

Strength of FSW Joints in Aluminum Extrusions and Simulation

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ABSTRACT

The use of aluminum extrusions joined by friction stir welding (FSW) was examined under the supposition that such a method might produce a vehicle body structure with highly efficient joints that is also lightweight and low cost. The strength of an FSW joint of aluminum was compared with MIG and laser MIG welding in the fabrication of such a structure. Static and dynamic tests were performed in order to evaluate the collision strength of the FSW joint. As a result, it was determined that welding conditions largely determine the dynamic strength performance of the FSW joint. Additionally, modeling of an FSW joint was attempted and simulation methods were devised.

1. Introduction

Due to global warming, air pollution, and rising oil prices, it continues to be important to make lighter vehicle bodies to conserve fuel. One technique for so doing is to adopt structures that join aluminum extrusions with cast or stamped parts. Structures of this kind are already being mass-produced⁽¹⁾. This article examines structures composed of extrusions fabricated with a reduced mold investment and without the use of cast or stamped parts for joints. The use of friction stir welding (FSW) allows for continuous joints, as opposed to the spot joints produced by spot welding, and this makes possible structures with greater joint strength. These structures are also less subject to thermal strain than those produced by MIG welding, making it easier to achieve precision in the vehicle body. In addition, the required investment is lower than laser welding, and the application of FSW is therefore expected to increase in the future, with an emphasis on use in low-volume production vehicles.

Several studies of FSW^{(2)–(4)} have been conducted, and it has begun to be used for some parts in railroad rolling stock and motor vehicles. But there are few reports on the dynamic properties and

strength of lap joints that take into account the application of this method to vehicle frames, including the question of productivity.

Strength tests were therefore performed on the aluminum extrusion frame fabricated with lap joints using FSW, and an evaluation of the FSW joints was conducted. MIG and laser MIG welds that are accessible from one side were selected for comparison purposes. A method for simulating FSW joints was also devised.

2. Test Specimen and Methods

2.1. Shape of Test Specimen and Contents of Tests

The areas of the vehicle body structure to be investigated were the joints of the floor frame, outrigger and side sill on the front section of the vehicle frame, which are typical body structures. These areas not only require static strength; they also demand dynamic strength during collisions. The specific structure is shown in Fig. 1. Aluminum extrusion was applied to the areas in question, and the structure of section closed by FSW joints was investigated. For the testing, test specimens that took load direction in these areas into consideration were used. Static load testing and falling

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weight impact testing were carried out, and the joints were evaluated. High-speed tensile testing was also conducted to devise a method of simulating FSW joints, and the resulting dynamic properties were studied.

2.2. Test Materials and Welding Conditions

The parent material for testing was A6063S-T5 aluminum extrusion, a material with a track record in mass-produced space frames⁽¹⁾. The test specimens were fabricated by cutting them from extrusions. The test specimens and stock thickness were selected to match each test. The chemical composition and mechanical properties of the test materials are shown in Tables 1 and 2.

MIG joints and laser MIG joints were selected to provide comparison with the strength of FSW joints. The various welding conditions were decided by quality in terms of external appearance and observation of cross sections using an electron microscope to confirm that there were no flaws. The FSW was performed using a tool with a shoulder diameter of 15 mm. As welding conditions for FSW, MIG and laser MIG welding, welding feed rates of 200, 1500 and 2000 mm/min, respectively, were used. The welding conditions for the test specimens used in the below tests were all identical unless otherwise noted.

2.3. Static Test Method

The static strength test was carried out with test specimens in shapes that simulated portions of a vehicle body structure. Figures 2 and 3 show overviews of the test specimens and test device. A universal testing machine was used for the compression

Table 1 Chemical composition of parent materials A6063S-T5 (%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.40	0.15	0.00	0.03	0.47	0.00	0.00	0.02	Bal.

