Fracture toughness of structural aluminium alloy thick plate joints by friction stir welding

M. Mochizuki*[1], M. Inuzuka[2], H. Nishida[2], K. Nakata[3] and M. Toyoda[1]

The fracture toughness in a friction stir welded joint of thick plates of structural aluminium alloy type A5083-O is investigated. A joint between two 25 mm thick plates is fabricated by one sided, one pass friction stir welding. The Charpy impact energy and critical crack tip opening displacement (CTOD) in the friction stir weld are much higher than those in the base metal or heat affected zone, whereas mechanical properties such as stress–strain curve and Vickers hardness are not conspicuously different. The effects of the microstructure on crack initiation and propagation are studied in order to clarify the difference in fracture toughness between the stir zone and base metal. The analyses of the fracture resistance curves and the diameters of dimples in the fracture surface after both tensile and bending tests show that the fine grained microstructure in the stir zone helps to increase ductile crack initiation and propagation resistance. It is found that the high fracture toughness value in the stir zone is affected by the fine grained microstructure in friction stir welds.

Keywords: Friction stir welding, Fracture toughness, Fracture resistance curve, Ductile crack, Microstructure, Structural aluminuim alloy

Introduction

Friction stir welding (FSW)[1] has been increasingly applied to various thin structures because of the soundness of the welded joint, the lower distortion level, environmental reasons, etc. The weld phenomena of FSW have been approached from both the physical side[2–4] and the mechanical side[5–8] in order to clarify the characteristics of friction stir welded joints. These valuable results help to develop further applications of FSW.

Structural aluminium alloy has high strength, ductility, corrosivity and toughness at low temperatures; hence, it is used for high speed hydrofoils and liquefied natural gas (LNG) tanks.[9,10] When applying a welded joint to structural members, not only mechanical properties such as the stress–strain relation and hardness, but also the fracture toughness are important. The mechanical properties of friction stir welded joints have already been evaluated.[11–16] Fracture toughness has also been investigated in general,[17–20] but the properties of a friction stir joint composed of thick plates have not been studied because of the difficulty of fabrication. Because structures such as the LNG tank demand a thickness of >40 mm, a joining method and its evaluation are needed for the application of FSW to heavy components.

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In this study, a friction stir welded joint of 25 mm thickness is manufactured, and then a tensile test is performed for stress–strain behaviour, and Vickers hardness, Charpy impact energy and critical crack tip opening displacement (CTOD) are measured in order to investigate characteristics of the base metal, heat affected zone and stirred zone in the welded joints. Ductile crack initiation and propagation are also studied in order to understand the difference in fracture characteristics.

Friction stir weld for aluminium thick plates

The chemical composition of type A5083-O aluminium alloy plate for structural members is shown in Table 1, and the mechanical properties are shown in Table 2. The plate thickness is 25 mm and no tempering is performed. A joint is made by friction stirring with the appropriate rotational tool conditions of the apparatus. A schematic illustration of the method of FSW for type A5083-O aluminium plate of 25 mm thickness is shown in Fig. 1. The tool for structural aluminium alloy thick plate is used with 28 mm radius of the shoulder and 8 mm radius of the pin.[21] The rotational speed of the tool is 200 rev min^{-1} and the welding speed in the longitudinal direction is 51·5 mm s^{-1}.

The cross-section of the friction stir welded joint is shown in Fig. 2. The joint between the two 25 mm thick plates is fabricated by one sided, one pass FSW. The stir zone and narrow heat affected zone of both sides of the stir zone are observed, but the thermomechanical affected zone, which is usually called the TMAZ, is not observed in this specimen.

