Influence of Friction Stir Welding Parameters on Joint Defects, Temperature and Hardness of AA6061-T6 and S27JR Mild Steel FSW Joint

W M Syafiq¹, M Afendi¹and M N Mazlee¹

¹ Faculty of Mechanical Engineering Technology, Pauh Putra Campus, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia

wanmohdsyafiq@unimap.edu.my

Abstract. The influence of welding parameters such as tool plunge depth, tool travel speed and tool tilt angle on welding temperature during friction stir welding of AA6061-T6 and S275JR mild steel was the focus of this research. Thermocouple placed in the aluminum alloy plate prior to welding was used to measure the temperature during the welding of joints under different set of parameter values. Joint appearance as well as defects occurring on the surface or within the joint was observed. Microhardness profiles were also taken by measuring microhardness values across the cross section of joints. Excessive flash, tunnel defects and insufficient welding were the type of weld defects observed on different joints with different parameters. Defects were attributed to the varied parameter values affecting the heat generation as well as the flow of the plasticized material. Highest temperature was recorded by the joint fabricated using the largest tool plunge depth, owing to the increased downwards pressure. Microhardness profiles were seen to be similar for all the welded joints. A “plateau” of low microhardness value was observed for all joints associated with the thermomechanically affected zone (TMAZ) and heat affected zone (HAZ). A wider plateau was observed for joints welded with higher tool plunge depth due to higher temperature.

1. Introduction
The joining of aluminum alloy and steel has gained industrial interest over the past decade. The combination improves strength-to-weight ratio, which is certainly a point of attraction for industries such as aerospace and automotive where reducing vehicle weight, boosting fuel efficiency and decreasing fuel emission are critical [1], [2]. However, welding the two dissimilar materials together can be challenging due to the strong tendency to form large amounts of intermetallic compounds (IMC) as a result of mutual diffusion at elevated temperatures during welding [3]. Friction stir welding is a solid-state joining technique using frictional heat generated between a tool and the pieces to be welded [4]. The low process temperature during FSW makes it an optimal technique to perform welding to join aluminum alloy and steel.

The process temperature during FSW can be controlled by manipulating its various parameters. Several researchers have investigated different FSW parameters such as tool rotational speed, tool travel...
speed and tool tilt angle and their effects on various combinations of aluminum alloys and mild steel [5]–[7]. However, studies on the combination of aluminum alloy AA6061-T6 and mild steel S275JR was found to be lacking. The influence of tool travel speed, plunge depth and tilt angle on joint appearance as well as defects are investigated in this study. Microhardness profiles taken across the cross section of joints are also presented in this study.

2. Experimental Procedure

Butt joints of aluminium alloy AA6061-T6 and mild steel S275JR plates with 5 mm thickness were prepared using FSW. A custom made FSW tool was prepared in order to enable FSW on a conventional milling machine. Welding was performed parallel to the rolling direction of the plate. The FSW tool was made from H13 tool steel hardened to 54 HRC. The dimensions of the tool are displayed in Figure 1.

![Figure 1. FSW tool](image)

The joints welded and the parameter values used during the welding of the joints are tabulated as Table 1. After welding, welded pieces were removed from the clamping jig and their appearances were observed for defects. Cross section samples were extracted from the weld line of joints to allow defects observation. Microhardness profiles were taken at the middle of the samples starting from the steel side towards the aluminum alloy side using a Vickers microhardness tester. Temperature data was collected for each joint by placing a K-type thermocouple at the middle position of the weld line via a groove under the AA6061-T6 plate as show in Figure 2. The thermocouple was connected to a data logger for data collection.

| Weld | Tool Plunge Depth (mm) | Tool Travel Speed (mm/min) | Tool Tilt (°) |
|------|------------------------|----------------------------|--------------|
| S1   | 0.2                    | 30                         | 3            |
| S2   | 0.2                    | 45                         | 3            |
| S3   | 0.2                    | 110                        | 3            |
| S4   | 0.1                    | 45                         | 3            |
| S5   | 0.5                    | 45                         | 3            |
| S6   | 0.2                    | 45                         | 1            |
| S7   | 0.2                    | 45                         | 5            |

3. Results and Discussions

Surface appearance of all the welded joints are shown in Figure 3. Superfluous materials were seen deposited on top of joints S5 and S7 as excessive flash, which are products of increased heat generation during welding [8], [9]. For joint S5, this defect is due to the increased downwards pressure from a higher tool plunge depth value. Frigaard et al. defined the heat input model during FSW as seen in Equation 1,
\[ Q = \frac{4}{3} \pi \mu P \omega R^3 \]  

(1)

\( Q \) is net power (W), \( P \) is the downwards pressure (Pa), \( \mu \) is the friction coefficient, \( R \) is the tool shoulder radius (m) and \( \omega \) is tool rotational speed (rev/s). As per the heat input model above, as downwards pressure increased, heat generation also increased. Superfluous material was also deposited on top of joint S3. High tool travel speed used when welding the joint (110 mm/min) resulted in less period of time per unit length spent by the tool pressing plasticized materials downwards into the void.

Figure 3. Surface appearance of FSW joints

Figure 4a&b shows excessive flashing that occurred on joints S5 and S7. As explained before, the excessive flash observed on joint S5 was due to increased heat generation. However, in the case of S7, the defect was caused by the improper tool shoulder position. As the tool tilt angle was 5° during the welding of this joint, the plasticized material was seen to propagate towards the back of the tool during the plunging stage. The improper tool tilt angle caused the tool to be positioned such that it was unable to adequately contain the plasticized materials beneath the shoulder, thus causing it to spill towards the trailing edge of the tool. This resulted in the noticeably different surface appearance of S5 relative to the other joints.

