Mechanical properties of friction stir welded butt joint of steel/aluminium alloys: effect of tool geometry

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Abstract. This paper described the mechanical properties from hardness testing and tensile testing of Friction Stir Welded (FSW) materials. In this project, two materials of aluminium and steel are welded using conventional milling machine and tool designed with different profile and shoulder size. During welding the temperature along the weld line is collected using thermocouples. Threaded pins was found to produce stronger joints than cylindrical pins. 20 mm diameter shoulder tool welded a slightly stronger joint than 18 mm diameter one, as well as softer nugget zone due to higher heat input. Threaded pins also contributed to higher weld temperature than cylindrical pins due to increase in pin contact surface. Generally, higher temperatures were recorded in aluminium side due to pin offset away from steel.

1. Introduction
In present days, many large and complex structures are formed due to the needs of the public. Most of the structures are using metals such as steel and aluminium as raw materials because of their strength and toughness. There are times where there is a need to join two materials together. Therefore, a joining technique is needed to hold the structure together strongly. Among all the joining techniques there is a process called welding where a small portion of the parts-to-be-joint’s volume will be melted, later it will stick together as it cools. There are several types of welding processes such as tungsten inert gas (TIG) welding, friction stir welding (FSW), electron beam (EB) welding and fiber laser welding [1].

However, there is a serious problem when two dissimilar alloys such as aluminium and steel are joined because there will be a formation of intermetallic compounds (IMCs) in the weld zone. Such occasion occurs by the differences between the physical and chemical properties of the two alloys such as melting point, thermal conductivity, coefficient of linear expansion and heat capacity. Even though there are few different techniques have been applied, obtaining a solid joint between aluminium and steel looks very tough [2]. In 1991, a welding process was invented by The Welding Institute (TWI) in United Kingdom to join the aluminium alloys. It is called as friction stir welding (FSW) which is a solid state joining process where the frictional heat is produced between the rotational tool and the material to fuse the two working metals [3]. In comparison with other conventional joining methods, FSW holds the advantages with reduced porosity, cracking, distortion,
and reinforcement dissolution. Therefore, FSW can produce low-cost and high performance joints. Besides that, due to its low energy consumption, no gas emission and no consumable materials needed, FSW is known as an environmental-friendly technology in joining process[4].

In this experiment, two specimens of aluminium and steel are prepared to weld using friction stir welding process on a conventional milling machine. Mechanical properties of the friction stir welded butt joint such as tensile strength and hardness are evaluated. The influence of tool geometry and welding speed on aforementioned mechanical properties as well as the resulting temperature are investigated.

2. Experimental Procedures
To conduct this experiment, 5 mm thick plates of aluminium alloy 6061-T6 and mild steel were prepared. FSW was performed on a conventional belting milling machine (MASTIKA). FSW tools and a clamping jig were designed and fitted onto the milling machine in order to enable FSW on it. FSW tools with different geometries were designed for the purpose of this study. Tools with different shoulder diameter (18 mm and 20 mm) and different tool pin profile (cylindrical and threaded) were chosen to investigate their effects on the joint. Joints with different parameters were welded as presented in table 1.

| Specimen | Rotational Speed (rpm) | Travel Speed (mm/min) | Pin Profile | Shoulder Diameter (mm) |
|----------|------------------------|-----------------------|-------------|------------------------|
| A        | 650                    | 50                    | Threaded    | 18                     |
| B        | 650                    | 50                    | Cylindrical | 18                     |
| C        | 650                    | 50                    | Cylindrical | 20                     |
| D        | 650                    | 70                    | Cylindrical | 18                     |
| E        | 650                    | 70                    | Threaded    | 18                     |

Four thermocouples (CH001, CH002, CH003, CH004) were inserted into the jig to measure the temperature distribution along the weld line. Holes were drilled 3 mm below the welded samples in the jig to fit four thermocouples. The positions of thermocouples are shown in figure 1. Thermocouple CH002 is located 3 mm into the steel side, while thermocouple CH004 is directly on the joint line border between steel and aluminium alloy. Thermocouples CH001 and CH003 are located 6 mm and 10 mm into the aluminium alloy side respectively. After the FSW process, the specimen was cut using EDM wire cut to obtain a dumbbell shape according to ASTM E8-E8M-13a[5] that will be used for tensile testing. Tensile testing was done on a universal testing machine (SHIMADZU TCE-N300) with a crosshead speed of 1 mm/min. Vickers Micro hardness test was done on a cross section of the joint, with readings taken at mid thickness of the joint. The indenter was a square-based diamond pyramid and a load of 200 N was applied with dwell time of 15 seconds.
3. Results and Discussion

3.1. Tensile Strength

The tensile strength results of all welded joints are tabulated in Table 2, and the influence of different tool geometries on the tensile strength is illustrated in Figure 2. From these results, it was seen that the highest ultimate tensile strength (UTS) was obtained by Specimen A at 117.5 MPa. The lowest UTS was recorded at 35.7 MPa by Specimen D. Generally, joints that were welded by a threaded pin (Specimens A and E) outperform joints welded with a cylindrical pin (Specimens B and D) with other parameters kept constant. Joint that was welded with a bigger shoulder diameter of 20 mm (Specimen C) recorded a small improvement over the joint welded with 18 mm shoulder diameter (Specimen B) whilst keeping other parameters constant. It is also noted that when the tool travel speed was increased from 50 mm/min to 70 mm/min, welded joints recorded lower UTS values, as can be seen comparing the UTS values of Specimen B with Specimen D, as well as Specimen A with Specimen E.

