Research Article

Effect of Dwell Time on Fracture Load of Friction Stir Spot Welded Dissimilar Metal Joints

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The dissimilar materials joining in heavy structural fabrication industries is tedious work for welding and design engineers, since the weld region’s criticality is encountered by hot cracking and its associated problems. Moreover, dissimilar materials are joined by mechanical locking such as rivets, bolt and nuts, and screws. Nowadays, the fasteners are eliminated by friction stir welding (FSW). The friction stir spot welding (FSSW) is a variant of FSW; it can be avoided by seam welding. Hence, in this investigation, FSSW is used for joining AA6061 aluminum alloy with mild steel using tool rotation speed, plunge depth and rate, and shoulder to pin diameter ratio. The experimental method observed that the joint fabricated with a rotational speed of 1000 rpm, plunge rate of 5 mm/min, plunge depth of 6 mm/min, and shoulder diameter to pin diameter ration of 3.0 yielded highest fracture load. The optimum heat input could obtain the improvement in FSSW joint strength. Recrystallized grains and favorable intermetallic compound formation are the primary factors for sound welding.

1. Introduction

Friction stir spot welding (FSSW) technology has been successfully utilized to weld aluminium and magnesium alloy used in automotive and aerospace industries. Aluminum alloys have widespread applications in manufacturing aerospace and structural components due to their high strength [1]. The FSSW procedure was employed by Chowdhury et al. [2] which used FSSW on AA5754 and AZ31Balloy. Choi et al. [3] conducted an experiment using a tool constructed of high-strength steel and consisting of shoulder, shank, and probe. The tool had a shoulder, pin, and height which were 13 mm, 9 mm, and 0.5, respectively. Intermetallic compounds were found to develop at the interface of Al/Mg alloy joints. By accelerating the rotational speed of tool and holding time, the formation of the IMC...
layer grew to a certain extent, which had a considerable influence on the joint strengths. The Mg and Al and alloy weld has a maximum fracture load (FL) of around 1.4 kN. When the holding time and tool speed were augmented beyond the extreme limit, the load value fell. Threaded profile pin tool was used by Freney et al. [4] to investigate the influence of tool plunge and depth rate and tool speed on FL of AA5052 and discovered that a low tool speed resulted in a superior weld interface, leading to greater weld strength. Shen et al. [5] deployed HSS tool with concave shape shoulder in AA6061 sheet and found that greater tool speed and shorter dwell time resulted in good joint. Tozaki et al. [6] used a shoulder diameter, plunge rate, and plunge depth of 10 mm, 25 mm/min, and 0.3 mm, respectively, to join 2 mm thick sheets utilizing various-pin profile. In addition, tool speed and dwell time were changed to 2000 rpm, 2500 rpm, and 3000 rpm, respectively, and 0.5 s, 2 s, and 3 s. The microstructure of the weld changed dramatically depending on tool speed, pin length, and dwell time, with shear strength rising as pin dimension rose. Welds on AA6111 and low carbon steel were noted by Chen et al. [7], the orbital path of the probe had a radius of 2.5 mm, resulting in an 8 mm diameter swept area on the steel surface which conceived the peak load. Bozzi et al. [8] used a tungsten tool to join 1.2 mm AA6016 to 2.0 mm galvanized steel and instituted that the IMC surface thicknesses rise with rising tool speed and depth of penetration. Figner et al. [9] used two different thicknesses of AA5754 alloy for FSSW. The result showed that the maximum FL was found as 8.4 kN by an optimal tool speed and dwell time. The thickness of the IMC between two plates was improved as the tool speed and holding time increase [10]. Similarly, Heideman et al. [11] investigated the traces of peak load by changing FSSW parameters.

From the previous work done by researchers, it is concluded that a lot of research has been done on the effect of process parameters on mechanical and metallurgical study. The influence of dwell time on fracture load study is scanty. Hence, an effort has been taken to analyze and study the influence of dwell time on shear fracture load on AA6061 with carbon steel dissimilar materials.

2. Experimental Work

In this investigation, 2 mm thick sheet of AA6061 aluminum alloy and mild steel dissimilar materials were used. The results of chemical and mechanical properties are presented in Tables 1 and 2, respectively. FSSW processes parameter range for dissimilar weld which was fixed based on being free from visual defects (Table 3). The specimens were initially cut as per the dimension given in Figure 1(a), using a power hacksaw machine. Methanol was used to remove the foreign materials and greases. The high-strength steel sheet was fixed as the top sheet, and the low-strength aluminum alloy sheet was set as the bottom sheet in lap joint configuration. The tool used in this work was a nonconsumable tool made of high-strength steel. Figure 1(b) shows the fabricated tool. FSW machine was used to fabricate the FSSW dissimilar materials. Figures 1(c) and 1(d) show the samples prepared for this research work. The joints were cut in a transverse cross-section to record hardness properties and microstructural features at various locations in the nugget zone. The hardness test was carried out in a Vickers hardness measurement tester with a load of 0.05 N and a holding time of 30 sec. Similarly, the microstructural evaluation was carried out after polishing fine-grade sandpaper followed by aluminum oxide. A light optical microscope revealed the microstructure feature at a different location in FSSW joints. A high-resolution SEM was used to display the fracture pattern in the fractured region.

