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Energy absorption of friction stir welded 1050 aluminum sheets through wedge tearing

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ABSTRACT

In this research, 1050 aluminum alloy sheets were welded through Friction Stir Welding technique at different rotational speeds (ω) and advance rates (V) in order to investigate the effects of welding parameters on the energy absorption. Wedge tearing test was then conducted on the specimens in two directions of 0 and 90 degrees relative to the weld line. Energy absorption was revealed to be much higher in the welded specimens in comparison with the non-welded sheets. This increase in the amount of absorbed energy is due to the fine equiaxed grain structure formed in the stir zone of the weld which increases the strength. It was also concluded that when movement of the wedge is parallel to the weld line (i.e. through the weld metal), the amount of energy absorption is considerably higher than when the wedge moves perpendicular to the weld line. The energy absorption increases with decreasing the ω^2/V. This is attributed to the changes of grain size in the stir zone with heat input. It was also observed that the maximum energy absorption in parallel direction to the weld line, for all advance rates, belongs to the specimens welded at the rotational speed of 600 rpm.

1. Introduction

One of the underlying issues in the structures and especially in the body of structures is their amount of energy absorption in collision with objects, obstacles or other bodies. High capacity of energy absorption is crucial for decreasing losses in human and material resources.

In collisions, metal components of the structures undergo a high amount of deformation and fail in variety of crumpling, folding or tearing processes [1,2], depending on the type of the colliding object. Tearing happens when an acute rigid body collides with the structure. For investigating the sheets tearing process in collisions, wedge tearing test is developed, in which a rigid wedge penetrates and cuts into a sheet. This process is in fact an idealized and simplified model of striking structures with obstacles and collision damage as in ship groundings [1,3]. Fig. 1 shows schematic of tearing by a wedge and related parameters.

Many researchers have used this method for understanding the tearing phenomenon in metal sheets and have developed empirical or mathematical formula to predict the amount of energy absorption [1,3–7]. Based on the attempts accomplished, researchers reported that three mechanisms contribute to the energy absorption in tearing process as follows; 1) near tip energy dissipation resulting from cutting or membrane stretching, 2) far field energy dissipation resulting from bending of flaps behind the wedge (Fig. 1), and 3) friction between wedge and sheet [3,6–8].

Some researchers [1,4] reported that yield stress plays the major role in energy absorption of metal sheets during wedge tearing. Some other researchers [3,5] proposed the flow stress as the most effective mechanical property of the material in energy absorption. In addition, Zhang [3] included fracture strain of the sheet as another parameter affecting the energy absorption with less impact than that of the flow stress.

Other parameters affecting the energy absorption during wedge tearing are as follows; material thickness, length of cut, wedge angle, sheet angle relative to wedge and friction coefficient between wedge and sheet.

Although, energy absorption during tearing process of sheets/plates has been well analyzed, this phenomenon has not yet been fully studied for welded sheets. Apart from the research in which Beygi et al. [8,9] investigated the energy absorption of cold roll welded Al-steel bilayers, no other attempt has been made on welded sheets.

Lots of difficulties are associated with fusion welding processes of aluminum and its alloys [10,11]. Among all solid state welding processes, Friction Stir Welding (FSW) is an appropriate process for joining Al alloys since it provides the fine grained microstructure and desirable mechanical properties [10,11].

Aluminum alloy sheets joined by friction stir welding have numerous applications in construction of metal structures and their bodies. Since the welding process affects properties of the material, the absorbed energy is also affected. Thus, studying the energy absorption of Al alloy sheets welded by FSW process is of great importance.

As parameters of the friction stir welding such as rotational speed and advance rate control the properties of the weld and its surroundings, variation of these parameters may also change the energy

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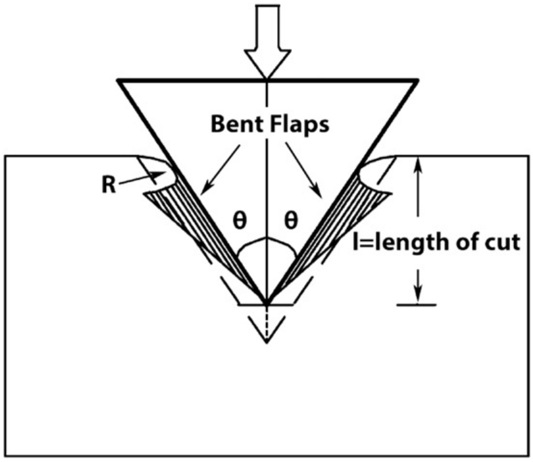

Fig. 1. Schematic of sheet tearing by a wedge [3].

absorption and should be studied. In the present study, two 1050 aluminum alloy sheets are friction stir welded at different rotational speeds and advance rates to investigate the effect of the two welding parameters on the energy absorption in wedge tearing test. Wedge tests are carried out in two directions of 0° and 90° relative to the weld line.

