Correlation between sheet formability and joint strength of A1050-O/SPCC butt laser welded tailored blanks

JIN Jianchen[1,a *], SAKAMOTO Hiromu[2,b] and IIZUKA Takashi[3,c]

[1]Department of Engineering Design, Kyoto Institute of Technology, Matsugasaki Goshokaido-cho, Sakyo-ku, Kyoto 606-8585, Japan

[2]Advanced Technology Center, Kyoto Institute of Technology, Matsugasaki goshokaido-cho, Sakyo-ku, Kyoto 606-8585, Japan

[3]Faculty of Mechanical Engineering, Kyoto Institute of Technology, Matsugasaki Goshokaido-cho, Sakyo-ku, Kyoto 606-8585, Japan

[a]d1821502@edu.kit.ac.jp, [b]sakamoto@kit.ac.jp, [c]tiizuka@kit.ac.jp

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Abstract. Laser-welded tailored blanks are useful for lightweight automobiles. However, three major problems remain unresolved: low joint strength, low formability, and galvanic corrosion. Although considerable research has been conducted on the lap form, the studies on the use of lasers to weld dissimilar metals in the butt form are scarce. For practical applications of dissimilar metal tailored blanks, formability must also be investigated. In this study, Japan Industrial Standard A1050-O aluminum and SPCC steel were welded as dissimilar metal tailored blanks and used for Erichsen, flat punch stretch, and hole expansion tests. Welded materials with different joint strengths were produced to investigate the correlation between joint strength and formability. Two patterns of fracture owing to differences in joint strength were observed during the flat punch stretch test. The results of the formability test confirmed that the formability improved with an increase in the joint strength.

Introduction

Extreme weather conditions are occurring more frequently owing to greenhouse gas emissions. To prevent this situation from worsening and create a better world for all human beings, emissions of CO_2 gas, which among the primary greenhouse gases, should be curbed. Worldwide, the Union Nations and governments have taken actions to decrease the CO2 gas emissions and increase the absorption capacity of those gases. Moreover, efforts have been undertaken to reach the goal of realizing emissions equivalent to absorption, which is referred to as carbon neutrality. Many developed countries have set the goal of achieving carbon neutrality by the year 2050. CO_2 gas emissions from automobiles account for a portion total such emissions and are thought to have decreased off late. To further decrease this type of emission, exhaust gas regulations for automobiles are becoming stricter annually. The European Union has even decided to ban engine vehicles from the market. Therefore, the development of engine vehicles has become unprofitable according to the policy, and automobile manufacturers have shifted their direction of development to electric vehicles. However, even if engine vehicles are outdated, lightweight capability remains an important issue for electric vehicles for increasing the driving quality and maximum driving distance. The use of light metal and tailored blanks is an effective method for achieving lightweight requirements [1]. Through multi-materialization, the total weight of vehicles decreases by approximately 34% and has a lower production cost than light metal [2]. By preferring to light metals, tailored blanks appear to be better method for automobile manufacturing.

Tailored welded blanks (TWBs) are semi-finished blanks used for pressing processes and is welded from different metals or metals with different thicknesses using laser welding, friction stir welding, or other welding methods. Although similar metal TWBs produced from steel using laser welding have been widely used in automobile manufacturing, dissimilar metal TWBs, particular aluminum/steel TWBs, are considered more effective. However, three main issues remain regarding the development of aluminum/steel TWBs. Difficulty in welding owing to the formation of intermetallic compounds, low formability, and low corrosion resistance owing to galvanic corrosion.

The first issue of difficultly in welding was solved by using solid-phase welding such as friction stir welding. Aluminum/steel welded material achieved joint efficiency of over 100% was achieved by using friction stir welding [3,4]. Laser welding is widely used in automobile manufacturing because aluminum/steel laser welding is required to produce products. Cao et al. welded 5052 aluminum alloy and press-hardened steel (PHS) and obtained joint strength of 129.6MPa [5]. Itani and Iizuka welded Japan Industrial Standard (JIS) A5052P-H aluminum and JIS SPCC steel in butt form and obtained a joint strength of approximately 80% of that of the raw materials [6]; however, this should be further improved.