Table 2 Mechanical properties of parent materials A6063S-T5

Tensile strength [MPa]	Yield stress [MPa]	Elongation [%]
223	202	12

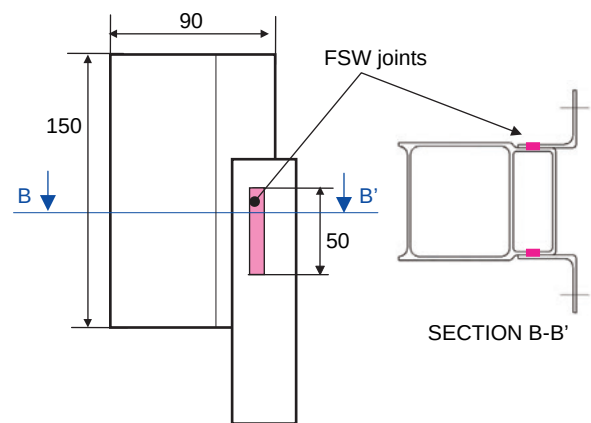


Fig. 2 Test specimen

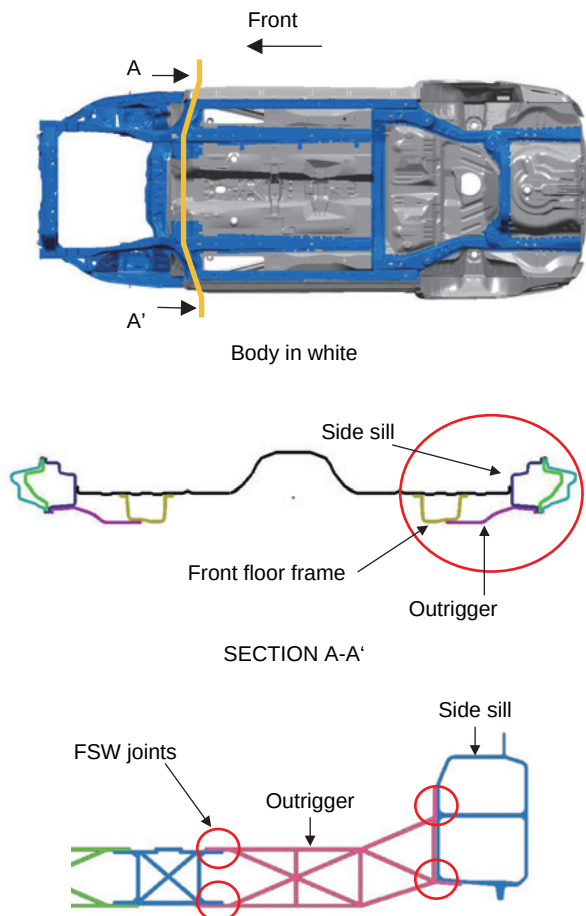


Fig. 1 Body structure with FSW joints

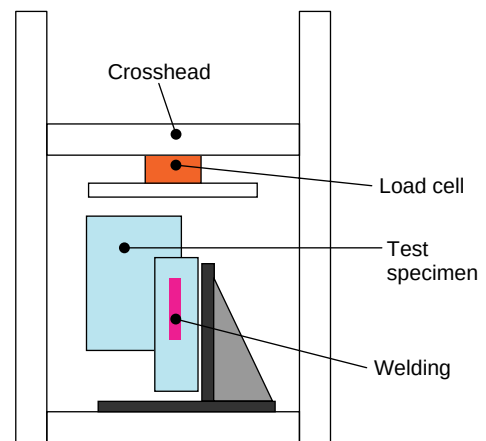
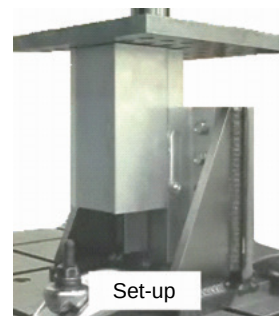


Fig. 3 Device of static load test and set-up

testing device. The load was measured using a load cell attached to the crosshead, and the crosshead displacement value was taken as the stroke. The load centers were positioned at the joint centers on the assumption that the load would be applied there during actual use, and a complex load composed primarily of a shear load was applied to the joints. The test speed was set to 10 mm/min.

The test specimens for FSW and laser MIG were joined with lap joints. In the interests of practicality, the MIG joints were joined by overlapping their flange edges and fillet welding them. All the joints were made a uniform 50 mm in length. The direction of the joints was the direction of the extrusions.

2.4. Dynamic Test Method

The dynamic strength was evaluated by means of a falling weight impact test. Test specimens in shapes simulating portions of a structure, as in the static test, were used so that the test could be compared with the static test. The direction of the load applied to the joints was also the same as in the static test. For the purpose of stability of the joints and the load applied to them, the dynamic test was set up to support the test specimen on both ends instead of just one end, and the length of the joints was extended to 170 mm. Figures 4 and 5 show an overview of the test device and the test specimens. The test was set up to allow a weight to fall freely from