3. Results and Discussion

3.1. Effect of Dwell Time. The dwell duration has a substantial influence on the FL of the joints, according to the tensile test results. The joints FL grow as dwell duration increases from 3 to 7 sec. The joint produced at a dwell duration of 7 sec had the greatest FL of 9.46 kN. The joint created at a dwell duration of 3 sec produced the lowest FL of 8.39 kN. The influence of dwell time on FSSW joints is shown in Table 4. Hook width (HW), hook height (HH), and hook initiation distance (HID) at shoulder to work piece interface were measured from the macrographs and are listed in Table 4. Regardless of process state, rise in HW rises the FL, but an increase in HH lowers the FL. With a few exceptions, the HID at the interface of the weld begins to rise as the FL increases. The maximum FL attained by the joint produced with a dwell time of 7 sec has HH of 0.75 and HW of 1.77 mm, whereas the lowest FL has HW of 2.01 mm and HH of 1.25 mm. Figure 2 shows the hardness profiles for the various dwell periods. The dwell period has a substantial impact on the hardness, as evidenced by the hardness profile. At all dwell durations, the extreme hardness is measured near the keyhole. Regardless of dwell duration, the lowest hardness of the joint is measured at the interface of the less heat input zone (heat affected zone: HAZ) and partially heat input zone (Thermo-mechanically affected zone: TMAZ) regions. The hardness of the nugget zone (NZ) rises when the dwell period is increased from 3 to 5 sec. The joint produced at a dwell period of 5 sec has the greatest NZ hardness of 179 HV. The joint produced with a dwell duration of 3 sec had the lowest NZ hardness of 170 HV.

The optical micrographs of symmetrically sectioned (perpendicular to the rolling direction) joints manufactured using different dwell periods are shown in Figure 3, and it is observed from the micrographs that the dwell time has a considerable influence on the formation of grain at TMAZ, NZ, and HAZ. In all the joints, the NZ exhibited fine and recrystallized grains from coarse and grains by the thermo-mechanical action of tool. Throughout all joints, the grains in the TMAZ were found deformed heavily by the tool shoulder and tool speed and slanted towards in an upward direction. But, the sizes of grains in this region were bigger than the grains in the NZ. On another hand, the grain size at the HAZ was equiaxed, like in the NZ, but greater in size. Regardless of all zones in FSSW, the grain size reduces as dwell time rises. In the NZ of the 5 sec manufactured joint, very tiny grains can be seen. The superior mechanical and metallurgical characteristics of the specimens are mainly due
to their fine grain refinement induced by the rapid solidification process [12]. Variable grain configuration with preferred texture improved the corrosion resistance [13]. The images of the top and bottom surfaces of fractured region are shown in Table 5. The cracked surface of the joint manufactured with dwell times of 3 sec, 6 sec, and 7 sec shows the “nugget debonding” mechanism of failure, according to fracture surface analysis. The ‘nugget pull-out’ kind of failure may be seen on the cracked surface of joints manufactured with a dwell duration of 5 sec [14] and presence of porosity in the specimen leads to decrease in shear strength [15]. The partly curved form of failure is revealed by the broken surface of the joint manufactured with a dwell period of 4 sec. The manner of failure of the FSSW joints is influenced by dwell duration [16]. The cycle time increases as the dwell duration increases [17].

Table 1: Chemical composition of BMs.

| Component | C  | Mn  | P   | Si  | Al  | Mg  | Cr  | Fe  | Cu  |
|-----------|----|-----|-----|-----|-----|-----|-----|-----|-----|
| AA606     | —  | 0.13| —   | 0.3 | 95.7| 0.7 | 0.03| 0.6 | 0.31|
| CS        | 0.08| 0.21| 0.007| —  | —   | —   | —   | 65.5| —   |

Table 2: Mechanical properties of BMs.

| Materials | 0.2% Y.S “MPa” | UTS “MPa” | Elongation “%” | Hardness @0.5 N, 30 sec “HV” |
|-----------|---------------|-----------|----------------|-------------------------------|
| AA6061    | 279           | 310       | 14             | 105                           |
| CS        | 271           | 350       | 16             | 342                           |

Table 3: FSSW parameters used to fabricate the joints.

| Dwell time | N “rpm” | R “mm/min” | T “sec” | D  |
|------------|---------|------------|---------|----|
| 1000       | 1000    | 5          | 4       | 3  |
| 1000       | 1000    | 5          | 5       | 3  |
| 1000       | 1000    | 5          | 6       | 3  |
| 1000       | 1000    | 5          | 7       | 3  |
| 1000       | 1000    | 5          | 8       | 3  |