The formability of aluminum/steel-welded materials is also an important issue. However, considerable research has been conducted on the overlapping form, but the formability of these materials has not been investigated. On the other hand, only a few studies on the formability of laser-welded materials have been reported, such as the one by Iizuka et al., which JIS A1100 aluminum and JIS SPC steel butt laser welded materials were produced for formability tests. After Erichsen and punch stretching tests were conducted, welded materials showed low formability, with 20% of the raw steel materials and 50% of the raw steel materials in the Erichsen value (IE) and limit demo height (LDH). Consequently, the welded materials gained a joint strength that exceeded that of the raw aluminum materials [7].

And corrosion resistance is also an important issue, because galvanic corrosion occurs between aluminum and steel-welded materials. Galvanic corrosion leads to an unknown corrosion resistance, which should be investigated through corrosion tests. Research like Jin and Iizuka investigated the corrosion resistance of JIS A6000 series aluminum and JIS SPCC steel friction welding materials [8].

Due to lack of study in formability on aluminum/steel butt laser welded materials. It is considered that formability should be further studied. Thus, in this study, aluminum/steel dissimilar metal TWBs were welded using JIS A1050-O aluminum and SPCC steel via laser welding in the butt form. Four welded materials were produced at different joint strengths and formability tests were conducted separately. First, the distribution of joint strength for all types of welded materials were confirmed. Then three types of formability test were conducted: Erichsen, punch stretching, and hole expansion test. Finally, the punch load and stroke line were compared to investigate the correlation between the joint strength and formability.

Experimental methods

Butt laser welding. Solid-phase welding such as friction welding, use friction heat to soften the metal and welds the material by apply compression. Here, it is considered that if laser beam could achieve similar effect to heat metal like solid-phase welding. Thus, a laser welding method with compression applied to one side was developed and used in this study. Fig. 1 illustrates the mechanism of this laser welding method. Like friction welding, compression was applied to the aluminum and the steel side was fixed, and then the laser beam irradiates the materials, as shown in Fig. 1(a). As aluminum has a high reflection from the laser beam, it was considered that almost no energy was input into the aluminum, and the laser would only heat the steel side in this situation. After the laser energy increased on the steel side, the steel melted, and a melt pool occurred. As the temperature increased, heat conduction occurred between aluminum and steel, as shown in Fig.

1 (b). As shown in Fig. 1 (c), the heat conducted from the steel softened or melted the aluminum. With compression on the aluminum side, the oxide layer was pushed out from the weld interface, and a new weld interface occurred between the aluminum and steel raw material. Using this method, a maximum joint strength of 140MPa was achieved by welding JIS 5052P-H34 aluminum and JIS SPCC [6]. A joint strength of approximately 95 MPa which is almost equivalent to that of basic aluminum materials was achieved [7].

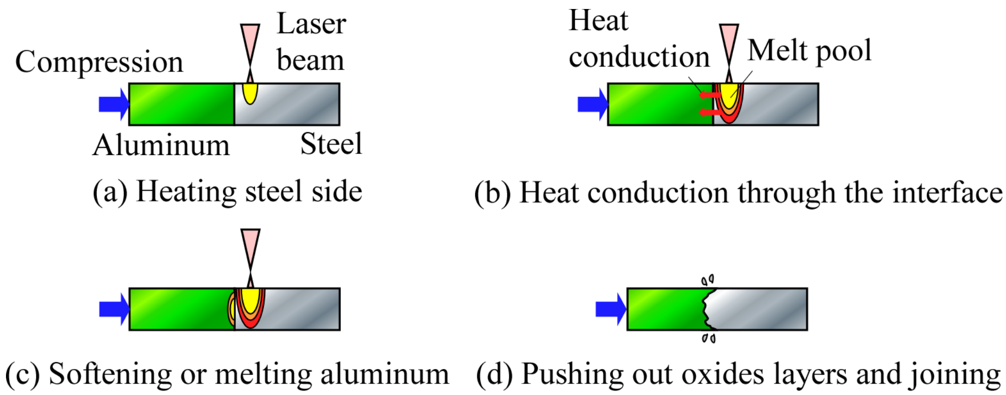


Fig.1 Mechanism of butt laser welding.