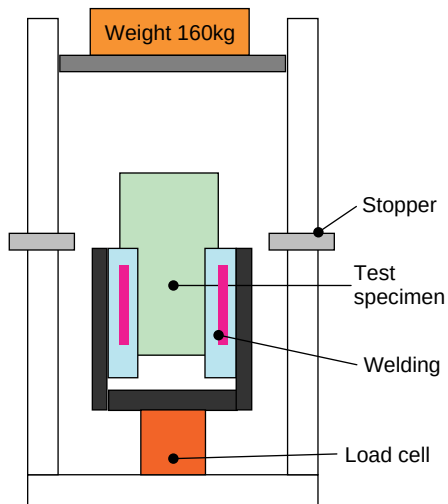


Fig. 4 Device for falling weight impact test

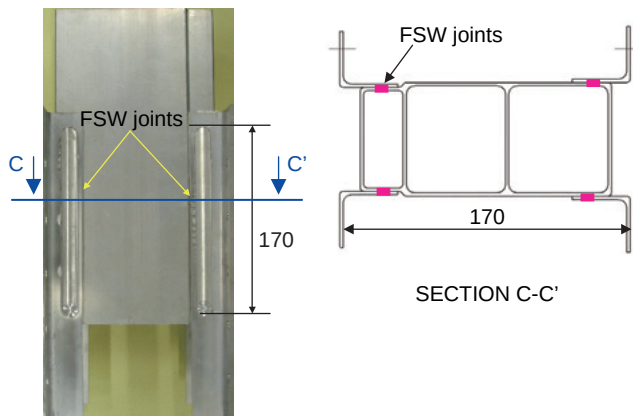


Fig. 5 Test specimen for falling weight impact test

a height of 3.5 m so that the weight would be falling at a rate of 8.3 m/sec at the moment of impact. The load was measured by means of a load cell placed beneath the test specimen, and the stroke was determined by measuring the position of the weight using a laser displacement meter.

3. Test Results

3.1. Static Test Results

Figure 6 shows the static test results. The point in the graph where the load drops abruptly indicates that the joints fractured. The FSW joints and the laser MIG joints fractured at a stroke of 7.5 mm, while the MIG joint fractured at 4.5 mm. The maximum load for the FSW joints was the same as for the MIG joints, and was low at 20% of the laser MIG joints. The length of the stroke up to the point where the FSW joints fractured was the same as for the laser MIG. The test confirmed that the strength of FSW joints is equal to or greater than that of MIG joints.

Figure 7 shows photographs of the joints after they fractured. The fracture pattern in the FSW joints shows that increasing strain in the area of the joints is accompanied by deformation of the L-shaped flanges, and the fractures occur along a straight line that originates at the FSW keyhole. That fracture cross section is shown in Fig. 8. This confirms that the fractured area is at the end point of the unjoined area. The fracture of the laser MIG joints occurred after the deformation of the flange, but the final fracture patterns were not all alike, and instead showed variation. The MIG joints all fractured at the weld bead.