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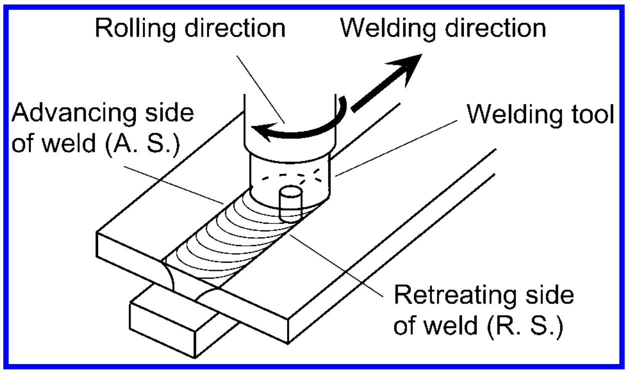
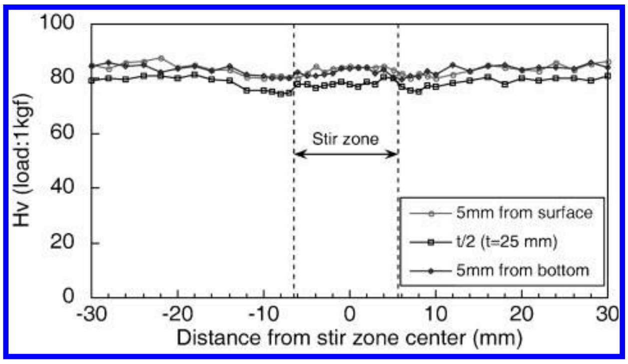
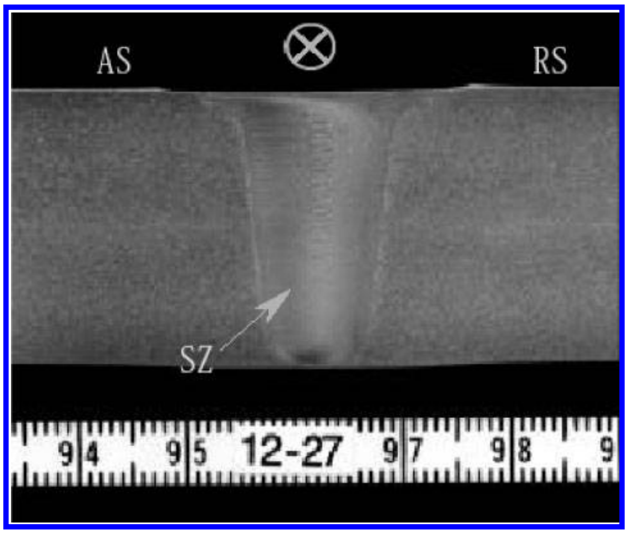


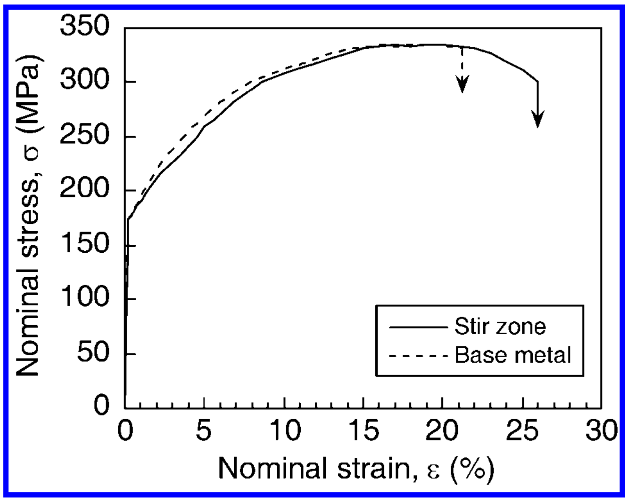
1 Friction stir welding for type A5083-O aluminium thick plate



3 Distributions of Vickers hardness around stir zone of FSW joint



2 Cross-section of FSW joint with thickness of 25 mm



4 Nominal stress and strain curves by tensile test specimen machined from stir zone and base metal

Mechanical properties of friction stir welded joint

Figure 3 shows the distributions of Vickers hardness around the stir zone of the friction stir welded joint. Three horizontal lines are chosen to measure the hardness. The locations of these lines are as follows: the centre of the thickness, 5 mm from the top and bottom surfaces. There is no obvious difference or softening region in the whole welded joint, even near the heat affected zone. The magnitude of hardness between the stir zone and base metal is nearly the same. The friction stir welded joint has the same characteristics for Vickers hardness distribution as a A5083-O aluminium alloy joint welded by gas metal arc (GMA) or gas tungsten arc (GTA).[9] Furthermore, the distribution in the advancing and retreating sides in the heat affected zone has the same tendency.