Fig. 2 (a) shows the top view of compression apparatus for butt laser welding. Two linear guides were set on the backing plate. Fixed, and moveable holders were installed on the linear guide for setting raw materials. On the left side of the backing plate, three air cylinders were set, and an air compressor was connected to air cylinders to apply compression. The moveable holder was pulled onto the fixed holder to provide compression to the welded materials during laser welding. Steel was set on the fixed holder and aluminum was set on the moveable holder owing to the low deformation resistance of the latter. Fig. 2 (b) shows the butt laser welding in the side view. Compression was applied on weld materials through cylinder and holder. The laser beam irradiated welded materials in vertical direction.

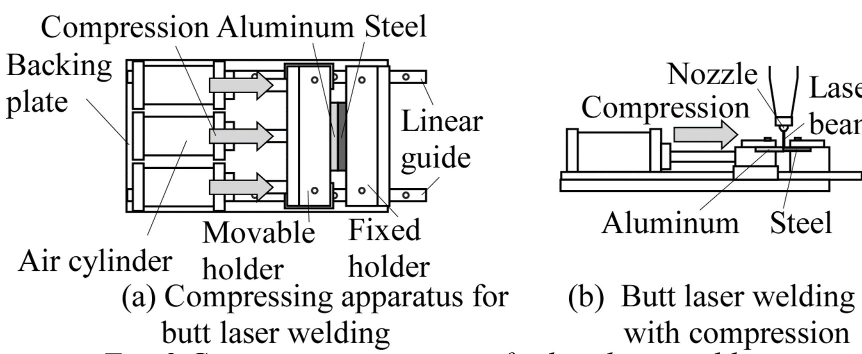
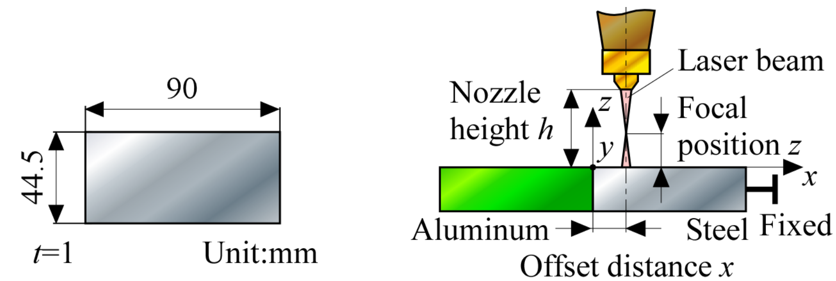


Fig. 2 Compression apparatus for butt laser welding.

Test materials and welding parameters. Herein, 1mm-thickness JIS A1050-O aluminum and JIS SPCC steel were used as test materials. Both the raw materials were milled to 44.5mm × 90mm, as shown in Fig. 3 (a). Further, 90mm side of each material was butted to each other during welding. The definitions of the butt-laser welding parameters are shown in Fig. 3 (b). A CO_2 laser was used to produce the welded materials in this study. An *x*-*y*-*z* coordinate system was set on the material surface during welding to determine the laser beam status. The *x* and *y* axis defined the position of laser irradiation on the surface of the material. *x* axis was defined as vertical to the weld interface and *y* axis was parallel to the weld interface. The origin of *x* axis was set on the welding interface; the steel side was defined as the positive direction and aluminum side as the negative direction. The laser beam moved from the outer direction to the direction along *y* axis. The *z* axis defines the focal position of the laser beam. The focal position was positive when setting the above material surface and negative below the surface. The details of the welding parameters are listed in Table 1. The laser output and frequency were set as 400 W and 100 Hz, respectively. The focal position was 1.5mm above the surface of the material. Compression was set as 31MPa, and it should pay attention to this mean 2790 N force was apply on the materials through air cylinders. Laser welding was performed between offset distance of 0 and +0.40 mm. The welding speed was set to 600 mm/min. The laser output, frequency, and other parameter would all influence joint strength of the welded materials. In this study, only the offset distance was varied to produce welded materials with different joint strengths.



(a) Size of raw materials (b) Geometrical parameters

Fig.3 Size of raw materials and geometrical parameters of laser welding.

