Investigation of Interface Layer Failure and Shear Strength of CMT Brazed Lap Joints in Dissimilar Materials†

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Abstract

In order to save fuel consumption by reducing the weight of automobile body, the use of aluminum alloys has a great advantage. However, how to join aluminum alloys with steels becomes a big problem in the assembly lines. Cold metal transfer (CMT) is a promising joining process for steel/Al dissimilar materials. To evaluate the shear strength and to investigate the failure modes of CMT brazed lap joints of dissimilar materials, both experimental observation and numerical simulation are performed. A numerical model for the interface layer and for the failure criteria of the interface layer between steel and aluminum is developed. The interface layer of CMT brazed lap joint can be modeled by the interface element. The failure stress and failure energy at the interface element are proposed as the failure criteria for the prediction of shear strength of CMT lap joints. If steel sheet thickness becomes thicker, stress distribution and concentration at interface layer elements have some change and shear strength at the interface layer can be improved. Then the failure occurring at the interface element may transfer to the fusion line at the side of the aluminum alloy sheet.

KEY WORDS: (Cold metal transfer), (Steel/Al dissimilar materials joint), (Interface layer), (Shear strength), (Numerical estimation)

1. Introduction

In order to save the fuel consumption, how to reduce the weight of vehicle body is always an important research subject in the fabrication of automobile bodies. The most usual approach is to use light weight materials such as aluminum alloys or high strength steel. Aluminum alloys have proved to be the most acceptable material for weight reduction for automobile bodies. However, the process of how to join aluminum alloys to the traditional materials such as low carbon steel or high strength steel has to be developed in vehicle body assembly.

Joining dissimilar materials is always very difficult because of the differences in the chemical components and material properties. If aluminum alloys and steels are joined by fusion welding, brittle inter-metallic compounds at the interface of aluminum and steel may be easily formed. Recently it was reported that if the thickness of inter-metallic compound layer between aluminum and steel is less than 10 μm, the mechanical properties of aluminum and steel joint can be accepted[1)]. The zinc coating on steel can be helpful for metal flow or spreading during welding. Thus fusion welding process can also be a potential way to join the aluminum and steel[1)].

Cold metal transfer (named as CMT) joining process is known as a modified metal inert gas welding process based on a short-circuiting transfer process with low heat input and no-spatter, which was developed by the Fronius company[2)]. The principal innovation is that the motions of the wire have been integrated into the welding process and into the overall control of the process. The wire retraction motion assists droplet detachment during the short circuit. Thus the heat input and spatter can be decreased greatly. Therefore it is suitable to join the very thin sheets which are widely used in the automobile bodies. In order to join aluminum alloy to steel, the welding/brazing process powered by CMT are employed here, in which the aluminum part is molten and spreads on the steel surface with zinc coating while steel part is little fused.

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 of the

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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

failure modes and strength evaluation of CMT brazed joints of dissimilar materials are few. Before the CMT joint is applied to automobile bodies, the strength and safety must be verified. In this study, the failure modes and joint characteristic of CMT brazed joints of aluminum alloy and steel are investigated in details by both the experimental observation and numerical simulation. A numerical model to estimate the strength of CMT brazed lap joints of dissimilar materials is developed. The influencing factors on CMT brazed joint strength are presented.

2. Experimental Observation of Interface Failure of CMT Lap Joint under Shear Loading

2.1 Joint shape and dimensions

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

After brazing, the testing pieces are cut off from the brazed joint to investigate the shear strength and failure modes. The shape and dimension of the testing piece is shown in **Fig. 1**. The measured bonding length is about 6 mm which almost does not change with the overlap length.

2.2 Micro observation of joining section

The photograph of the cross section of the brazed joint is shown in **Fig. 2** and **Fig. 3**. After brazing, there are some unavoidable micro defects such as porosity and lack of fusion in cross section of the joint as shown in **Fig. 2**. The micro defects exist mainly in the fused aluminum side and can be accepted for products because they are very difficult to control by CMT brazing process. However, the effects on the joint strength have to be investigated by experimental measurement and FEM simulation.

2.3 Measurement of micro hardness

During brazing, the aluminum alloy sheet is melted by the fusion filling wire while the steel part was not melted. In order to examine 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. 3**. **Figure 3** 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.