The nominal stress and strain curves measured by a tensile round bar specimen machined from the stir zone and base metal are shown in Fig. 4. The tensile test is conducted at room temperature.[22–24] The yield stress and tensile strength do not change between the stir zone and base metal, and the ductility in the stir zone is a little bit larger than that of the base metal. This tendency is considered to be natural according to the distribution of hardness of the same level between the base metal and stir zone.[25–28]

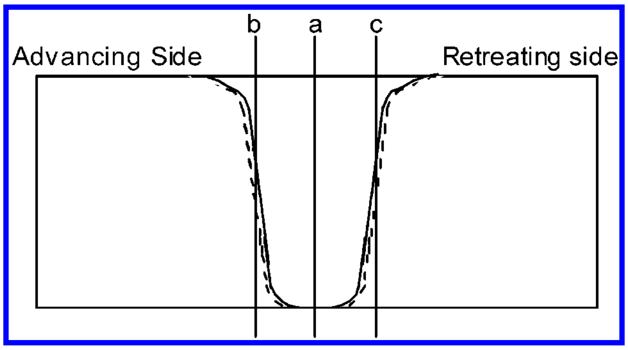
A Charpy impact test specimen is extracted along the evaluation line of the fracture surface set for each microstructure, as shown in Fig. 5. The temperature dependences of the Charpy absorbed energy in the base metal, stir zone and heat affected zone of the advancing and retreating sides are shown in Fig. 6. The absorbed energy in the stir zone is much higher than that in the base metal or heat affected zone. This result is remarkable because only the stir zone has a high absorbed energy, although there is little difference in the mechanical properties in these regions. A conventional welding method such as GMA or GTA produces the same level of impact energy between the weld metal and base metal in a structural aluminium alloy plate welded joint.[9] Further study is carried out in the next chapter in order to clarify the mechanism of increasing toughness.

Table 1 Chemical composition of type A5083-O aluminium alloy

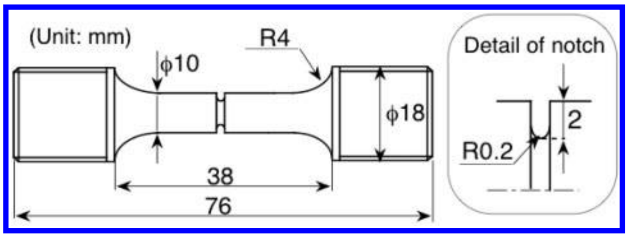
Si	Fe	Cu	Mn	Mg	Cr	Ti	Zn
0·1	0·21	0·03	0·61	4·78	0·09	0·02	0·04

Table 2 Mechanical properties of type A5083-O aluminium alloy

$\sigma_{0\cdot2}$, MPa	σ_T, MPa	El., %
178	326	27·7



5 **Evaluating position for Charpy impact specimen and three point bending CTOD specimen of FSW joint of thick plates: a – stir zone (SZ); b – heat affected zone (advancing side); c – heat affected zone (retreating side)**



7 **Configuration of round bar specimen with circumferential deep notch for ductile crack initiation and propagation test**

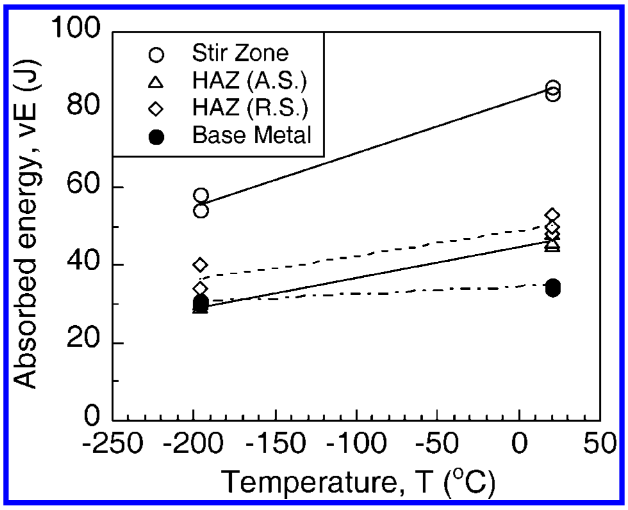
Effect of microstructure on fracture toughness

A tensile test using a round bar specimen with deep notch and a three point bending test using a CTOD specimen are performed in order to clarify the mechanism of increasing toughness in the stir zone compared with that in the base metal. Ductile crack initiation and propagation are observed in details with consideration of the microstructure.