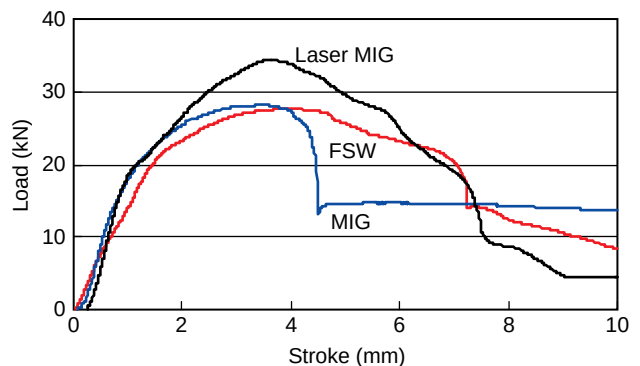


Fig. 6 Stroke – static load for welded joints

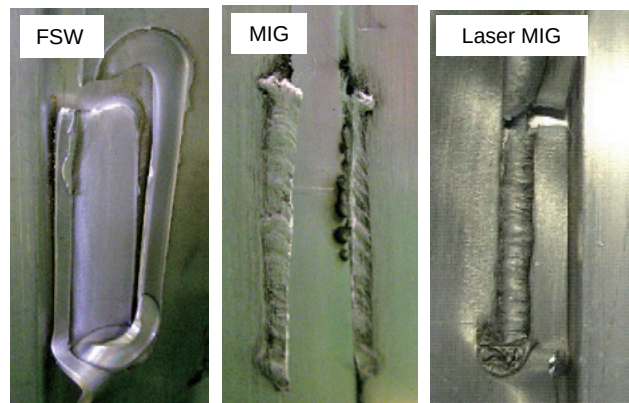


Fig. 7 Welded joints after static load test

3.2. Dynamic Test Results

Figure 9 shows the relationship between load and stroke, and Fig. 10 shows the appearance of fractures in the test specimens. The FSW joints fractured along a straight line at the end point of the unjoined area. The MIG joints fractured in a straight line along the weld bead and the heat-affected zone (HAZ). With the laser MIG joints, the upper portion of the test specimens collapsed, and no fracture occurred in the joints. The fracture patterns in the FSW joints and MIG joints were the same as found in the static test. Because the test specimens collapsed, the load on the laser MIG joints occurred at or after a stroke of 10 mm and fluctuated between 100–200 kN. The maximum load on the MIG joints was 10% lower than that on the laser MIG joints, and the fracture occurred after the stroke reached 15 mm. The maximum load on the FSW joints was the same as on the MIG joints, but the fracture in the joints occurred with fewer strokes than it did in the MIG joints. This result does not agree with the tendency found in the static test, and it indicates that the FSW joints are more easily damaged by impact.

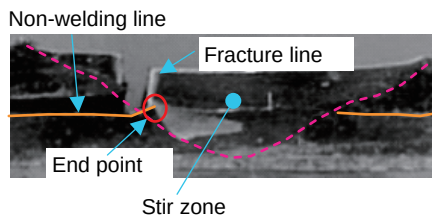


Fig. 8 Section of FSW joint after static load test

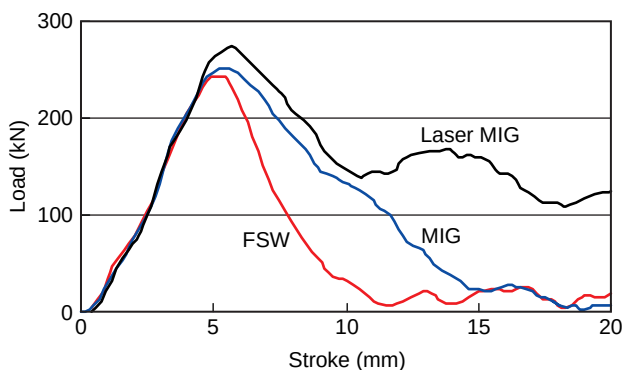


Fig. 9 Stroke-dynamic load for welded joints

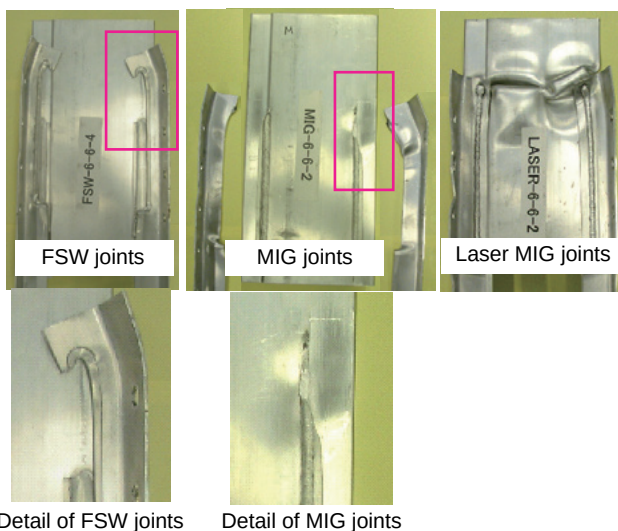


Fig. 10 Specimen after dynamic load test

4. Discussion

4.1. Discussion of Static and Dynamic Strength

The dynamic test results showed that the FSW joints have less dynamic strength than the other joints. Cross sections of the FSW joints were observed to analyze the causes of this weakness. Figure 11 shows the cross section. It is clearly evident that the material in the bottom plate is raised upward in the boundary area between the stir zone and the parent material. This is a phenomenon that occurs because of characteristics that originate in the creation of the FSW. In the case of a lap joint as seen in Fig. 12, the parent materials in the bottom must be stirred together with the parent materials in the top. The boundary area between the upper and bottom plates is raised upward, creating a kind of notch. It is thought that, as a result, the shape effect of the notch is to reduce the dynamic fracture toughness so that the amount of energy absorbed by the joint is decreased. This was proved from the report of an experimental application of the Hopkinson bar method, in which it was found that the dynamic fracture toughness of an aluminum alloy was lower than the static fracture toughness⁽⁶⁾.

