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Gap tolerance allowance and robotic operational window for friction stir butt welding of AA6061

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ABSTRACT

In this work, it was determined that with increasing weld pitch, the occurrence of a "lazy S" defect in the weld nugget of friction stir welded (FSWed) AA6061 became increasingly pronounced, though its impact on the bend performance of the weld was negligible. For a fixed weld pitch of 0.48, the effect of gap, i.e. the spacing between two sheets at the butt joint interface, on the joint quality of AA6061 was evaluated in terms of the welding defects, microstructure, hardness and bend performance. Fully penetrated welds without metallurgical defects such as wormholes were obtained up to a joint gap of 0.5 mm. Though the overall microhardness and bend performance of the welds remained unaffected until a joint gap of 0.8 mm, the decrease in the forge force during FSW beyond a joint gap value of 0.5 mm may represent a more critical limit in regards to the industrial application of the process; this is especially important when applying force control during processing to ensure a constant shoulder penetration in the material for addressing practical considerations, such as thickness variations in the assembly, clamping distortions and tool wear. Based on these results and using force amplitudes recorded during the welding experiments, a robotic scenario was synthesized with an appropriate operational window for continuous-path friction stir butt welding (FSBW) of 3.18-mm-thick sheets clamped to a 1 m × 1 m horizontal welding table. An appropriate industrial robot model was selected and the associated geometric workcell layout was developed for this application. This scenario was implemented in a physical prototype and used to successfully produce 1-m-long FSWed assemblies that exhibited good tensile mechanical performance.

1. Introduction

FSW is a solid-state thermo-mechanical joining process (a combination of extruding and forging), invented by The Welding Institute (TWI) in 1991, that has become a viable manufacturing technology for the structural assembly of metallic sheet and plate materials for applications in various industries, including aerospace, automobile, defence and shipbuilding. The process is recognized as a cost-effective joining technique for high strength aluminum alloys with low weldability, such as crack sensitive grades of the 2XXX (Cavaliere et al., 2005), 6XXX (Cavaliere et al., 2008) and 7XXX series (Azimzadegan and Serajzadeh, 2010). As the process utilizes low energy and achieves solid-state joining, consumables commonly required for conventional fusion welding of aluminum alloys, such as filler wire to adjust the chemistry of the weldment (lower crack sensitivity) and shielding gases to protect the molten weld pool, are not needed in FSW (Khalid Rafi et al., 2010). According to Arbegast (2007), additional inherent advantages of the process include low tendency for the formation of oxides, porosities and cracks (due to absence of liquid phase formation), as well as low shrinkage, residual stresses and distortion (due to low energy input). Moreover, the process has the flexibility to join extruded and rolled materials without requiring complicated surface preparation.

Though ideally material preparation prior to FSW is targeted to ensure good fit-up, realistically, certain manufacturing processes, e.g. extrusion, impart dimensional variations that must be accommodated for the application of FSW in a production environment. In FSW, the introduction of a gap at the interface has a propensity to cause the escape of the plastic material from the process zone, which can lead to a reduction in the effective cross-sectional area of the weld (Yang et al., 2008). Thus from the perspective of FSW being an automated and autogenous process, delimiting the gap tolerance is of importance to ensure the weld integrity and performance so as to manufacture cost-effectively by employing a reduced intensity of skilled laborers and minimal edge preparation for geometrical fit up of the abutting surfaces. Though the effect of various operating parameters on the microstructural characteristics and mechanical performance of FSWed aluminum alloys have been widely considered, as reviewed by Mishra and Ma (2005) and

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Nandan et al. (2008), understanding of the practical gap tolerance for FSW is relatively limited. Shultz et al. (2010) showed that the maximum attainable joint efficiency decreases with increasing gap width. Takahara et al. (2006) investigated the allowance of deviation and gap for butt welding of 3-mm-thick AA5083-O plates and found that gap spacing within 2 mm did not affect the tensile properties of their welds. Also, Yang et al. (2008) used power spectral density of the delta plunge force to detect the presence of a gap during FSBW of AA2024. In this work, the joint gap tolerance for FSBW of 3.18-mm-thick AA6061 was studied concomitantly with process parameter optimization with a view toward targeting industrialization of the process using low-cost serial industrial robots. Recent investigations have demonstrated, indeed, that heavy payload serial industrial robots offer promising characteristics in terms of payload, workspace and 3-dimensional capabilities for a much lower industrialization cost of the FSW process. Smith and Hinrichs (2006) were able to achieve friction stir welds in AA6061-T6 with penetrations up to 1 inch using standard industrial robots. Voellner et al. (2006) highlighted the capability of a modified high payload KUKA KR500 industrial serial robot for 3-dimensional seam geometries by performing circular bead-on-plate welds in different welding positions as well as on a convex–concave clamping device. Soron and Kalaykov (2006) also proved that 2- and 3-dimensional FSW were feasible using a modified industrial serial robot, although the lack of stiffness and low payload capabilities limit both the welding speed, plate thickness and material that can be welded. While Zimmer and Laye (2009) recommended the use of a seam tracking system to compensate for robot deflection due the limited robot stiffness during FSW, Monsarrat et al. (2009) used model-based real-time compensation of tool deviations to allow the robotic motion to be analogous to that of a rigid FSW CNC machine. Challenges exist, however, when designing the robotic scenario to ensure that the robotic operational window is compatible with the process conditions deliberated for the weld properties. A methodology is presented in this paper to address that problem in the case of a planar test-case. This is of particular relevance as this planar welding configuration is encountered in a majority of the industrial butt and lap FSW applications.

