig. 13 Comparison of L-D curve under different steel thickness and strength grade (simulating and experimental results)

From the comparison of simulating and experimental results, it can be concluded that when steel thickness and strength grade is increased, the simulating strength and failure mode of CMT brazed joint have the same trend with the experimental results. These results all suggest that the established FE model can be used to estimate the joint lap-shear strength and failure mode of CMT dissimilar materials brazed joint (Al to steel joint).

The comparisons of joint strength and failure mode between simulating and experimental results under various CMT brazed joint are also shown in Table 2.

Tab. 2 Comparison of joint strength and failure mode between simulating and experimental results for CMT dissimilar materials brazed joint

Case	Steel strength grade	Thickness (mm)	Failure mode (same results for simulating and experiments)	Joint strength (kN)	
				FEM	EXP
1	Low carbon steel (270MPa)	0.7	 interface fracture	2.1	2.1
2		1.2	 fusion line fracture	2.5	2.5
3	DP600 (590MPa)	0.7		2.5	-
4		1.2		2.5	2.5

6. Conclusions

(1) Two failure criteria are established and validated to model the failure process of CMT dissimilar materials brazed joint under lap-shear loading.

(2) Steel thickness and strength grade can have obvious effect on joint strength and failure mode of CMT dissimilar materials brazed joint under lap-shear loading because of stress concentration near interface layer.

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