4.2. Analysis of Internal Joint Shape

In order to analyze the impact on the joint strength from the raising that occurs when the FSW joint is formed, the FSW welding conditions were changed so as to create joints with less raising. The cross section of a modified FSW joint is shown in Fig. 13. It is clearly evident in this cross section that less raising has occurred in the boundary area. This state of the joint is described in the

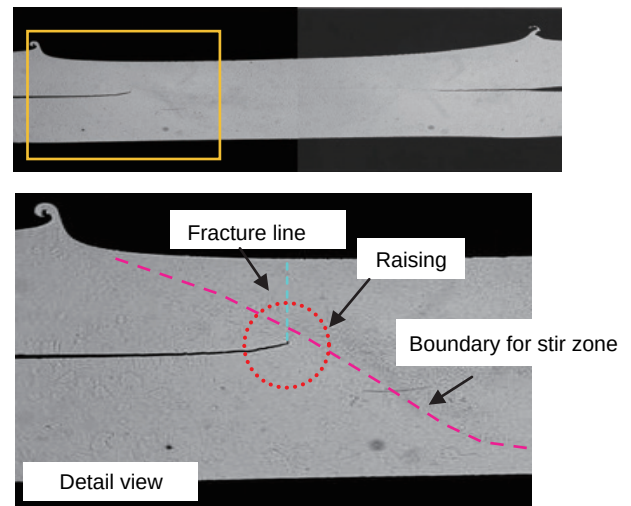


Fig. 11 Section of FSW joint

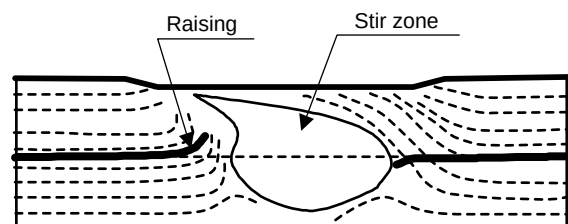


Fig. 12 Principle of FSW

below explanation as being without raising. The static strength test conducted in Section 4 was carried out and the strength with and without raising was compared. The results are shown in Figs. 14 and 15. Compared to the joints with raising, the joints without raising have increased the amount of energy absorbed. This is the result of a change in the fracture pattern. In the case of the joint with raising, one side of the stir zone fractured along a straight line, but in the joint without raising, the fracture occurred on both

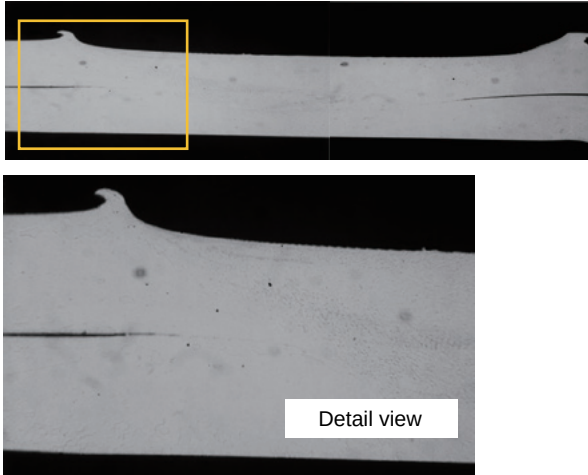


Fig. 13 Section of FSW joint under new conditions

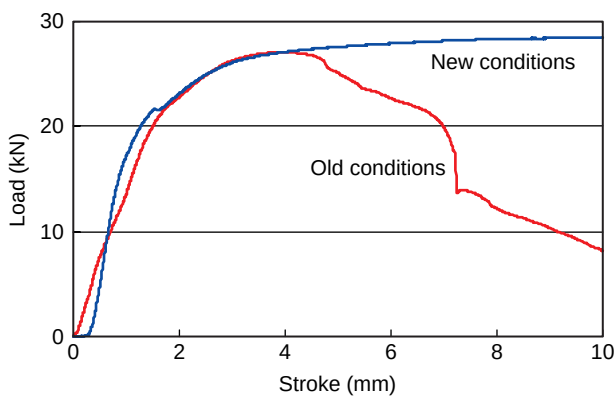


Fig. 14 Comparison of load under new and old conditions

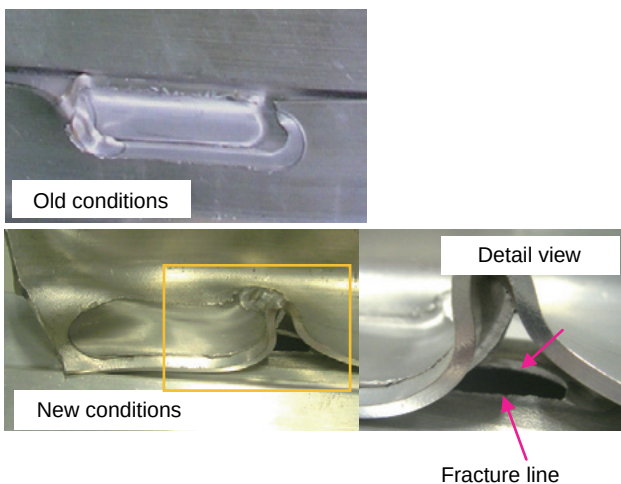


Fig. 15 Comparison of fracture mode of new and old conditions

sides of the stir zone. In this case, the crack did not propagate immediately as it did when the fracture was on just one side. The amount of energy absorbed can be said to have increased as a result. It is clear that the state of raising that occurs according to the welding conditions has the effect of changing the fracture pattern and the load properties.

