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Comparison of residual stress distributions in conventional and stationary shoulder high-strength aluminum alloy friction stir welds

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ABSTRACT

The residual stresses generated in stationary shoulder friction stir welds (SSFSWs) produced in a typical high strength aluminum alloy (AA7010) in 6.3 mm thick plate has been mapped over full weld cross sections, using the contour method, and compared to those introduced by conventional friction stir welding (FSW) for welding speeds ranging from 100 to 400 mm/min. Compared to in conventional FSW, as a consequence of the material flow being affected by only a rotating probe, the SSFSW process produced a narrower and more uniform weld nugget and heat affected zone profile through the plate thickness. For both processes, 'M' shaped residual stress distributions were determined. However, the peak stresses measured in the SSFSWs were slightly lower than those found in the conventional FSWs and the width of the tensile region was appreciably reduced when using a stationary shoulder welding tool. This is shown to be resulting from a more focused temperature distribution obtained from using only a rotating probe to generate heat in the SSFSW process. In both processes, increasing the welding speed led to a narrower residual stress profile, but higher peak tensile residual stresses.

1. Introduction

Friction stir welding (FSW) was invented by Wayne Thomas at the TWI in 1991 (Thomas, 1991). As discussed in a comprehensive reviews by Threadgill et al. (2009) and Mishra and Mahoney (2007), FSW has since attracted considerable interest for joining aluminum alloys, because it produces welds with excellent mechanical properties and avoids important detrimental issues normally found with fusion processes, such as solidification and liquation cracking. However research, for example by Long et al. (2007), has shown that the peak weld zone temperatures still reach close to the material's incipient melting point and as a result significant residual stresses and distortion can still be generated despite the solid-state nature of this welding process.

With the conventional FSW it is customary to employ a tool with a conjoined conical probe and a wider diameter shoulder that both rotate at the same rate. The function of the shoulder has been discussed by Threadgill et al. (2009) and is to constrain the plasticized material from escaping from the cavity produced by the pin as the tool translates. In the FSW community there is a general consensus (see for example work by Neto and Neto, 2013) that more heat is generated by the rotating shoulder than the probe, owing to its higher relative surface velocity, and this energy is conducted into the workpiece from the deformation zone under the shoulder, where the tool couples with the top surface of the plate. Because a significant downforce is normally employed on the tool, this accentuates the generation of heat at the top surface by the shoulder, which can be as high as 70–80% of the total welding power, although the ratio of power dissipation between the shoulder and probe depends on the probe length and contact conditions between the tool and work piece surface (Threadgill et al., 2009). As reported by Long et al. (2007) friction stir weld zones thus tend to be wider at the top surface of a joint and significant through-thickness temperature gradients have been observed by, for example Hassan et al. (2003), to cause associated microstructure and property gradients. Threadgill et al. (2009) have also reported that the use of a rotating shoulder constrains the weld geometries that can be joined and can generate flash as well as a poor surface finish.

More recently a variant of the conventional friction stir welding technique has been proposed by Russell (2008) that involves a tool design with a non-rotating shoulder. In this modification to the original welding method the shoulder contains a bearing housing through which the pin rotates, so that it remains 'stationary' relative to the pin and only slides across the workpiece surface as the tool is translated. As has subsequently been shown by Wu et al. (2015), with this tool configuration the sliding shoulder

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contributes little to heat generation and virtually all the welding energy is dissipated as plastic work from the interaction of the rotating pin with the workpiece. Davies et al. (2011) were one of the first groups to report employing a stationary shoulder tool for FSW. In their work the technique was applied to joining titanium alloys because their low conductivity makes it difficult to produce welds in thicker sections with a conventional FSW process without overheating the workpiece surface. They showed that when using stationary shoulder friction stir welding (SSFSW) to join Ti6Al4V, a more homogeneous through-thickness microstructure could be obtained.

To date comparatively little has been published on SSFSW of aluminum alloys. However, Wu et al. (2015) and Avettand-Fènoël and Taillard (2016) have recently reported several advantages of applying the SSFSW technique to welding aluminum; including a narrower and more uniform through-thickness thermomechanical affected zone (TMAZ) and heat affected zone (HAZ), superior joint mechanical properties, and a much improved surface finish. Wu et al. (2015) has also shown that welds can be produced with lower power by SSFSW because it is more efficient to generate heat through-thickness with just the probe, than when it is also conducted into the weld from the near the top surface by the action of the shoulder. Because the diameter of the probe is much smaller than the shoulder, the work of Wu et al. (2015) have also found that with the tool dimensions they used, a higher tool rotation rate was needed with the SSFSW process to generate sufficient heat to prevent probe failures. However, despite an overall difference in the welding power, the peak weld temperatures were found to be of a similar magnitude in both processes.