Table 2. Ultimate tensile strength (MPa) for tensile testing specimens.

| Specimen | Ultimate Tensile Strength (MPa) |
|----------|---------------------------------|
| A        | 117.5                           |
| B        | 86.5                            |
| C        | 91.1                            |
| D        | 35.7                            |
| E        | 77.7                            |

Figure 1. Position of thermocouples with respect to plates to be welded.

Figure 2. Ultimate tensile strength of specimens welded with different tool geometries.
3.2. Hardness

The hardness profiles of the welded specimens are presented in figure 3. Note that 0 is located at the joint line border between the two dissimilar plates. Steel and aluminium alloy sides are assigned negative and positive direction respectively. At 5 mm into steel side, it is seen that Specimen C recorded the highest hardness value at 202.8 HV, while the other specimens recorded values close to each other, with Specimen D recorded the lowest value at 165.1 HV. In the nugget zone, i.e. 5 mm into the aluminium alloy side, Specimens D and C recorded the maximum and minimum hardness values, with measurements of 90.1 HV and 76.9 HV respectively.

For all hardness profiles, similar patterns were obtained that hardness increased from distance of -25 mm to -5 mm. Values decreased from -5 mm to 5 mm when crossing the joint line from steel to aluminium alloy, before increasing again at 25 mm. Maximum and minimum hardness values were obtained at -5 mm and 5 mm respectively for all hardness profiles.

![Figure 3. The hardness profiles of all the specimens taken at mid thickness.](image)

3.3. Temperature

3.3.1. Maximum Temperature of Welds

Four thermocouple channels (CH001, CH002, CH003, CH004) were used to record temperature variation during welding. Only the maximum temperature recorded by each thermocouple during the entire welding run is considered, and the term “highest maximum temperature” refers to the highest temperature recorded during FSW of the specimen by any thermocouple. The highest maximum temperatures recorded during welding for Specimens A to E are 218.2 °C, 198.5 °C, 247.1 °C, 168.6 °C and 182.1 °C respectively.

For Specimens B to E, the highest maximum temperatures were recorded on thermocouple CH001, whereas thermocouple CH002 recorded the highest temperature during the FSW of Specimen A. From Table 3, it is noted that Specimen C was welded with the highest temperature at 247.1 °C, while Specimen D was the least hot at 168.6 °C. It is noted that the holes to fit the thermocouples were drilled 3 mm below the top surface of the jig, therefore the temperatures recorded by the thermocouples are not the exact temperatures on the workpieces, however the difference in temperatures recorded when performing FSW with different parameters was clearly exhibited.
Table 3. Maximum temperature and its respective thermocouple recorded during FSW.

| Specimen | Maximum Temperature(°C) | Thermocouple |
|----------|--------------------------|--------------|
| A        | 218.2                    | CH002        |
| B        | 198.5                    | CH001        |
| C        | 247.1                    | CH001        |
| D        | 168.6                    | CH001        |
| E        | 182.1                    | CH001        |

3.3.2. Temperature across the Weld Joint from Steel to Aluminium
Figure 4 shows the temperature across the weld from steel to aluminium for all the specimens. Most of the plots show fluctuation along the distance. It can be seen that thermocouple CH001 recorded most of the highest maximum temperatures achieved for the welded samples, whereas the lowest maximum temperatures were recorded by thermocouple CH003. It is noted that even though thermocouple CH004 is located under the tool pin’s passing path at the joint line, the recorded temperatures are less than the values recorded by thermocouple CH001 positioned in the aluminium side, a few millimetres away from the pin passing path.

3.4. Discussion
From the tensile strength result, it is seen that joints welded with threaded pins have higher ultimate tensile strength than joints welded with normal cylindrical pins. Specimen A and Specimen E were welded as a comparison to Specimens B and D, as both A and E are welded with threaded pins as opposed to B and D that were welded with cylindrical pins. From figure 2 it is seen that joints welded with a threaded pin were stronger. The design of the thread was such that during welding, plasticized material will be pushed from the top towards the bottom of the pin. The presence of threads is known to improve material consolidation and mixing, as the plasticized material’s movement around the pin is better facilitated with the presence of threads, compared to an unthreaded cylindrical pin [6]. Increasing tool shoulder diameter from 18 mm to 20 mm also had a positive influence on the UTS,
albeit only by a small margin. A larger shoulder diameter will be able to push more plasticized material into the void left behind by the traveling pin, therefore improving material consolidation[7].