Ductile crack initiation and propagation in round bar specimen with deep notch

The configuration of the round bar specimen with a circumferential deep notch for ductile crack initiation and propagation test is shown in Fig. 7. A radius of 0·2 mm is machined at the notch tip. The tensile loading in this test is unloaded just after ductile crack generation is initiated. The loading level in the ductile crack observation is nearly the same between the stir zone and base metal, but the elongation level of the stir zone is larger than that of the base metal at ductile crack initiation.

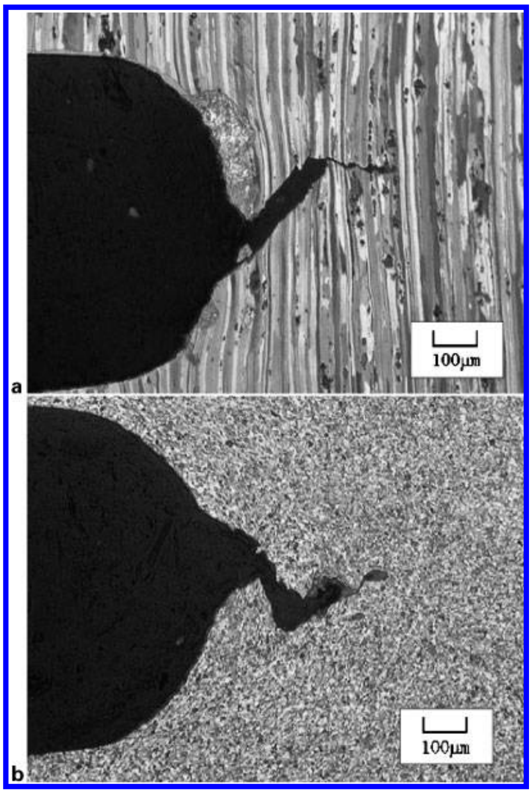
The unloaded specimen with ductile crack initiation is then cut in the longitudinal direction, and the relation between the microcrack and microstructure is studied by observing the cutting section. A polarising microscope is used for the observation. Figure 8 shows the difference in the microstructure with ductile crack initiation in the tensile round bar specimen test. In the base metal, a rolled structure is remained near the centre of the thickness, and a void is generated from inclusions concentrated in the grain boundary along rolling layers, and the connection of voids becomes ductile crack propagation. In the stir zone, inclusions are milled and dispersed; thus, voids from inclusions in the stir zone do not become as large as in the base metal and heat affected zone. As a result of the generation of small voids, the stir zone has higher tolerance of void coalescence than the base metal, and the elongation until ductile crack initiation in the stir zone becomes larger than that in the base metal.



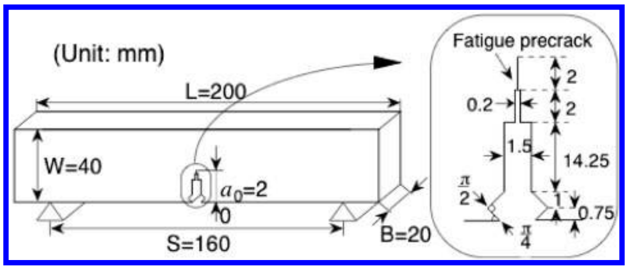
6 **Temperature dependences of Charpy absorbed energy in base metal, stir zone and heat affected zone of FSW joint**