As has been discussed in the review by Withers (2007), large tensile residual stresses can be produced during welding processes which are of particular concern in aerospace applications because they can lead to premature fatigue failure. Richards et al. (2010) and Altenkirch et al. (2008), have investigated residual stresses in friction stir welds with high-strength aluminum alloys. They have typically found an 'M' shaped longitudinal stress distribution, where the peak tensile residual stresses are located near the HAZ and weld nugget zone (WNZ) boundary in the region below the edge of the shoulder and reach about 50% of the material's room temperature yield stress. The origin of this characteristic 'M' shaped residual stress profile has been attributed by Richards et al. (2008b) to the diffuse nature of the thermal field seen in FSW relative to other welding processes, combined with the high level of softening that occurs with high-strength aluminum alloys at elevated temperatures. In addition, both Lombard et al. (2009) and Peel et al. (2003) have found that in FSW, the peak tensile residual stresses rise with increasing travel speed and this is the dominant welding parameter that determines the level of maximum residual stress. Finally, several methods have been found to be effective for reducing the residual stresses in FSW including the application of mechanical tensioning, or local cooling, by Richards et al. (2008a) and (2010) and post weld seam rolling by Huang et al. (2013).

Although residual stresses are an important issue in FSW, particularly when aerospace applications are considered, currently the distribution arising from stationary shoulder welding has not been reported. Of particular interest, in this context, is whether the narrower weld zone and lower power input possible with the SSFSW process leads to a reduction in the peak tensile residual stresses. Before applying this new welding technique commercially it is also essential to understand how the welding parameters influence the residual stress distribution. To this end, in this paper the residual stresses generated by conventional FSW and SSFSW have been directly compared for both processes using welding tools with the same overall geometries, in welds produced with a typical high strength aluminum aerospace alloy (AA7010). The aim of this study was to explore the extreme bounds in residual stress distributions obtained between welding with conventional FSW having the maximum possible shoulder heat input and virtually no shoulder heat generation, and that with a stationary shoulder tool. A relatively high down force was thus employed to produce the FSW baseline welds which, as discussed by Upadhyay and Reynolds (2012), maximizes coupling between the workpiece and the shoulder. The welding conditions selected were based on a previous study by Wu et al. (2015), who adopted a systematic approach to finding equivalent welding parameters that could be used to directly compare the two methods. This was achieved by evaluating their torque rotation rate decay curves to find the region of minimum welding power for each process. The welds' macrostructures, hardness distributions, and thermal histories have also been characterized to assist in interpretation of the residual stresses developed in each process variant.

The residual stress measurements have been made using the contour method. This technique has recently been reviewed by Prime and DeWald (2013) and has certain advantages compared to diffraction based methods, such as synchrotron X-ray and neutron diffraction. For example, it is more cost-effective and there is no requirement to measure the 'd_0' unstrained lattice parameter, which in aluminum aerospace alloys is strongly affected by variation in the local matrix solute content within the weld zone. As discussed by Prime et al. (2006) the contour method also allows 2D residual stress maps to be determined across full weld cross-sections, which is particularly useful when evaluating the effect of a stationary shoulder on the residual stress distribution in FSWs.

2. Experimental details

2.1. Welding procedure

The geometries of the FSW and SSFSW tools manufactured for the welding trials were as comparable as possible. Both tools are shown in Fig. 1 and had a shoulder diameter of 18 mm and a 5.9 mm long conical threaded tri-flat pin, with root and tip diameters of 6.2 mm and 4 mm. However, as is standard practice (for example see Mishra and Mahoney, 2007) to reduce material loss the FSW tool had a slightly concave shoulder and the FSW welds were produced with a 2.5° tilt. In contrast, no tilt was used with the SSFSW tool and the shoulder had a slightly convex surface to allow it to slide more easily across the plate. FSW welding was performed in position control with a plunge depth of 0.2 mm to ensure maximum coupling between the shoulder and material. This approach was used to minimize slip under the tool shoulder and thus produce welds under conditions which represent the largest possible shoulder heat generation, and maximum difference between the two processes. In contrast SSFSW was carried out with a constant downforce of 30 kN and the tool did not sink appreciably into the colder plate surface. Full details of the processing conditions can be found in Wu et al., 2015.

The alloy used in the experiments was a 6.3 mm thick, hot rolled plate of AA7010-T7651 (nominal composition in Table 1) which was machined into 126 mm × 300 mm coupons. Welds were produced in a bead-on-plate configuration down the center line of each plate. The full matrix of welding conditions used in the trials is summarized in Table 2. The difference in rotation speeds between the rotating and stationary shoulder FSW was necessary to ensure that sufficient heat was generated with the stationary shoulder tool to avoid tool failure (see Wu et al., 2015). However, it is evident from Table 2 that the energies determined from torque measurements delivered to the weld were comparable between the two methods. For the baseline FSW welds, only the travel speed was varied because, as pointed out by Lombard et al. (2009), this is known to be the most important parameter influencing peak stresses.