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Asymmetric mechanical properties and tensile behaviour prediction of aluminium alloy 5083 friction stir welding joints

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ABSTRACT

The asymmetric material flow, severe plastic deformation and thermal cycle imposed on the base material during friction stir welding (FSW) result in unique microstructural development, which causes a gradient in local mechanical properties in the weld region. Micro-tensile and indentation testing were applied to determine the local mechanical properties in a friction stir welded joint. The local stress–strain curves exhibited a drastic change at the advancing side (AS) due to a steep gradient of mechanical properties. Finite Element Model (FEM) predictions of the tensile performance of the welded joints, based on the local mechanical properties measured by micro-tensile testing, were in very good agreement with the macro-tensile test data.

1. Introduction

In conventional welding processes that employ inert or active shielding gas, e.g., Gas Metal Arc Welding (GMAW), the microstructural and mechanical properties of both sides of a weld are symmetric, as observed in the case of a butt joint. This symmetry exists because the temperature field is identically mirrored when similar metals are welded; the temperature field is the main factor that affects the microstructural and mechanical properties of the heat affected zone (HAZ). Friction stir welding (FSW) is a solid-state welding method, which was developed less than 20 years ago. During FSW, the base metal is severely deformed and heated by a rotating tool with a pin. The pin stirs the plasticised material, and the weld joint is formed by the plastic deformation of the softened metal. The simultaneous rotation and transverse motion of the pin creates asymmetry between the two sides of the weld. The pin rotation and welding direction are the same on the advancing side (AS) and are opposite on the retreating side (RS) of the weld. The asymmetry of the welded joint is a unique characteristic of the FSW method.

The micro- and macrostructure of aluminium alloy FSW joints have been investigated by many researchers [1–4]. Traditional tensile specimens are often used to describe the mechanical properties of FSW joints [3,5–7]. The specimens are usually machined perpendicular to the weld line, and each specimen covers the base metal, the HAZ, the thermo-mechanically affected zone (TMAZ) and the stir zone (SZ) regions. Therefore, the macro-tensile testing results describe the complex structural response that results from the interplay among all of these regions. Thus, it is hard to investigate the asymmetric mechanical properties of a FSW joint with conventional macro-tensile specimens. Some studies have examined the microstructural asymmetry of FSW joints [5,8,9]. Due to their dissimilar heat inputs, the temperature fields measured on the RS and the AS are different [10]. However, as the local mechanical properties across the FSW joint are not easily measured, the asymmetry at the RS and the AS, especially the mechanical properties of the two sides, have not been fully investigated, which is the main subject of this work. Although the local strain in a FSW joint can be measured using the electronic speckle pattern interferometer technique [11], the local stress distribution due to the inhomogeneous deformation of the macro tensile specimen must be measured to determine its local mechanical properties.

The 5083 aluminium alloy is a light metal alloy that has a high degree of corrosion resistance combined with an excellent balance of mechanical properties. Therefore, it is widely used as a structural material in transportation applications. In this study, a micro-tensile method was applied to evaluate the spatial dependence of the mechanical properties of an Al 5083 FSW joint in detail. Stress–strain data from indentation experiments were taken from previous work for comparison [12]. Residual stress will not significantly affect the micro-tensile results considering

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the size of the micro-tensile specimens and the manufacturing method used to produce them [12]. The asymmetry of microstructural and mechanical properties between the AS and the RS of the Al 5083 FSW joint were investigated and discussed. A Finite Element Model (FEM) was then carried out to evaluate its predictive capabilities for each approach used to measure the local mechanical properties.

2. Experimental procedures

2.1. Production of welded samples

The base material consisted of a cold rolled H-temper Al 5083 aluminium alloy (Al-4.5 Mg–0.6 Mn) plate that measured 120 mm in width, 400 mm in length, and 3 mm in thickness. Friction stir butt welds were made using a tool with a 12 mm concave shoulder and a 5 mm conical pin. The welds were produced with a rotational speed, welding speed and axial force of 1800 RPM, 1000 mm/min and 9.5 kN, respectively.

Two samples were cut perpendicular to the welding direction. One of these samples was used for metallographic analysis and hardness testing. The specimens were mounted, polished and etched for 75–90 s in Barker's reagent. The etched surface of the sample containing the FSW joint was observed in an optical microscope, and the hardness testing was conducted along the transverse section of the welded joint in a Shimadzu HMV-2000.

2.2. Micro- and macro-tensile testing

The local changes in the mechanical properties across the welded joint were determined by micro-tensile testing. To obtain micro-tensile specimens, a rectangular section of the welded plate was sliced into many specimens using spark erosion. The dimensions and orientation of the micro-tensile specimen are illustrated schematically in Fig. 1. 51 micro-tensile specimens were produced that spanned approximately 15 mm on each side of the weld centreline. Micro-tensile testing was carried out on a Zwick/Z005 tensile machine with a strain rate of 0.2 mm/min.