5. Simulation Model

5.1. High-speed Tensile Test

A high-speed tensile test was carried out to devise a method for simulating FSW joints. The items studied were the tensile strength of the joints and the effect of strain rate on that strength. The test specimens used were 2 mm thick and 5.4 mm wide. The testing was carried out on butt welded joints. The three strain rates of 0.1, 10 and 200/s were used. The local strain in the 20 mm section centered on the joint was also measured to provide a reference for determining the size of the simulation model shell. For the local strain, parallel portions of the test specimens were marked at 1 mm intervals and their elongation was measured.

The tensile strength of the parent material with a strain rate of 200/s tended to be 6–7% higher than at 0.1/s. Figure 16 shows the test results for each joint. The FSW, MIG and laser MIG joints were all like the parent materials in that they did not display any major difference in tensile strength according to the strain rate. The tensile strength of the FSW and laser MIG joints was confirmed to have risen 15%. The fracture areas in the FSW joints were all in an HAZ.

Next the distribution of the local strain was examined. Figure 17 shows the results from measurement of strain distribution in the

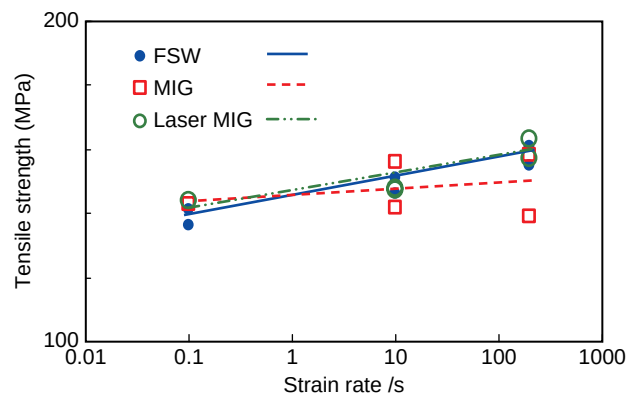


Fig. 16 Tensile strength for strain rate of welded joints

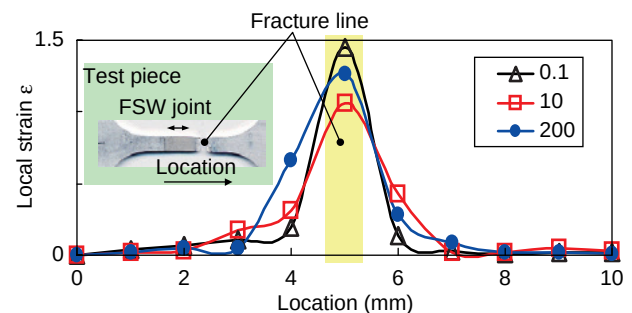


Fig. 17 Local strain for FSW joints under high-speed tensile test

FSW joints. This figure emphasizes the strain in the fractured areas. The lateral axis represents the location of the test specimens. The elongation in 10 mm sections centered on the fractured area in the test specimens increased 19% with a strain rate of 200/s relative to a strain rate of 0.1/s. It was confirmed that greater strain occurred locally within a range of 2–4 mm centered on the fractured area.

5.2. Creation of a Simulation Model for FSW

A simulation model was created from the high-speed tensile test results and FSW joint cross section. Figure 18 shows the conceptual approach for that simulation model. The shell model was created divided into the stir zone (A), the HAZ (B) and the parent material (C), and their respective material characteristics were configured. The reduction that takes place during welding was taken into account when determining the stock thickness. The size of the offset for the thickness of overlapping areas was kept as small as possible to avoid a shape effect. It has already been confirmed that the hole that develops in the terminal area when making an FSW joint does not have any impact on the maximum strength so long as the joint is of a certain length or longer. The modeling of this aspect was therefore omitted.

Figure 19 shows the maximum and minimum values calculated for the various local strain distances (the length of lateral axis sections in Fig. 17) from the local strain quantities in Fig. 17. The maximum values were calculated for strain at the center of the fractured area. The minimum values were calculated for strain at the edge of the fractured area. It can be seen that when the distance was 4 mm, the minimum strain was 0.45 and the maximum strain was 0.65. The shell size was determined from the stock thickness and from the strain distribution in Fig. 17. The pattern of strain

distribution varies according to the strain rate. The strain is concentrated within a distance of 4 mm in any case, however, and it was therefore judged that a shell size of 2–4 mm would be appropriate.