Table 1 Parameter of butt laser welding.

Laser output [W]	400	Compression [MPa]	31
Frequency [Hz]	100	Offset distance [mm]	0 ~ +0.40
Focal position [mm]	+1.5	Weld speed [mm/min]	600

To confirm the welding parameters and produce welded materials with different joint strengths, the correlation between the joint strengths and the offset distance was first investigated, and the results are shown in Fig.4. Dots shown the joint strength of joint material whose offset distance was between 0 to 0.4mm, 0.05mm interval. The welded materials had a joint strength of approximately 40 MPa on the welding interface and slowly increased to approximately 60MPa at 0.1 mm and reached a maximum joint strength of approximately 70MPa when the offset distance reached to 0.2 mm. After the offset distance exceeded 0.2 mm, joint strength slowly decreased to approximately 60 MPa at 0.3 mm and then rapidly decreased to 0 MPa on 0.4 mm. The welded materials with offset distances 0, 0.1, 0.2 and 0.3 mm were chosen as test materials and are highlighted in red in Fig.4.

Tensile and formability tests. The welded materials and fabrication method of tensile test pieces is shown in Fig. 5. The welded materials had a length of 90 mm and width of 89.5 mm and used as the formability test pieces. However, the distribution of the joint strength at the welding interface should be confirmed before the formability tests. Because defaults may occur near the laser start and end positions, 5 mm of welded materials from the two positions were cut, and the remaining welded materials were cut into 10mm pieces to investigate the joint strength of the welded materials.

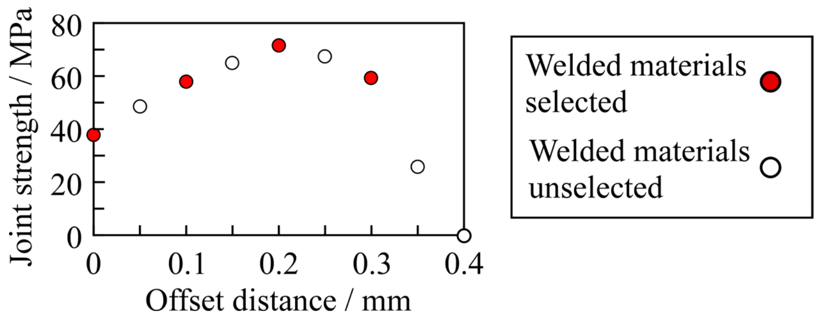


Fig. 4 Correlation between joint strength and offset distance of welded materials.

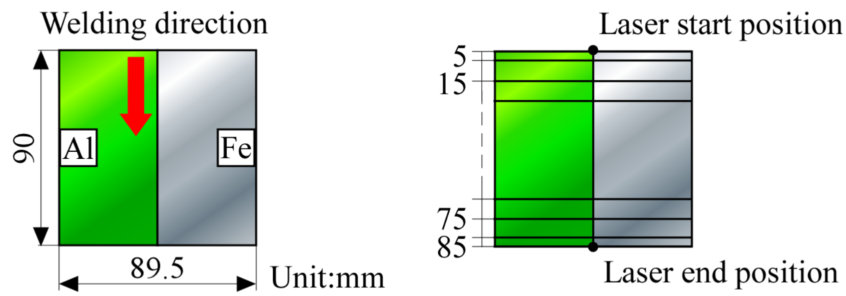


Fig. 5 Production of tensile test pieces.

Fig.6 shows the molds used in this study. In Erichsen tests, a common ball head punch with ball head diameter of sφ20mm was used. The inner diameter of dies and blank holder were φ27 and φ33 mm, respectively. The outer diameter was 55 mm for both the dies and blank holder. Blank holder force was set to 10 kN during the test. In the flat punch stretch test, a flat punch instead of round head punch was used. The diameter of this punch was φ29 mm and that of the dies was φ31 mm. Owing to the use of mold without a bead, blank holder force was set as 50 kN to provide the material-flood in the flange. Finaly, a φ39 mm diameter punch with a 60° head angle was sued for the hole expansion test.