2.4 Observation of failure modes under shear loading

The shear loading test results show that CMT brazed lap joint fails in the two failure modes. One is interface failure mode and the other is base metal failure mode. The interface failure occurs at the interface layer between aluminum and zinc coating steel as shown in **Fig. 4**. This failure mode was only observed if the steel sheet is thin and weak, such as low carbon steel with 0.7mm thickness. The joint strength is about 2 kN.

The fusion line failure occurs at the boundary between the weld metal and aluminum base metal as shown in **Fig. 5**. This failure mode was observed if the steel sheet is stronger than aluminum sheet, such as the cases of low carbon steel with 1.2 mm thickness. The joint strength of fusion line failure is usually above 2.5

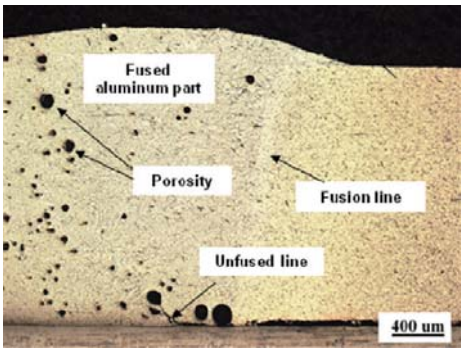


Fig. 2 Micro defects in cross section after brazing.

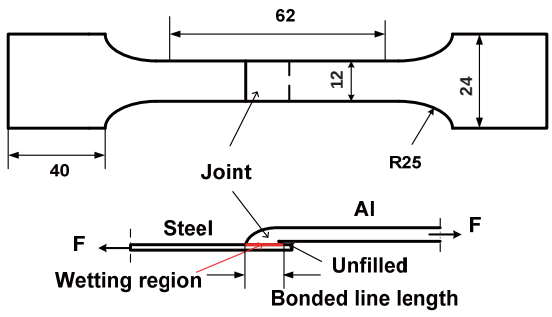


Fig. 1 Shape and dimension of sample for lap-shear test.

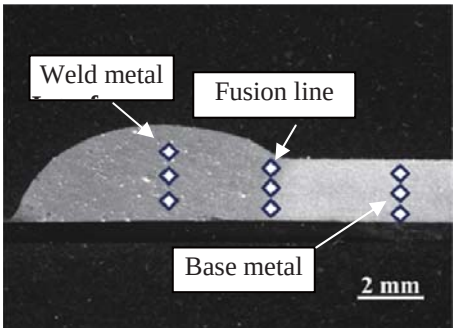


Fig. 3 Micro hardness in weld metal, fusion line and base metal of aluminum alloy.

KN which is higher than the strength of interface failure.

The above experimental observation gave us a 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 failure modes is to be conducted.

3. FEM Modeling for Interface Layer Failure and CMT Joint's Shear Strength

3.1 FEM mesh

Based on the measured shape and dimensions of real CMT brazed lap joints of aluminum alloy and steel, a finite element 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 and the total element count is 35676. The thickness of the interface layer is assumed to be 0.05 mm. Commercial FEM code ABAQUS explicit was employed for the computation[5].

3.2 Material model for mild steel and aluminum alloy

In this finite element model, low carbon steel with zinc coating and aluminum alloy 6061 are set as elastic-plastic materials. Their stress-strain curves are shown in **Fig. 7**. Their Young's moduli are 210 GPa for low carbon steel and 70 GPa for aluminum alloy AA6061, respectively. The Poisson's ratio is assumed to be 0.33 for both materials.

3.3 Material model for weld metal

Since there is some porosity at the weld zone of the aluminum part after brazing shown in **Fig. 2**, which may influence the macro Young's modulus of the molten aluminum used in simulation. Therefore, the macro Young's modulus of the molten aluminum E_{weld} is set as

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

where, E_{base} is the Young's modulus of the base metal AA6061 and α 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 Young's modulus is about 66.5 GPa～67.9 GPa.