The material constants were identified using the strain rate factor obtained through testing together with the line chart of stress and strain. An isotropic elasto-plastic model was used for the material model. In modeling the aluminum extrusion, the angular edge areas were represented by shells, and the thickness of those areas was set in proportion to their area⁽⁵⁾. In correlating with the tests, the two figures for strain rate factor and ultimate strain were revised. As a result, the ultimate strain for the FSW joint areas of the simulation model came out about 10% lower than the test figures. This strain figure was smaller than the strain range test figures shown in Fig. 19. One conceivable explanation follows.

The strain figure was taken from testing not with lap joints but rather with butt welded joints. Butt welded joints are not affected by the decreased fracture toughness caused by the shape effect of raising as found in the lap joints. Consequently, the results of high-speed tensile tests on lap joints yield lower values for ultimate strain than tests on butt welded joints.

5.3. Results of Calculation

Figures 20 to 23 show a comparison of the static and dynamic test results with the calculation results. They present comparisons of the load-stroke diagram and the fracture patterns after testing. The comparison of testing and calculation shows that the maximum load and energy absorption results are both within 5%. There is a close correlation between the test and the model, and the fracture patterns are also in agreement.

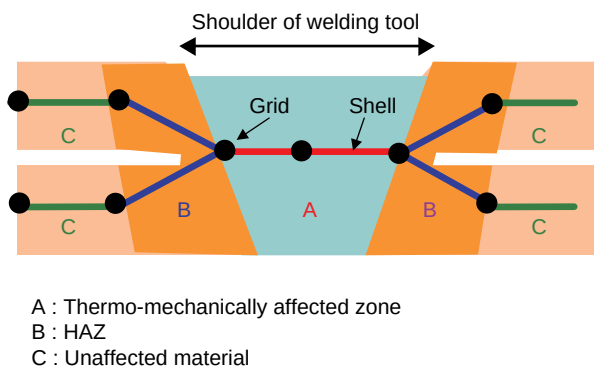


Fig. 18 Simulation model for FSW joints

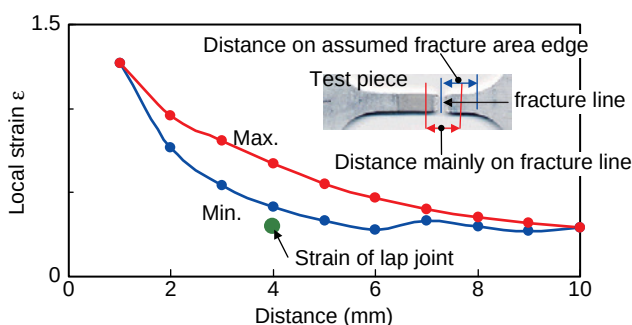


Fig. 19 Local strain distance on assumed fracture area

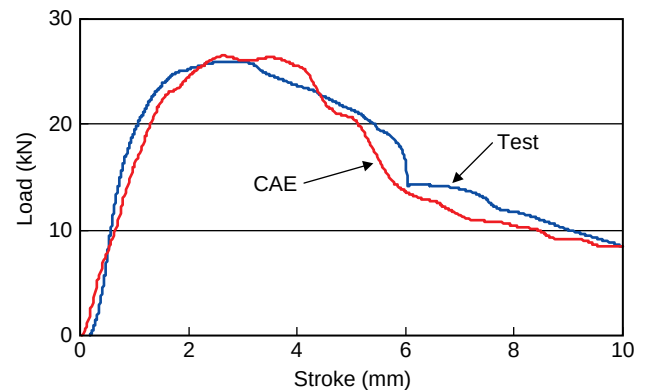


Fig. 20 Comparison of static load of test versus CAE

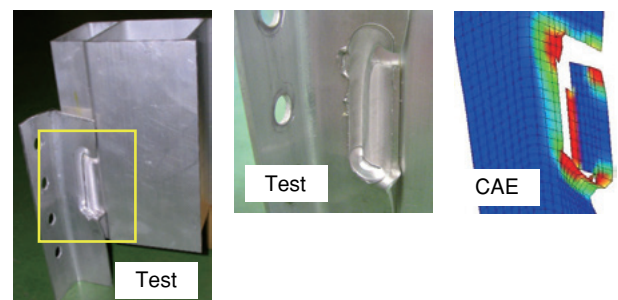


Fig. 21 Comparison of fracture mode of static load test versus CAE

5.4. Verification of Raising in the Simulation

The fracture toughness is not decreased in FSW joints where raising does not occur. It can be projected, therefore, that such joints will experience collapse in the parent material area without any fracture in the joints, just as seen in the laser MIG joints during the falling weight impact test. This was verified in simulation. The results of the analysis of internal joint shape were used for test comparison of the static strength resulting under different welding conditions. This showed that maximum load did not vary while energy absorption increased. It is clear from this result that there is an increase in the allowable strain before fracturing. When only