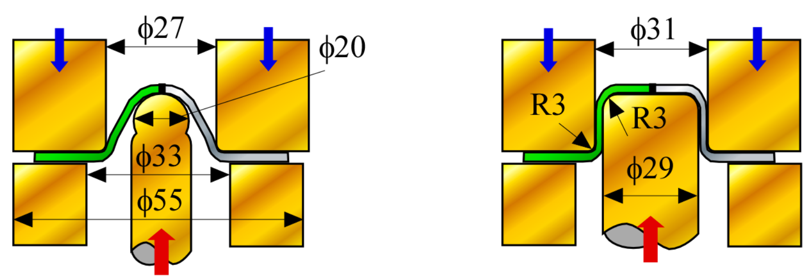


Fig. 6 Mold using for Erichsen and flat punch stretch tests.

Results

Tensile test results. Before this study, tensile strength of the raw aluminum materials was investigated and confirmed that was approximately 74 MPa. The distribution of joint strength for each welded material is shown in Fig. 7. The distance from the laser starting point indicated the position of tensile test pieces. The welded materials with an offset distance of 0 mm exhibited a joint strength of approximately 48 MPa near the laser starting point. As the laser beam moved away from the starting point, the joint strength decreased slowly to a minimum of approximately 38 MPa near the laser end position. For the welded materials with an offset distance of 0.1 mm, a maximum joint strength of approximately 61 MPa was observed near the laser start position. The joint strength decreased slightly to approximately 59 MPa at the center of the welded materials and then returned to approximately 61 MPa at the laser end position. The welded materials with an offset distance of 0.2 mm exhibited the highest joint strength among all welded materials. The same tendency was observed; a higher joint strength of approximately 65 MPa was observed at laser start and end positions, and a lower joint strength of approximately 60 MPa was observed at the center of the welded materials. Finally, the welded materials produced at offset distance 0.3 mm showed a different tendency: a low joint strength of approximately 51 MPa was obtained at the laser starting point, and then the joint strength increased slightly to 58 MPa at the center part. Therefore, the joint strength decreased slightly before the laser end point. All the different types of welded materials exhibited stable joint strengths under these welding conditions, in addition to an offset distance of 0 mm. A decrease in the joint strength of approximately 10 MPa was confirmed. It is considered that a slight deviation of the laser irradiating position occurred, which caused the laser spot to irradiate aluminum side more than the steel after 40 mm during welding. Owing to the high reflection of the laser beam, the energy input to the steel side decreased, and consequently, the joint strength decreased. It is confirmed that the welded material exhibited a stable joint strength distribution in this study. However, welded materials with joint strengths exceeding the tensile strength of the raw materials were not obtained this time. Hereinafter, these welded materials are referred to as 40 MPa (offset distance of 0 mm) welded material, 60 MPa (0.1 mm) welded material, 65 MPa (0.2 mm) welded material, and 55 MPa (0.3 mm) welded material.

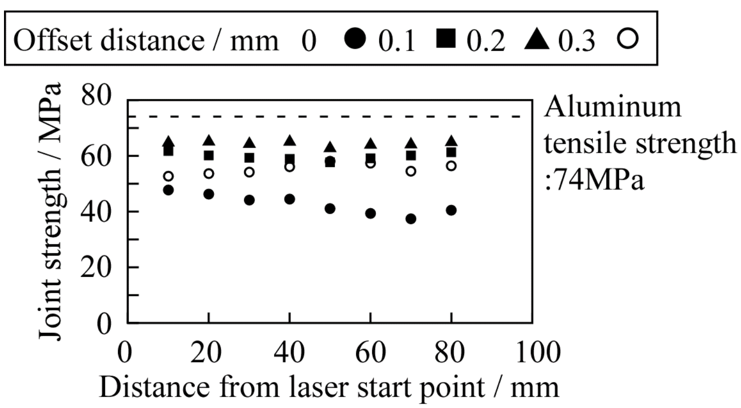


Fig. 7 Distribution of joint strength for all types of welded materials.

Table 2 lists the average joint strength of each welded material. The joint strengths of the welded materials at offset distances 0, 0.1, 0.2, and 0.3 mm were 42.5, 59.6, 64.8 and 55.2 MPa, respectively. Compared to the results in Fig. 4, the joint strengths at offset distances 0 and 0.1 mm were approximately the same, however, those at 0.2 and 0.3 mm decreased slightly.