Seen from **Fig. 3**, the micro hardness of weld metal is only 75% of that of base metal at the aluminum part after brazing, which can influence the final tensile strength of the weld metal. The relationship between tensile strength TS and micro hardness *Hv* of aluminum alloy is given by following equation[6],

$$TS(Hv) = 55.63249 + 2.173155Hv \quad (2)$$

The yield stress σ_Y for weld metal at any equivalent plastic strain $\bar{\varepsilon}^p$ is assumed to be proportional to the tensile strength given by following equation.

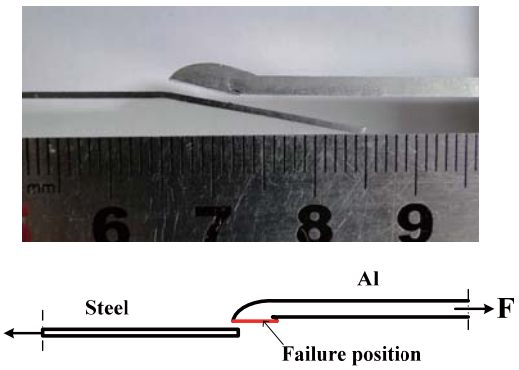


Fig. 4 Interface failure mode of CMT brazed lap joint.

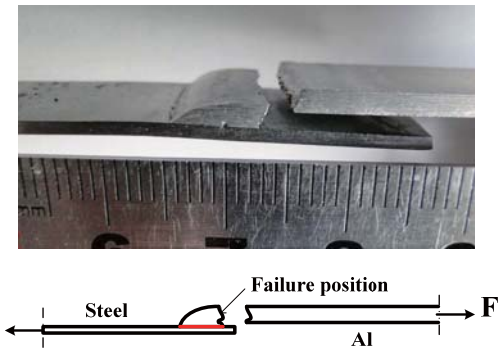
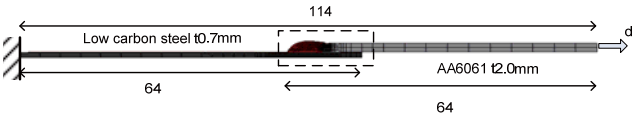
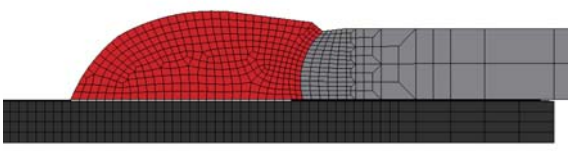


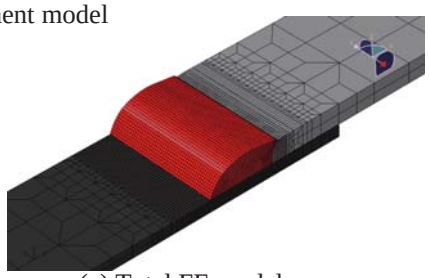
Fig. 5 Fusion line failure mode of CMT brazed lap joint.



(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).

$$\frac{\sigma_{Y-weld}(\bar{\varepsilon}^p)}{\sigma_{Y-base}(\bar{\varepsilon}^p)} = \frac{TS_{weld}}{TS_{base}} \quad (3)$$

Therefore, if the hardness of both base metal and weld metal is substituted into **Eqs. (2)** and **(3)**, the yield stress for weld metal can be computed and its value is about 80% of that of the base metal, which was used in this computation.

3.4 Modeling of failure criteria of interface layer

In order to predict the failure of the interface layer between steel and aluminum alloy, the failure criterion needs to be determined for the material of interface layer. The Young's modulus of the interface layer material is assumed to be 70 GPa which is the same as AA6061. The material of interface layer is assumed to be ideal elastic plastic as shown in **Fig.8**[5]. If both of the maximal principal stress and deformation energy of the interface element reach the failure criteria, the interface layer elements will be deleted and the stress on deleted interface elements will reduced to zero immediately.