Increasing the weld travel speed from 50 mm/min to 70 mm/min deteriorated the joint’s strength, as demonstrated by Specimens B and D. The increase in weld travel speed effectively reduced the time spent by the tool to interact with the plasticized material at joint line. The decrease in heat input also affected material flow, which resulted in less than satisfactory contact between the plasticized material and the steel faying surface [8], [9]. However, under the same welding speed, adding a thread to improve heat generation as well as material flow improved the UTS of the joint as shown by Specimens D and E. The heat generated by a threaded pin is larger than a cylindrical pin, due to the increased pin surface area in contact with the workpiece [6], [10]. As a result, the material flow was improved, better contact between aluminium and steel was achieved, thus the UTS was also improved.

The hardness profiles of all specimens peaked in the steel side close to the joint line. This indicates work hardening effect of the tool shoulder onto the steel surface, as well as the stirring of the tool pin [11]. The increased contact area between the workpiece surface and the 20 mm diameter tool shoulder while welding Specimen C resulted in a higher degree of work hardening onto the steel side. All specimens welded with 18 mm diameter tool shoulders recorded similar hardness values with each other. The hardness values went down to a minimum when crossing the joint line border from steel to aluminium alloy at 5 mm, with Specimen D recording the highest hardness value here.

It is expected for the hardness values to decrease as the profile crossed the joint line, as the two dissimilar materials did not mix in the nugget zone. At 5 mm into the aluminium alloy side, the nugget zone which is the zone where the tool pin passed is found. The hardness of the nugget zone is lower than the base metal aluminium alloy due to the dissolution of hardening second phase particles during the stirring and heating of the FSW process [11], [12]. In FSW, severe plastic deformation from stirring and heat from friction causes dynamic recrystallization in the nugget zone, which resulted in fine equiaxed grains [13]. Specimen D was welded with a higher welding speed that reduced the heat input into the joint. This contributed to less grain growth and subsequently higher hardness values, which is in accordance to the Hall-Petch relation [14], [15].

The heat input per unit length in a friction stir welding process is given by the expression below [16], [17]:

\[ Q/v = \frac{4}{3} \pi \mu P \frac{v}{\nu} R_s^3 \]  

(1)

In Equation 1, \( \mu \) is the friction coefficient, \( P \) is the applied pressure, \( \omega \) is the tool rotational speed, \( v \) is the tool travel speed and \( R_s \) is the tool shoulder radius. It is seen from this expression that tool shoulder geometry has a large influence on the heat generation, which was why the maximum temperature recorded during the welding of Specimen C is the highest of all welded specimens. The increase in shoulder diameter contributed to an increase in contact area between the rotating shoulder and the workpiece. Specimen D was welded with a smaller 18 mm shoulder diameter tool, as well as a higher travel speed of 70 mm/min. These factors contributed to Specimen D’s lowest maximum temperature. It is noteworthy that specimens welded with a threaded pin recorded higher maximum temperatures that their cylinder pin counterparts. This is due to threaded pins generating more heat, as discussed previously.

In terms of temperature across the joint during welding, it was seen from figure 9 that thermocouple CH001 which was located in the aluminium side 3 mm away from the pin passing path recorded higher temperatures than CH004, even when CH004 is located under the pin passing path at the joint border line. This phenomenon is due to the tool pin mostly interacting with the aluminium alloy side. In FSW of aluminium alloy and steel, the tool pin is mostly plunged into the aluminium alloy side in order to protect the tool from excessive heat resulting from friction between the tool and steel [18]. Majority of the severe plastic deformation occurred at the aluminium alloy side, which is why the thermocouple CH001 recorded higher temperatures than CH004. Thermocouple CH003
recorded the lowest maximum temperatures due to it being located furthest away from the pin passing path.

4. Conclusion
This paper investigated the influence of different tool geometries such as shoulder diameter and pin profile on mechanical properties and temperature of the weld. From the results obtained, the following conclusions are made.

1. In terms of pin profile, threaded pins were found to produce joints with better tensile strength than joints welded by tools with cylindrical pins. Specimens A and E both outperform Specimens B and D that were welded with similar welding parameters except for the tool pin profile. The improved material flow offered by the threads improved material consolidation.

2. Increasing the tool shoulder diameter from 18 mm to 20 mm had a positive influence on joint strength, if only slightly. Specimen C benefited from the larger shoulder diameter thus better material consolidation.

3. Increasing tool travel speed was found to negatively impact on the joint strength, as demonstrated by Specimens B and D due to less time for the tool to interact with the steel faying surface and plasticized material.

4. FSW with a larger shoulder diameter tool was found to increase the maximum temperature during the welding, which is in agreement with the heat generation equation by Frigaard [17]. This is due to the increased area of contact between the rotating tool shoulder and the workpiece.

5. Joints welded by tools with threaded pins were found to be hotter than the ones welded with the straight cylindrical pins due to increased contact area between rotating tool pin and the workpiece.

6. Increasing the tool travel speed reduced the maximum temperature recorded at a particular location due to less time spent by the tool to interact with the workpiece per unit length.

5. References
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