Table 2 Average joint strength of welded materials.

Offset distance [mm]	0	0.1	0.2	0.3
Average joint strength [MPa]	42.5	59.6	64.8	55.2

Fracture in formability test. First, photograph of the fracture during Erichsen test is shown in Fig. 8. The fracture is indicated in red arrows and circles in the figure. In the 40MPa welded materials, the fracture occurred at the weld bead at the center of the punch part. For 55, 60, and 65 MPa welded materials, the fractures also occurred on the weld bead at the center of punch part.

Observing the fractured parts, all the fractures occurred parallel to the weld bead near the aluminum side. During the Erichsen test, the materials at head of the punch were in an equibiaxial tensile state. Parallel fracture indicated the lack of joint strength resulted in the fractures in all types of welded materials.

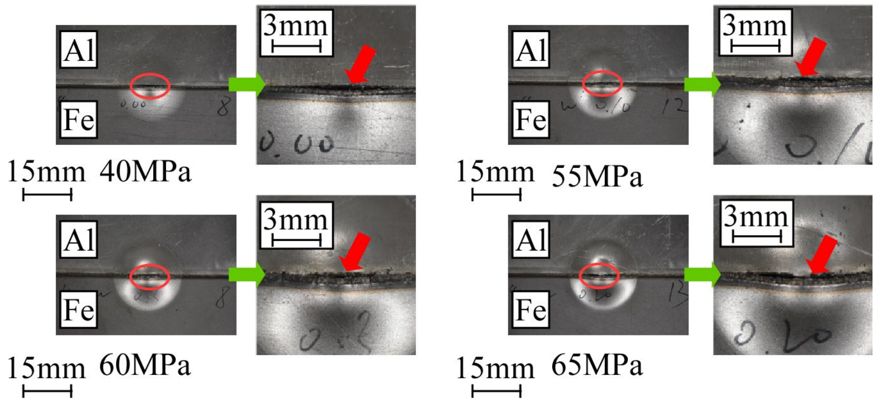


Fig. 8 Fractures in Erichsen tests.

Fig.9 shows the fracture of the welded materials during the flat punch stretch test. Evidently, the fracture on the 40 MPa welded materials was parallel to the weld bead, similar to that in case of the Erichsen test. Whereas 55 MPa welded materials, the fractures occurred parallel to weld bead on the punch shoulder parts of the welded materials. Similarly, the fracture on 60 and 65 MPa welded materials also occurred parallel to the weld bead on the punch shoulder parts of welded materials. Similar to Erichsen test results, the center of materials was in an equibiaxial tensile state and the lack of joint strength resulted in the fracture in the 40 MPa materials. However, the fractures on the punch shoulder part, which is parallel to the weld bead, indicated that the lack of ductility was the primary reason for occurrence of fractures.

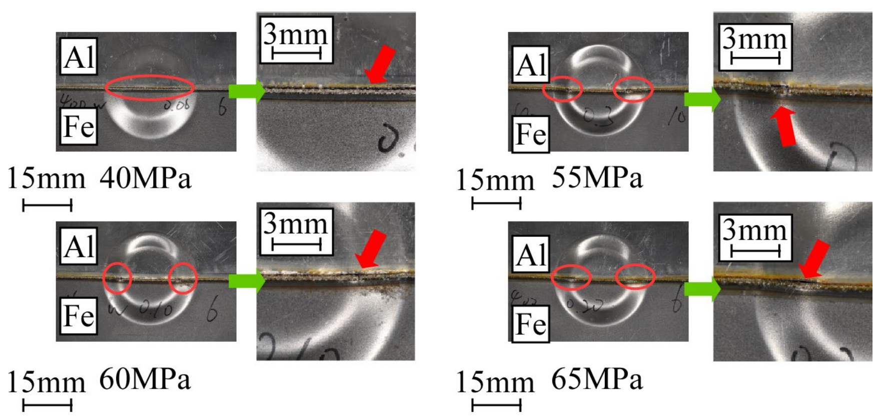


Fig.9 Fractures in flat punch stretch tests.