The deformation energy at interface element Q_e is given by following equation,

$$Q_e = V_e \int_0^{\varepsilon_f} \sigma \cdot d\varepsilon \quad (4)$$

The strain ε_f used for integrating deformation energy defined by **Eq. (4)** is assumed to be 0.05 as shown in **Fig.8** which is the same as that of the base material AA6061. Thus the failure criteria of interface layer material between low carbon steel and aluminum alloy can be express by following two equations,

$$\frac{\sigma_1}{\sigma_1^f} \geq 1.0 \quad (5)$$

$$\frac{Q_e}{Q_e^f} \geq 1.0 \quad (6)$$

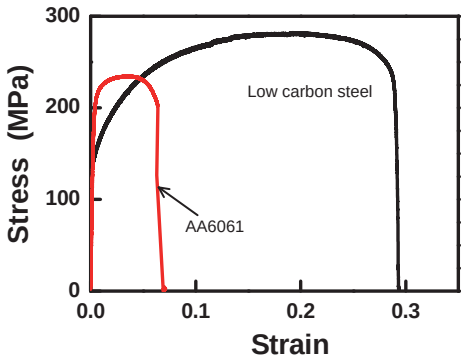


Fig. 7 Stress-strain relations of low carbon steel and AA6061.

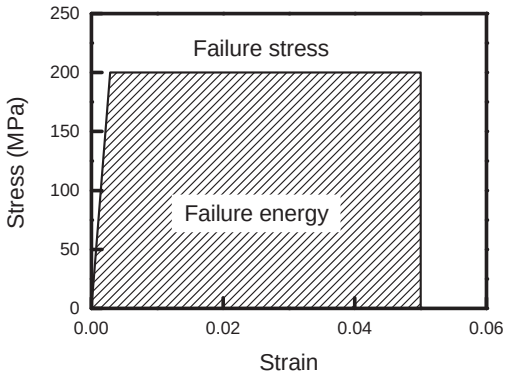


Fig. 8 Relationship between failure stress and energy.

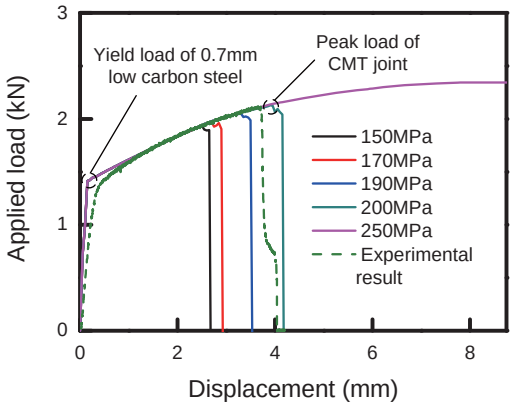
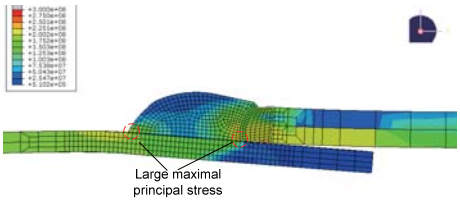
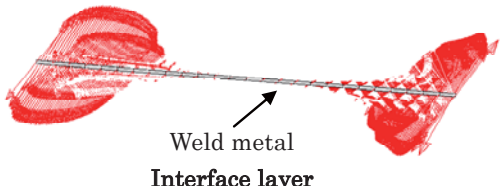


Fig. 9 Comparison of L-D curve between simulated and experimental results under different failure stress.



(a) Rotation of the brazed joint under lap-shear loading



(b) Orientation and distribution of the maximal principal stress at the interface layer

Fig. 10 Rotation and maximal principal stress orientation at the interface layer under shear loading.

where, σ_1^f and Q_e^f are the failure stress and failure energy of material of interface layer, respectively.

In order to determine the value of the failure stress, several trial computations with different values of failure stress are performed. Then the peak loads of the CMT brazed joint with 0.7 mm thick for low carbon steel and 2 mm thick for aluminum alloy are compared with the experimental result. The comparison between simulated and experimental results of load-displacement curves is shown in **Fig. 9**.

Thus the failure stress and failure energy density schematically shown in **Fig. 8** are about 200 MPa and 10 MPa (=200 MPa*0.05), respectively.

4. Discussion of Failure Mechanism at the Interface Layer of CMT Lap Joint

4.1 Stress distribution

Based on the established numerical model and failure criteria of the interface layer between low carbon steel and aluminum alloy, the shear strength of a CMT lap joint can be estimated. Under shear loading, there is a rotation motion at the brazed joint, shown in **Fig. 10(a)**. Then, the orientation of the maximal principal stress at the interface layer is almost normal to the thickness of interface layer, shown in **Fig. 10(b)**. And there is a large maximal principal stress near the edges of the interface layer, marked in **Fig. 10(a)**, which means that interface layer element starts to fail at the edges.