The micro-tensile specimens were extracted from the base material, the HAZ, the TMAZ and the SZ. The AS and the RS of the joint were sampled separately (Fig. 1, bottom). The thickness of each micro-tensile specimen was approximately 0.4 mm. The width in the gauge section and the total length were approximately 1.4 mm and 25 mm, respectively. The micro-tensile specimens were tested using a specially designed fixture that ensured the correct application of the load and prevented secondary bending and other unwanted movement of the specimens (Fig. 2). Before testing, the surfaces of the specimens were marked with white lines to allow for the measurement of strain using a laser beam scanning apparatus.

The macro-tensile testing was carried out on a conventional tensile test machine. The thickness of the specimen was 3 mm (the same as the original thickness of the weld plate). The specimen was cut from a weld plate that was 25 mm in width and 240 mm in length. The FSW line was placed on the middle of the specimen, perpendicular to the tensile loading direction (Fig. 1, top).

2.3. Indentation test

The indentation testing was performed using a Zwick test machine ZHU 0.2/Z2.5 that was equipped with a hardness measurement head and a fully automated X/Y table. A diamond Rockwell indenter with a spherical tip of radius $R=200\ \mu m$ was installed and used for all indentation tests. All tests were performed under load-controlled conditions in an air-conditioned room at a temperature of 21 °C.

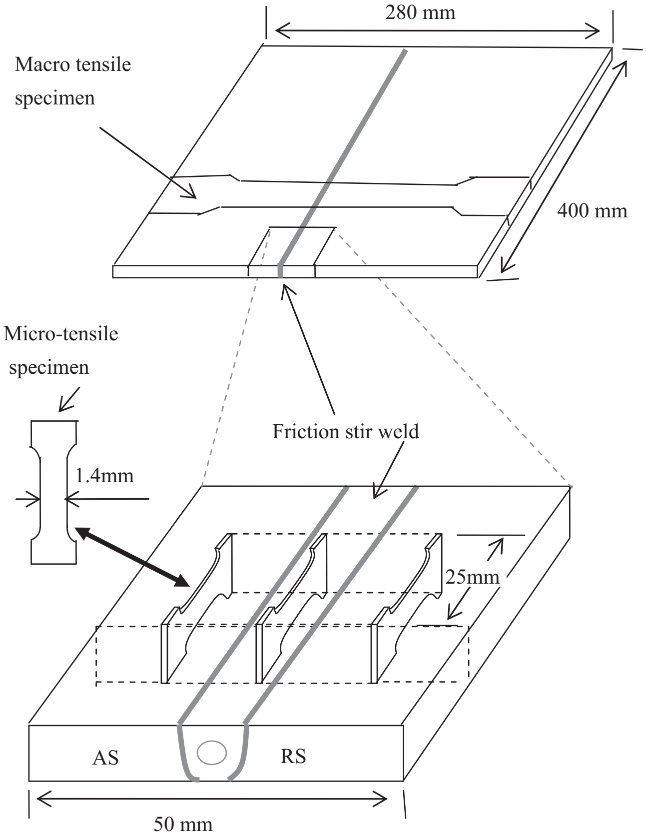

Fig. 1. Position and orientation of micro-tensile specimens.

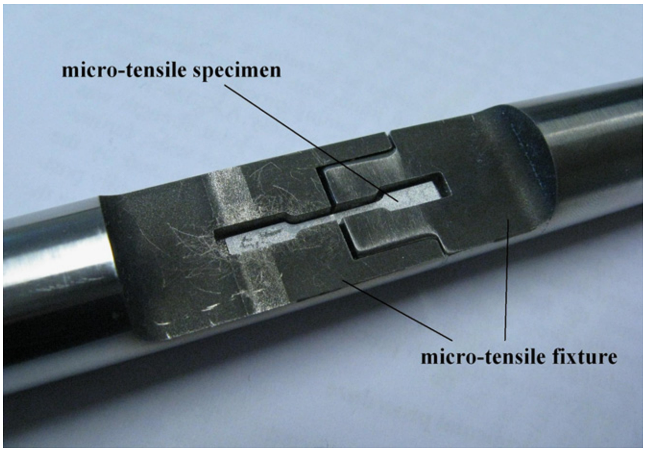

Fig. 2. Micro tensile specimen and test fixture.

The indentation approach used in this work has been published in detail in [12] and will be summarised here. The analysis of the indentation data provides a stress–strain curve for each individual indent, similar to a micro-tensile analysis. Indentation testing and Artificial Neural Network (ANN) analysis require only a well-polished surface, and they can be considered almost non-destructive compared to micro-tensile testing. With a spherical indenter, a hemispherical volume of material is tested locally under compression loading, producing a large hydrostatic pressure. Therefore, material failure does not occur; elongation to failure cannot be determined from an indentation test.