The fractures observed in the hole expansion test are shown in Fig. 10. The 40, 55, 60, and 65 MPa welded materials exhibited the same fracture pattern, wherein penetrating fractures occurred parallel to the weld bead on the hole edge. According to the deformation states, the materials were almost in a uniaxial tensile state at the hole edge, and the lack of joint strength resulted in the fracture during the hole expansion test.

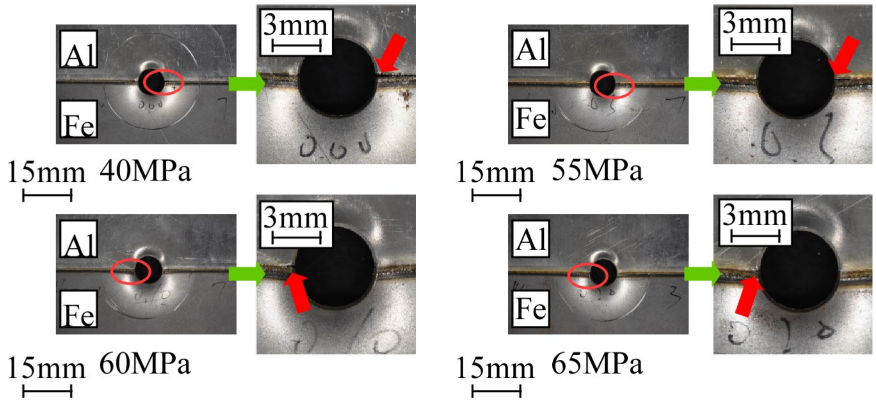


Fig. 10 Fractures in hole expansion tests.

Variations in Formability. To confirm the changes in formability during the Erichsen and flat punch stretch tests, the punch load-punch stroke curves are shown in Fig.11; where the cross marks indicate the breaking load on each welded material. Fig. 11 (a) shows the punch load-punch stroke curves obtained during the Erichsen tests. The 40 MPa welded materials exhibited a breaking punch load of approximately 1.5kN and was the lowest among all the welded materials. Further, the slope of this welded material was slightly smaller than that of the other welded materials. For the 55 and 60 MPa welded materials, the breaking loads were approximately 2.3kN each. The 65 MPa welded materials indicated a breaking load of approximately 2kN. Although the breaking load of the 65MPa welded materials was lower than of the 55 and 60 MPa welded materials, the difference between the breaking forces was only approximately 0.3kN and it could be considered to be same as other two welded materials. This was because individual differences occurred during welding. Apart from the results of the 40 MPa welded materials, the slopes of all the welded materials were the same during the Erichsen tests. Fig. 11 (b) shows the punch load-punch stroke curves during the flat punch stretch tests. Similar to the Erichsen test, the 40 MPa welded materials had the lowest breaking load of approximately 4 kN. The breaking load increased to approximately 5.8 kN when the joint strength increased to 55 MPa. The 60 MPa welded materials exhibited approximately the same breaking load as that of the 55 MPa welded materials. In contrast to the Erichsen test, in case of the 65 MPa welded materials, the breaking load was almost 1kN higher than that of the 55 and 60 MPa welded materials. Although a difference in the breaking load was observed, the slope of the punch load-punch stroke curves for all the welded materials were the same during the flat punch stretch test. Thus, it was confirmed that as the joint strength increased, the breaking load also increased during the flat punch stretch test.

Correlation between the formability and joint strength. The results of the formability tests are presented in Fig. 12. The Erichsen value and limit dome height were both approximately 2.3mm and the limit hole-expansion ratio was only 4.5% for the 40 MPa welded materials and was minimum value this study. The 55 MPa welded materials had approximately the same Erichsen value and limit dome height of approximately 3.5mm; the limit hole-expansion ratio was approximately 9%. When the joint strength increased to 60MPa, the Erichsen value increased slightly to 3.9mm and the limit dome height remained at the same level compared to that of the 55 MPa case. However, limit hole-expansion ratio increased significantly to approximately 11% and was the highest value among all the welded materials. The 65 MPa welded materials yielded an Erichsen value of 2.9 mm and the limit dome height was approximately 4mm. Further, the limit hole-expansion ratio was approximately 9.2%. However, several values of the formability at higher joint strengths were lower than those of the other welded materials. It is considered that the higher the joint strength resulted to higher Erichsen value, limit dome height, and limiting hole expansion rate.