2. Experimental procedure

In this research, 3 mm thick rolled AA1050 sheets of 99.6% purity were used. The aluminum sheets were annealed for 3 h at 350 °C and then cooled in the air. The sheets were then friction stir welded using the parameters shown in Table 1. Schematic of the FSW process and position of specimens in fixture are also illustrated in Fig. 2. The FSW tool used had a 12 mm diameter shoulder and an unthreaded pin with 2.7 mm length and 3 mm diameter. During the welding process, the angle of tool tilt with respect to the workpiece surface was kept constant at 2.5°.

Eventually, quasi-static wedge tearing test was conducted on both welded and non-welded specimens. In the test, a wedge penetrated into the sheets at a constant speed. The sheets to be tested were fixed into a fixture inclined relative to vertical at a constant angle. The reason for not holding the sheets in a vertical position was due to the flaps to be bent in one side of the sheet and thus, making the investigation of the energy absorption easier. Testing setup is shown in Fig. 3(a). Schematic of the test and test parameters including dimensions of the wedge and inclined angle of the sheet relative to vertical ($\alpha = 10°$) are illustrated in Fig. 3(b) and (c). The wedge tearing test was implemented on welded specimens in two directions relative to the weld line i.e. parallel with the weld line (x-direction) that the wedge moved through the weld (Fig. 3(b)) and perpendicular to the weld line (y-direction) (Fig. 3(c)). Fig. 3(d) shows the length of cut and bent flaps formed during the real wedge tearing test. Displacement speed of the wedge was considered to be 30 mm/min during the experiment. At the end of the test, a load–displacement curve was obtained. The area under the curve is calculated as the energy absorption of specimens.

Table 1
Parameters selected for FSW process.

Specimen code	Advance rate (mm/min)	Rotational speed (rpm)
ωV605	50	600
ωV6010	100	600
ωV6015	150	600
ωV905	50	900
ωV9010	100	900
ωV9015	150	900
ωV1205	50	1200
ωV12010	100	1200
ωV12015	150	1200

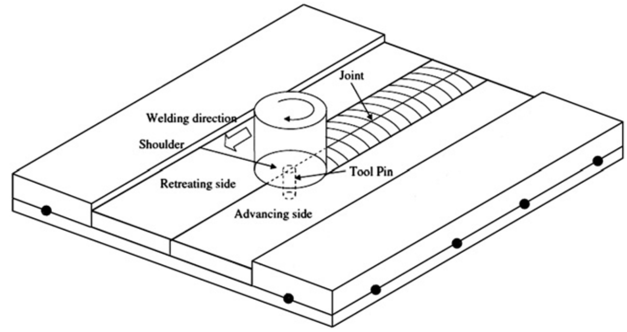

Fig. 2. Schematic view of specimens in fixture during welding process.

Tensile properties of the welded and non-welded metal sheets were also measured to analyze the energy absorption test results in the wedge tearing test. For studying tensile properties of welded sheets, tensile test specimens were prepared from two locations as shown in Fig. 4. For the transverse specimens, the stir zone was located in the center of guage length. Tensile specimens were machined according to the ASTM E8M standard. Tensile tests were carried out at room temperature in a machine operating at speed of 2 mm/min. Also, Vickers hardness of the base metal and stir zones of the welded specimens were measured using a load of 5 kg for 40 s. The reported hardness values are the average of five measurements.

For microstructural observations, the transverse cross section of the specimens were polished and electroetched using $HBF_4(4\%) + HF(0.5\%)$ solution at potential difference of 40 V for 180 s. Microstructures of the weld and base metal were then investigated by utilizing optical microscope.

3. Results and discussion

3.1. Microstructure

As the microstructure determines the strength and other mechanical properties of the material, and the energy absorption is remarkably dependent on these properties, investigation of the microstructure is needed here.

The base metal has equiaxed grains with mean size of 50 μm after annealing. Microstructure of the annealed specimen is shown in Fig. 5.

After friction stir welding, the microstructure of the specimens was studied in the weld zone. Fig. 6 shows the microstructure in the center of stir zone for welded specimens at different welding conditions.

Fine equiaxed grains can be seen in the stir zone from Fig. 6. Studies of other researchers confirm the existence of fine equiaxed grains in this zone [12–16]. This is due to a significant plastic strain imposed to the material in the stir zone during welding, and temperature increase due to friction between the tool and the specimen, which lead to the occurrence of a continuous dynamic recrystallization [12–15,17,18]. Average grain size in the stir zones is measured and the results are presented in Table 2.

As can be inferred from Fig. 6 and Table 2, increasing the rotational speed at a constant advance rate increases the size of grains in the stir zone. This is often attributed to the greater heat input generated with increasing the rotational speed of the tool. Therefore, the grains experience a further growth after recrystallization. Reduction of the advance rate increases the heat input. Thus, reduction of the advance rate leads to increase in the grain size of the stir zone which is clearly seen in Fig. 6 and Table 2. This trend (reduction of the grain size with increasing the advance rate) has been reported by many other researchers, Buffa et al. [19] and Sakthivell et al. [16]. Looking at Fig. 6 and Table 2 implies that the effect of advance rate on variations of the grain size is more significant at lower rates. This is in consistent with Buffa et al. [19] reports.