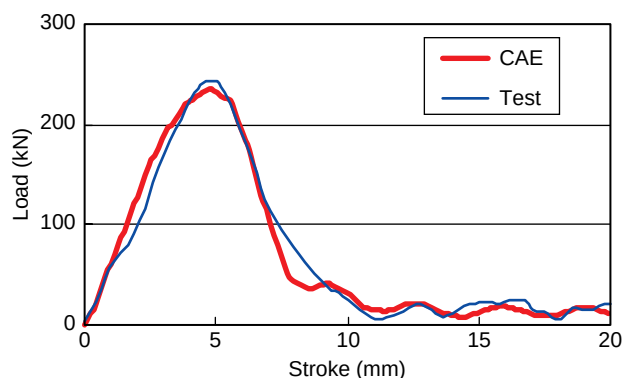


Fig. 22 Comparison of dynamic load of test versus CAE

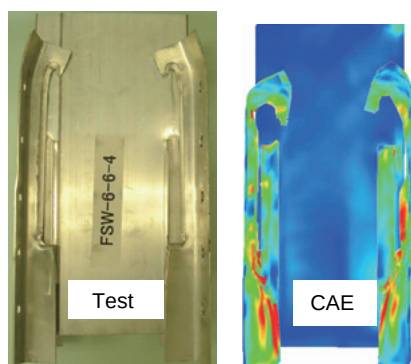


Fig. 23 Comparison of fracture mode of dynamic load test versus CAE

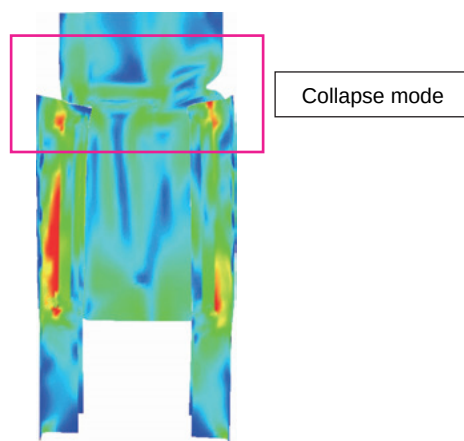


Fig. 24 Result of calculation that assumes non-raising in FSW

the figure for ultimate strain was increased in the simulation by comparison with the ultimate strain identified in the creation of a simulation model for FSW, it was projected that the joints would not fracture when simulating the falling weight test. Instead, there should be a collapse in the parent material area similar to what occurred with the laser MIG joints.

The maximum figure for average strain with a stroke of 4 mm obtained from Fig. 19 was used as the figure for ultimate strain in the simulation. According to these calculation results, the joints do not fracture but collapse does occur in the parent material area. It was evident that performance should be equivalent to that of the laser MIG joints. It can be confirmed from the calculation results in Fig. 24 that collapse occurs in the parent material area. It was confirmed in simulation of FSW joint strength that the welding conditions affect the ultimate strain and have a major effect on dynamic performance.

6. Conclusion

Evaluation was made of the static and dynamic strength of FSW joints on aluminum extrusions and research was conducted into methods for simulating such joints. The following results were obtained:

- (1) The static strength of FSW joint with raising was located between laser MIG joint and MIG joint, and the static strength of FSW joint with reduced raising was equal to that of the laser MIG.
- (2) The dynamic strength of FSW joint with raising was lower than that of the laser MIG joint and MIG joint.
- (3) The raising that occurs in the process of making an FSW reduces dynamic fracture toughness through the shape effect of the notch and has an impact on the fracture pattern and load properties.
- (4) Favorable simulations of static and dynamic behavior were achieved in the modeling of FSW joints by configuring the material characteristics for every area of the joints and by modeling them using shells.
- (5) The dynamic strength of FSW joint without raising was estimated in simulation, and a result equivalent to that of laser MIG joint was achieved.

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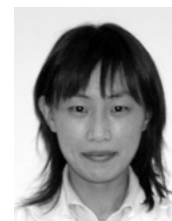
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