Thus the maximal principal stress distribution near the edges may influence the failure occurring at the interface layer and the strength of CMT brazed lap joint of steel/Al dissimilar materials.

4.2 Failure modes and stress concentration

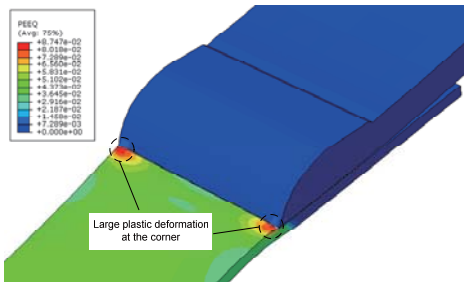
As mentioned above, there are two failure modes for CMT brazed lap joints of dissimilar materials under shear loading. If the steel sheet is 0.7 mm thick, interface layer failure occurs. If steel sheet is 1.2 mm thick, a fusion line failure will occur. This is because stiffness of the steel sheet may affect the stress concentration at the interface layer.

As shown in **Fig. 9**, if steel sheet is weak such as in the case of thin thickness (t=0.7 mm), plastic deformation will be produced under shear loading before the interface layer fails. Then, with the increasing of plastic deformation in steel sheet, the width and thickness of steel sheet will become smaller. However the interface layer and aluminum sheet have less deformation because they are still in an elastic state. Then at the edges or corners of the interface layer of the test piece, a plastic strain concentration occurs as shown in **Fig. 11(a)**. This strain concentration will also cause stress concentration at the interface layer shown in **Fig. 11(b)**. From the strain and stress distribution, it becomes easy to understand that the interface failure will occur from elements at the corner and then the total failure of the interface layer will happen. If the welded components undergo the shear loading, the failures may occur from the two ends of the weld line.

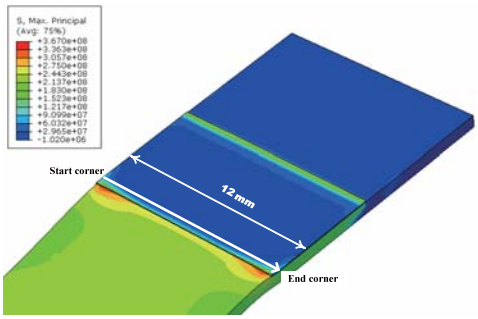
If the steel sheet becomes thicker (e.g. 1.2 mm thick), the plastic deformation at the steel sheet is not produced before the failure of interface layer. As a result, the stress concentration at the interface layer element near the corner is small. Thus the failure of the local element near the corner and the total interface layer will be pushed back. That means the strength of CMT lap joint can be increased with an increase of thickness of steel sheet.

Figure 12 shows the status of stress concentration on the line drawn in **Fig. 11(b)** under the same load (1.8 kN) for different steel thickness (0.7 mm and 1.2 mm). The steel sheet with 0.7 mm has undergone the plastic deformation with this load. Then there is a stress concentration at the start and end corners of the marked line shown in **Fig. 11(b)**, which causes the element failure earlier at the corner. But for 1.2 mm thick steel sheet, it is still in elastic deformation state at the same load (1.8 kN). Thus there is no stress concentration at the corner, which can push the element failure back.

Figure 13 shows the load-displacement curves obtained by simulation and experimental measurement, respectively, for both the thickness of steel sheet 0.7 mm and 1.2 mm, using the failure criteria of interface layer as



(a) Equivalent plastic strain 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 Plastic strain distribution and stress concentration at interface layer corners or edges

shown in **Fig. 9**.

It can be seen from **Fig. 13** that if steel thickness is increased from 0.7 mm to 1.2 mm, the interface layer is strengthened and the peak load for interface layer failure is higher, shown in **Fig. 13(b)**. Thus before the interface layer fails for 1.2 mm thick steel sheet, the applied load reaches the strength of fusion line at aluminum sheet and fusion line fails as shown in **Fig. 13(a)**. That is why the failure modes and joint strength changed for different steel sheet thickness.