Ductile crack initiation and propagation in three point bending specimen

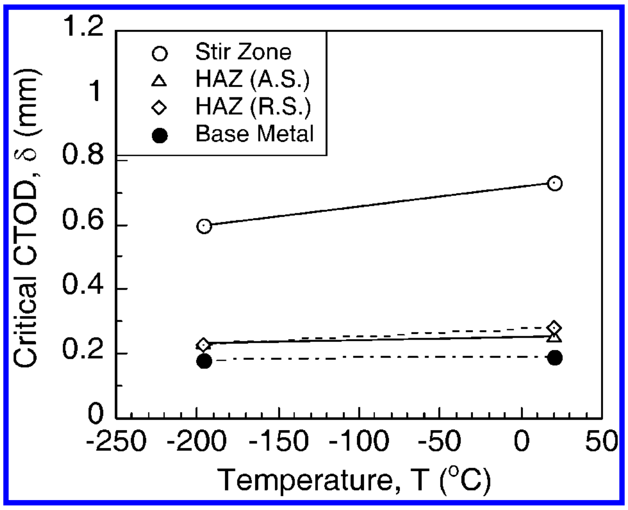
The three point bending test is used to determine the fracture resistance curves in the CTOD specimen in the next study of ductile crack initiation and propagation.



a base metal; *b* friction stirred metal
8 **Microstructure with ductile crack initiation in tensile test**



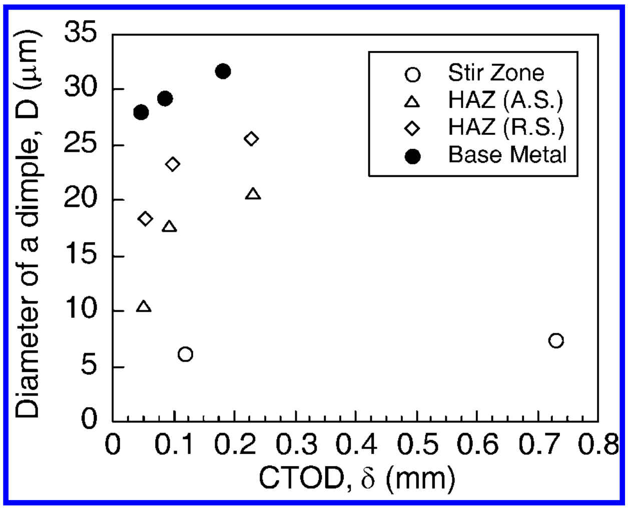
9 Configuration of three point bending specimen for ductile crack initiation/propagation test



10 Temperature dependences of critical CTOD values in base metal, stir zone and heat affected zone of FSW joint

The configuration of the three point bending specimen for the ductile crack initiation and propagation test is shown in Fig. 9. First, the critical CTOD in each position in Fig. 5 is measured in the same way as in the Charpy impact energy test. Figure 10 shows the temperature dependences of critical CTOD values in the base metal, stir zone and heat affected zone of the advancing and retreating sides of the friction stir welded joint. The critical CTOD in the stir zone is much higher than that in the base metal and heat affected zone. This is the same tendency observed in the Charpy impact test.

Fracture resistance curves are measured by three point bending of the specimen in the crack propagation and