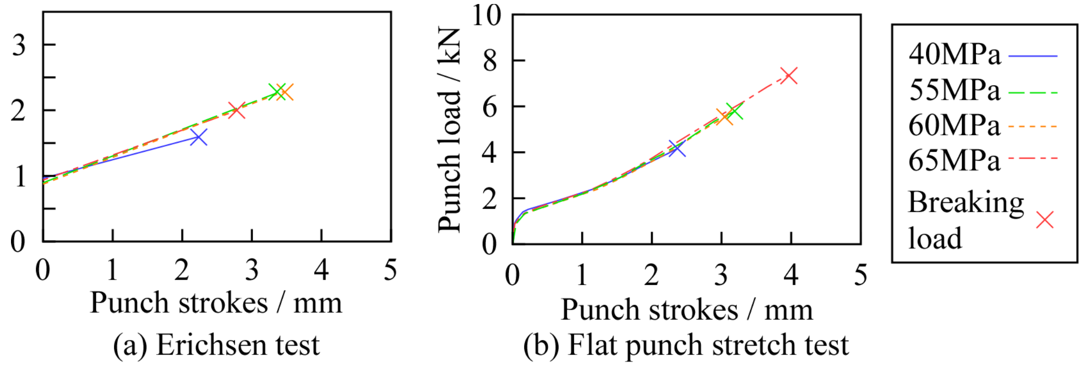


Fig. 11 Punch load-punch strokes curves of Erichsen tests and flat punch stretch tests.

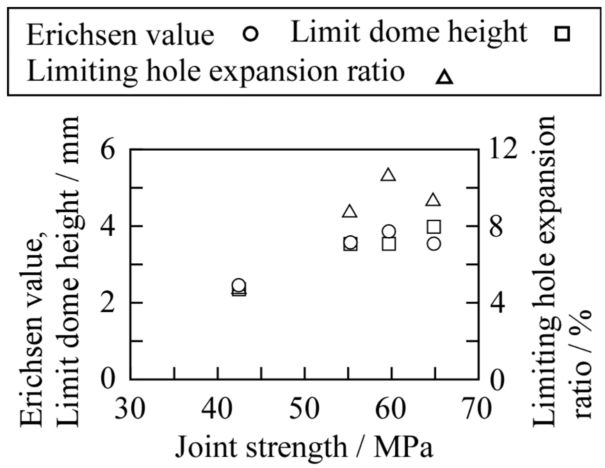


Fig. 12 Correlation of formability and joint strength.

Summary

This study welded aluminum/steel dissimilar metal TWBs in the butt form suing JIS A1050-O aluminum and SPCC steel via a new laser welding method. This laser welding method was performed under compression in a similar form to solid-phase welding. Four welded materials were produced at different joint strengths, and formability tests were conducted. Using butt laser welding, the welded materials with a stable joint strength distribution were used for the formability test. Regardless of the joint strength, in the Erichsen test, the fractures of all types of welded materials occurred parallel to the welded bead at the center of the punch owing to the lack of joint strength. By contrast, two fracture patterns were confirmed during the flat-punch stretch test. Fractures of the welded materials with low joint strengths were occurred at the center of the punch head. When the joint strength increased, a fracture on welded material was observed on the punch shoulder. The fracture on the punch head was results of lack of joint strength. Whereas fracture on the punch shoulder results of lac of ductility. The lack of joint strength also resulted in a penetrating fracture that occurred on the weld bead for all types of welded materials during the hole-expansion test. Welded material in higher joint strength obtained higher punch load and fracture occurred at lower punch load on welded material in low joint strength. It was confirmed that the formability improved with an increase in the joint strength; however, the causes of the fracture were considered to be the low joint strength of the bead and lack of ductility. The joint strength only changed by 15MPa among the 55, 60, and 65 MPa welded materials. Thus, formability did not change significantly in this study, and a higher joint strength is required for further studies. Microstructures near weld bead should be investigated for further studies.

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