As excessive flashing is caused by improper welding conditions, it can be treated as a sign or a precursor to other defects in FSW joints. Figure 4c shows joint S7 which detached easily once it was separated from the clamer. As implied by of excessive flashing at the plunging stage position, joint S7 suffered from defects which made it a failed weld. The tool’s inability to facilitate proper material consolidation due to improper tool tilt angle caused insufficient joining between the two plates.

Figure 4. Surface of (a) S5 and (b) S7, as well as (c) detached joint S7
Another joint that exhibited noticeably different surface appearance in the form of presence of aluminum layer (S3) also suffered from joint defect. Figure 5b shows cross section of joint S3. As highlighted by the red arrows, tunnel defects were present in both joints. As mentioned previously, the aluminum layer that appeared on the surface of S3 was caused by the high tool travel speed, causing less time spent by the tool pushing plasticized material downwards per unit length. As a result, tunnel defects were observed.

As per the mathematical model proposed by Zhang et al. to describe void formation in FSW, a lower tool travel speed will increase the volume of material pushed into the void [10]. In this study, by lowering the tool travel speed to 45 mm/min in welding S2, no tunnel defects were observed. However, lowering it further to 30 mm/min to weld S1 caused the reappearance of the defect as seen in Figure 5a. The lower tool travel speed increased the time spent by the tool interacting with the weld piece per unit length, thus increasing heat generation and period of exposure to elevated temperatures [5], [11]. The increased heat generation also lowered the flow stress of the plasticized aluminum [12]. This increased fluidity led to tunnel formation in the joint as tool shoulder was incapable of completely pushing plasticized materials downwards into the void.

Figure 5c shows the cross section of joint S4 which was also affected by tunnel defects. This phenomenon is due to lower downwards pressure by the lesser tool plunge depth value used during welding joint S4, which was 0.1 mm. Similarly, the mathematical model developed by Zhang et al. also applies in this case, where a higher downwards pressure will increase the volume of plasticized material pushed into the void [10]. Even though this study did not explicitly measure downwards pressure, it is accepted in FSW that downwards pressure onto the plasticized materials is proportional to the plunge depth [13], [14].

Table 2 shows the highest temperature during welding of joints. Joint S5 reached the highest maximum temperature due to the large plunge depth used when welding the joint. The lowest maximum temperature was observed during the fabrication of joint S7, due to the reduced contact area between tool and weld piece as a result of the high tool tilt angle (5°) used during its welding.

Table 2. Maximum temperature values by each joints

| Joint | Maximum Temperature (°C) |
|-------|--------------------------|
| S1    | 493.9                    |
| S2    | 482.2                    |
| S3    | 457.6                    |
| S4    | 457.6                    |
| S5    | 531.4                    |
| S6    | 479.9                    |
| S7    | 428.4                    |
Figure 6 illustrates the relationship between contact area between weld piece and tool shoulder for different tool plunge depth and tool tilt angle. Increasing tool plunge depth meant more of the tool shoulder was “submerged” into the weld piece, increasing its contact area with the weld piece. Conversely, increasing the tool tilt angle at constant tool plunge depth value decreased the contact.

**Figure 7** shows the microhardness plots of joints welded with varying parameters. Higher microhardness values were obtained on the steel side close to the interface, which was caused by the work hardening effect by the pressing of the tool shoulder and the stirring of tool pin [15]. The microhardness values of base aluminum alloy and mild steel were recorded at 102 HV and 140 HV respectively. In FSW, different welding regions (SZ, TMAZ and HAZ) record lower hardness values than the aluminum alloy base metal due to the dissolution of second-phase particles at these three zones which serve as hardeners [16], [17]. A region of minimum hardness values were seen for all joints which correspond to TMAZ and HAZ, a feature common to FSW joints of precipitation hardened aluminum alloys [18], [19]. This is caused by the dissolution of second phase particles which act as hardeners [16], [20]. This “plateau” of minimum microhardness values was seen in all joints. In **Figure 7a**, the hardness plateau was seen to be smaller and closer at 7 mm from the interface for joint S4. The hardness plateau for joint S2 formed slightly further at 8 mm from the interface. Meanwhile, the hardness plateau of joint S5 (0.5 mm tool plunge depth) was located similarly at 8 mm from the interface but was larger than the previous joints, ending at 13 mm from the interface.

![Figure 6. Illustration of the influence of tool (a) plunge depth and (b) tilt angle on contact area](image-url)
Figure 7. Microhardness profiles for joint with different tool (a) plunge depth, (b) travel speed and (c) tilt angle

4. Conclusions
The following conclusions can be made based on the results:
- Excessive flash was detected on joints S5, S7 and S3 due to incorrect parameter selection. As a result, this affected the tool shoulder’s ability to contain the plasticized materials under it.
- Tunnel defects were detected in several joints due to insufficient interaction between tool shoulder and plasticized material. Excessive material flow due to high heat generation was responsible for tunnel defect seen in joint S1.
- From the microhardness tests, lower microhardness values obtained at the SZ of joints was due to the dissolution of second phase particles. Wider “plateau” of low hardness values observed on the microhardness plots were due to an increased area affected by the heat generated by tool shoulder, as a result of increased tool plunge depth.

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