5. Prediction of Shear Strength Using Failure Criteria of Interface Layer

Using the failure criteria of interface layer, the shear strength of different bonding length of CMT lap joints with thin steel sheet (0.7 mm) can be predicted. The measured bonding length of steel/Al CMT brazed joints are from 5.4 mm to 6.4 mm. The measured failure load is from 1.95 kN to 2.2 kN and is almost not affected by the bonding length. The predicted strength agreed well with measured results as shown in **Table 1**.

This suggests that the established numerical model can be used to predict the shear strength of steel/Al dissimilar materials CMT brazed joint failing in interface layer failure mode.

6. Conclusions

1. The shear strength and failure modes of CMT dissimilar materials brazed joint are measured by experiment.
2. Principal stress and deformation energy in interface elements are proposed as failure criteria for interface layer between steel and aluminum and verified by experiments.

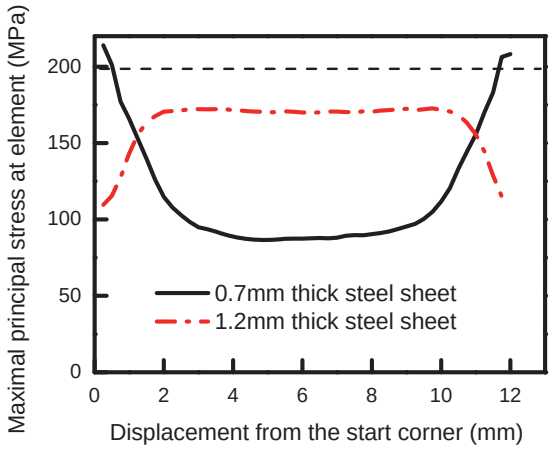
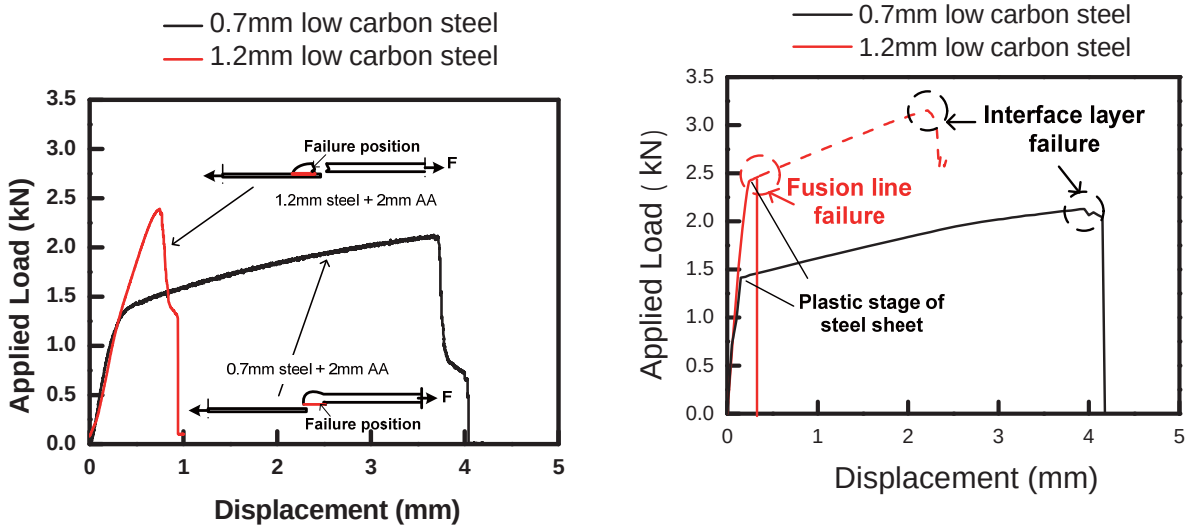


Fig. 12 Maximal principal stress distribution for different steel thickness under the same load (1.8kN).



(a) measured L-D curve for different steel thickness (joint strength and failure mode)

(b) computed L-D curve for different steel thickness (joint strength and failure mode)

Fig. 13 Comparison of L-D curves computed and measured for different steel thickness.

3. With an increase of thickness of steel sheet, the shear strength of CMT dissimilar materials joints is increased and joint failure mode is transferred to fusion line failure because of the stress concentration status variation at interface layer.

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