2. Experimental procedure

AA6061 in the T6 condition (solution heat treated at 540 °C for 1 h and artificially aged at about 160 °C for 18 h) was received in sheet form with a nominal thickness of 3.18 mm and a chemical composition of 0.95 wt.% Mg, 0.61 wt.% Si, 0.32 wt.% Cu, 0.30 wt.% Fe, 0.15 wt.% Cr, 0.06 wt.% Mn and the balance Al. The average Vickers microhardness of the AA6061-T6 was 100 ± 4 HV. FSBW of AA6061-T6 sheets was performed using coupons 400 mm long × 100 mm wide using a MTS I-STIR FSW machine. Prior to joining, the edges to be welded were milled and prepared for welding by degreasing the joint surfaces with ethanol, followed by grinding with a scouring pad to remove the surface oxides, and final cleaning with ethanol to remove any surface debris according to ISO standard TR 17671-7. The welding trials were conducted in the direction perpendicular to the rolling direction of the material using a tool with a shoulder diameter of 13 mm with a threaded pin having a diameter of 5 mm. To optimize the process, the weld pitch, or ratio of the advancing speed to the spindle rotation, was initially varied from 0.1 to 1.0 mm/rev. In this work, the advancing speed was varied from 1 to 18 mm/s and the rotational speed from 500 to 2000 rpm. Then at a fixed weld pitch of 0.48 mm/rev, the joint gap was varied from 0 (no gap) to 2 mm.

After welding, the samples were sectioned transverse to the weld and prepared for microscopic examination. The general microstructure of the welds was revealed using Kellers reagent and the grain structure was revealed by electrolytic etching at room temperature (RT) for 0.5–2 min in an aqueous HBF4 solution (5 g HBF_4 in 200 ml H_2O) with 6 V and an austenitic stainless steel cathode. An optical microscope with image analysis was used to examine the welds and determine the grain size according to ASTM E112. For select specimen conditions, Vickers microhardness profiles across the welds were measured at a 200 g test load and a dwell period of 15 s. For each weld condition, an average hardness profile was determined from three sets of hardness measurements across the joint, i.e. near the top, middle and bottom, which were made with an indent interval of about 0.2 mm. Also, as bend testing effectively concentrates strains locally in the welds, bend performance was used as a qualitative measure to detect the occurrence of cracking. On average four bending tests were performed according to CSA W59.2-M1991 using a bend radius of 5 mm to check the weld integrity of each process condition. For select conditions three tensile specimens having a standard sub-size geometry of 25 mm in gauge length, 6 mm in width and 3.2 mm in thickness

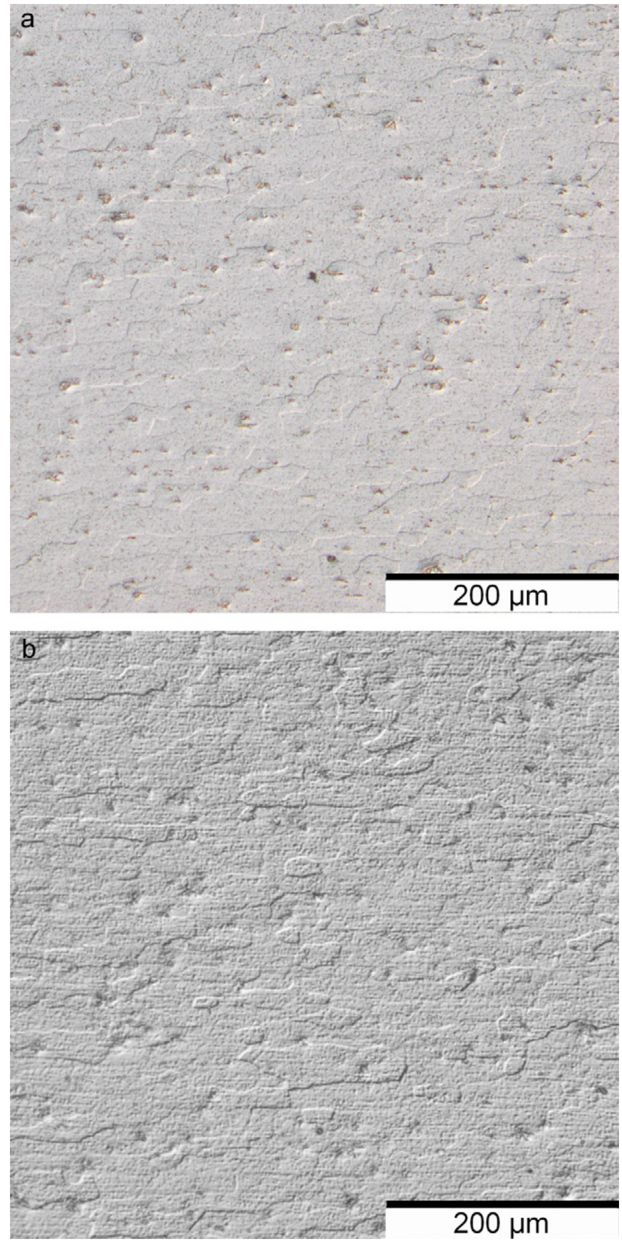

Fig. 1. As-received microstructure of AA6061-T6.