Figure 1: (a) Schematic diagram of FSSW joint, (b) fabricated FSSW tools, (c) fabricated joints (before testing), and (d) fabricated joints (after testing).
High dwell time produces excessive plasticization and coarser grains in the NZ because of the high temperature and increased heat input [14]. The finer grains in the NZ were generated by the modest peak temperature. The finer grain structure showed pronounced improvement in micro-hardness due to Hall–Petch strengthening phenomenon [18]. Also, the Orowan strengthening improves the load bearing ability of the grain boundaries [19]. The forging force is reduced as a result of the high heat input during longer dwell durations, resulting in poor metallurgical bonding between sheets and inferior hardness at the sNZ. With increasing tool-holding time, the nugget grows larger [20]. The frictional heat created between the spinning tool and the top sheet material increases as the processing duration increases. As a result, the plastic deformation at the interfacial region extents and increases the weld diameter. However, the strength is increased by increasing weld nugget area. This was due to the highly thermoplastic material being pulled by the tool while it was retracted at the maximum plunge depth due to high heat input [21].

3.2. Effect of Process Parameters on Failure Pattern. Regardless of process state, it can be shown that increasing HW increases FL, while increasing HH lowers FL. With increasing FL, the HID from the tool interface of the joints normally increases. The HID is contradictory owing to the volume of material pushed out and the TMAZ impact caused by the process parameters during manufacturing. The NZ breadth along the interface in the weld region was impacted by the peak temperature variation caused by changes in process parameters, in addition to the NZ volume. As a consequence, the HW and effective top sheet thickness were adjusted in accordance with the process parameters [22], and changes in geometrical characteristics were used to estimate failure modes and fracture values [23]. Presence of voids in the grain morphology will prompt fracture in the material when load is applied [24]. The actual resistive area created at the faying surfaces is seen to change the heat input, forging force, and duration as a result of the various process factors. These factors cause various types of failure and, as a result, have an impact on fracture values. When the force is applied, the crack begins at the upper-lower sheet boundary, propagates through the mechanical bonding, expands via metallurgical bonding, and ultimately reaches the NZ before failing. The fractures are discovered to be in the dimple rupture mode [25]. Despite the fact that the shown fractography inevitably contains dimples, it can be seen that the morphology of the dimples varies meaningfully depending on the FSSW parameters utilized in this study. The fractography clearly shows that the variation in fracture morphology is related to a change in grain size. At a lower tool rotating speed of 1000 rpm, cleavage type fractures with partly curved and nugget debonding mechanism of failure were found. Partially curved interfacial failure mode produces coarse and shallow dimples, whereas nugget pull-out produces fine and deep dimples. The size of the dimple has an indirect relationship with the joint’s strength and ductility [26]. The strength and ductility of the joint are increased when the dimple size is smaller [27]. Even while hook width is one of the main geometric factors in determining crack propagation and eventual fracture [28], the creation of these dimples is also linked to the presence of discontinuous oxide particles that reduce plasticity.

| Dwell time (sec) | Cross-sectional macrograph | Observation |
|------------------|-----------------------------|-------------|
| 4                | FL = 8.49 kN; HH = 2.16 mm; HW = 1.35 mm; HID = 2.11 mm; |             |
| 5                | FL = 8.81 kN; HH = 1.89 mm; HW = 1.38 mm; HID = 2.46 mm; |             |
| 6                | FL = 9.56 kN; HH = 0.78 mm; HW = 1.81 mm; HID = 2.75 mm; |             |
| 7                | FL = 9.28 kN; HH = 0.70 mm; HW = 1.78 mm; HID = 2.54 mm; |             |
| 8                | FL = 9.06 kN; HH = 0.65 mm; HW = 1.67 mm; HID = 2.02 mm; |             |

FL, fracture load “kN”; HH, hook height; HW, hook width; HID, hook initiation distance “mm.”

Table 4: Influence of dwell time on macrograph of FSSW dissimilar joints.

Figure 2: Microhardness distribution of FSSW joints.
| Dwell time | Nugget zone | TMAZ | HAZ |
|------------|-------------|------|-----|
| 3          | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| 4          | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 5          | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
| 6          | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 7          | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |

Figure 3: Influence of dwell time on microstructure of FSSW joints.
4. Conclusions

The influence of dwell time on the fracture load of AA6061-T6 with carbon steel was investigated in this study. The following key findings may be drawn from this investigation:

(i) The dissimilar materials are successfully joint using solid state technology FSSW. By using four major process parameters, the joint was performed in CNC-FSW machine under constant load mode.

(ii) The sound joint is obtained at tool rotational speed, plunge rate, dwell time, and shoulder to pin diameter ratio of 1000 rpm, 5 mm/min, 6 sec, and 3.0, respectively.

(iii) Recrystallized grains and favorable intermetallic compound formation are the primary factors to cause sound weld joint.

(iv) The maximum fracture load is obtained by the optimum HH of 0.75 mm and HW of 1.77 mm, whereas the lowest FL is observed in HH of 1.25 mm and HW of 2.01 mm.

Data Availability

The data used to support the findings of this study are included within the article.
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