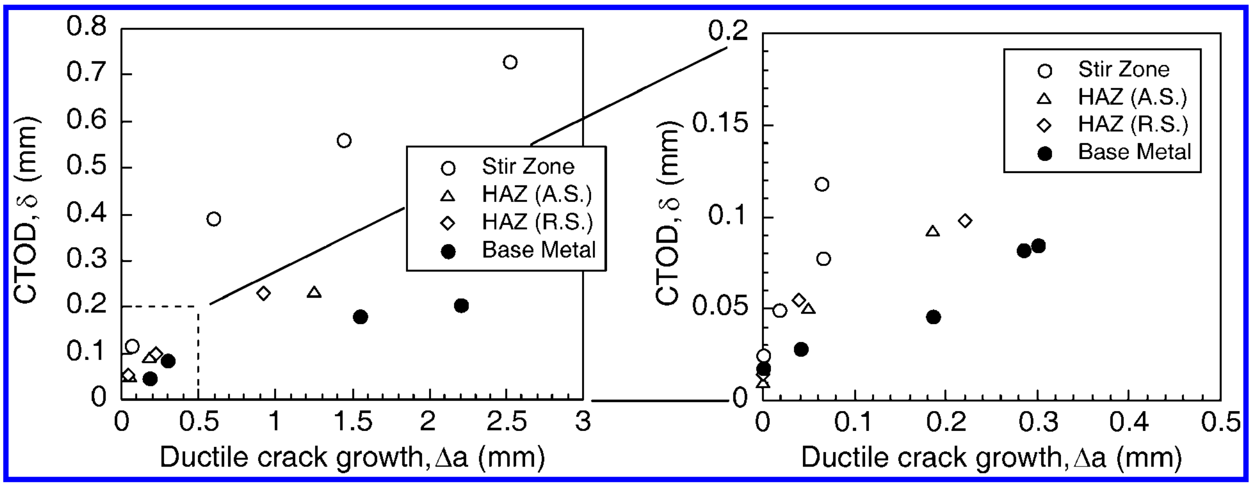


12 Relation between CTOD and diameter of dimples by three point bending tests

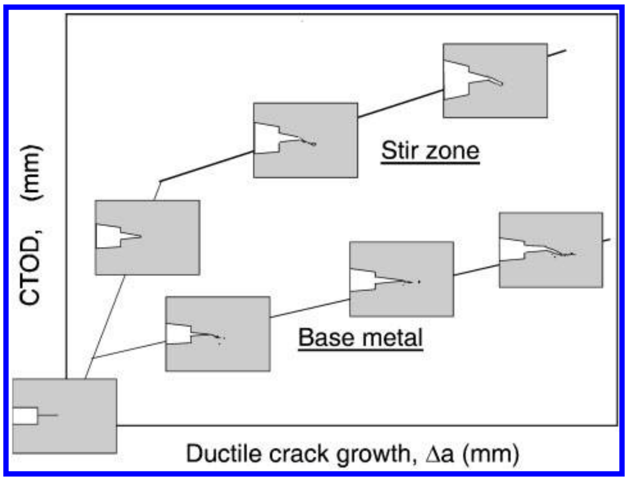
unloading test. Figure 11 shows a comparison of the fracture resistance curves in the base metal, heat affected zone and stir zone of the friction stir welded joint. The tensile strength level between the base metal and stir zone is nearly equal, but the ductile crack propagation resistance in the stir zone is larger than that in the base metal. The difference of crack propagating resistance occurs from the crack initiation point.

The fracture surface is observed and the diameters of dimples are measured. The average diameter of the dimples in the fracture surface and CTOD values are compared in Fig. 12. The diameters of the dimples in the stir zone are originally small and do not grow steeply, even as the deformation proceeds. The voids generated from inclusions in the stir zone do not become as large as in the base metal and heat affected zone, because the inclusions in the stir zone are milled and dispersed in stirred process.

Figure 13 shows a schematic illustration of the mechanism of ductile crack initiation and propagation in the three point bending specimen. This figure is based on the results of the observation of the cross-section after unloading tests. The coalescence of voids is dominant in the base metal, and hebetation of the crack tip occurs in the stir zone. It is considered that these differences in the mechanism of crack initiation and



11 Comparison of fracture resistance curve in each part of friction stir welded joint by three point bending tests



13 Mechanism of ductile crack initiation and propagation in three point bending specimen

propagation owing to microstructural morphology should advance the characteristics of fracture toughness.

Summary

The fracture toughness in a friction stir welded joint of thick plates of structural aluminium alloy type A5083-O is investigated. The Charpy impact energy and critical CTOD in the friction stir weld are much higher than those in the base metal or heat affected zone, whereas mechanical properties such as the stress–strain curve and Vickers hardness do not show a conspicuous difference. The effects of the microstructure on crack initiation and propagation are studied in order to clarify the difference in fracture toughness between the stir zone and base metal. The fracture resistance curves and the diameters of dimples in the fracture surface obtained from both the tensile and bending tests show that the fine grained microstructure in the stir zone helps to increase ductile crack initiation and propagation resistance. High fracture toughness is due to the property of high ductile crack propagation resistance.

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