Aluminum corner joint using friction stir welding

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Abstract. This article studies the feasibility of applying Friction Stir Welding (FSW) to an aluminum 6061 corner joint. The friction tool rotated at constant speed (2000 RPM) whilst feed rate varied in 10, 15 and 30 mm/minutes. Generally the lower feed rate produces higher tensile strength due to higher heat is embedded in the base metal, but the 15 mm/minute feed rate exhibited the least tensile strength. Lower feed rate reduces Mg alloy in base metal which in turn decreases the tensile strength. The final tensile strength is the compromise between higher heat input and lower Mg content that is why the 15 mm/minute has lowest tensile strength.

1 Introduction

Metals with high strength to weight ratio will be more broadly used due to their economical benefits [1]. The metal with higher strength to weight ratio such as aluminium will replace steel as the most applied metals [2]. Unfortunately, when fusion welding is applied, aluminum encounters problems such as: porosity due to the big difference of hydrogen solubility at liquid and solid forms [3], less compatibility owing to Al_2O_3 film [4], hot cracking because of the alloy element which is added intentionally to pure aluminium [5] and the strength loss while melting takes place [6]. The solid state welding is hoped able to overcome those problems. Most of solid state welding researches observed lap and butt joints that is why this article discusses corner joint to underline the wide opportunities of FSW application.

There are three major streams of welding study: analytical, numerical and experimental methods [7, 8]. This study used a true experimental method with independent variable is feed rate. The quality of the joint was represented quantitatively by the tensile strength as a dependent variable. SEM, hardness profile, XRD and ongoing temperature tests were performed to support the analysis.

2 Experiment setup

The base metal was a 10mm plate of aluminum 6061 series with chemical content shown in Table 1. The plate was cut in 50mm x 150mm square and the edge where the FSW will be

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applied is trimmed to 45°. Two plates then attached at a jig as shown schematically in Figure 1. The probe was attached at 2000rpm rotating chuck. The pressure around 500 kg and idle rotation around 10 seconds then applied; produce enough heat to soften the material in the nugget zone. After the idle rotation the feeding movement was applied with three different feeding speeds: 10, 15 and 30 mm/minutes. Certain specimen was equipped with a thermocouple to monitor the temperature histories at certain position as shown by Figure 2.

Table 1. Chemical composition of 6061 aluminum alloy (wt %).

Composition	Mg	Si	Cu	Mn	Fe	Cr	Ti	Zn	Al
Content	0.9	0.6	0.25	0.086	0.18	0.1	0.192	0.01	Bal.

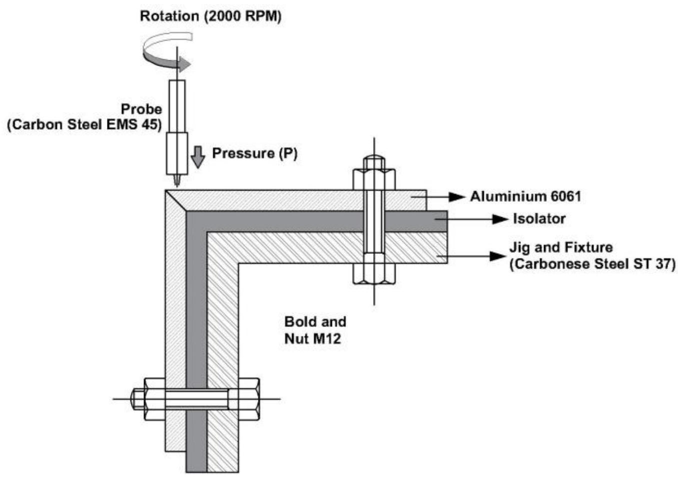

Fig. 1. Friction Stir Welding on The Corner Joint

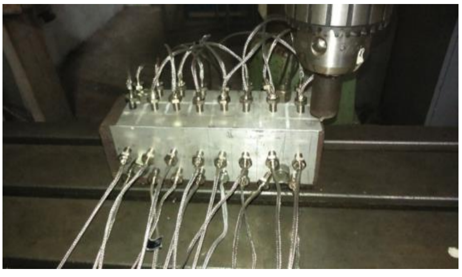

Fig. 2. Embedded thermocouple to record temperature histories.

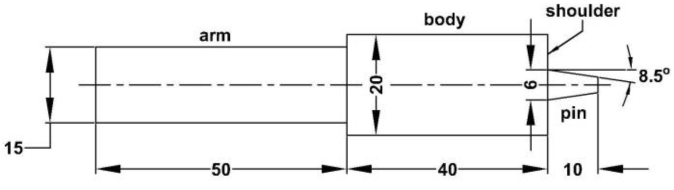

Fig. 3. Tool/probe design

The probe (friction tool) was made from hardenable EMS 45 steels. First an EMS 45 cylinder bar is formed using turning machine with geometry and measurement shown in Figure 3. All measurements in Figure 3 are in millimetres. After the probe was shaped then heat hardened by heating it in a furnace up to 1100°C and held in two hours. Suddenly, from the furnace the probe was quenched in oil and cooled down to room temperature. The tempering was applied following the hardening by heating the friction tool up to 300°C and held for two hours. From the furnace the tool was exposed to the ambient air to be naturally cooled down to the room temperature. With these two heat treatments the probe has enough hardness and ductility to carry out FSW on the aluminum plate.

Fig. 4. Tensile test for the corner joint using special jig

In this article the rotating speed of the probe was kept constant at 2000 RPM whilst the feed rates (welding speed) were varied at 10 mm/min, 15 mm/min and 30 mm/min. After the two plates have been joined the tensile test specimens were formed. A specifically jig was used as auxiliary equipment as shown in Figure 4. The tensile strength test is the main result. Temperature histories, hardness distribution, XRD and chemical composition data are used to explain and enhance the result obtained from tensile test.

3 Results and discussion

Visual inspection shows that the 10 mm/min feed rate provides neat upper surface while for the 15 mm/min the upper surface is a little bit rough. For the 30 mm/min the rough surface is found and some holes are found in certain places. The FSW surface for varied feed rates are shown visually in Figure 5.

Fig. 5. Visual inspection of 10, 15 and 30 mm/mins

Tensile test results are shown graphically in Figure 6 that it can be said the lower feed rate produce higher tensile stress. With the less feed rate the heat input (heat embedded for each length) will be higher. The higher heat input provides enough soft material (nugget zone) which is needed to perform mechanical bonding when the mixing force from pin is applied. The higher heat input is also confirmed by recorded temperature by thermocouple as shown in Figure 7. Figure 7 shown temperature histories of thermocouple 11 for varied feed rate, those are 10, 15 and 30 mm/sec. Higher temperature indicates the higher the heat is inputted to the work piece. For lower heat input longer time is needed to complete the FSW process and since the heat embedded to work piece for certain time is equal, as a result of equal RPM, the longer FSW process means higher heat input and in turn increase the peak temperature recorded by thermocouple 11 as it is demonstrated by Figure 7. This longer time also describes more intensive mixing since the RPM is kept constant.

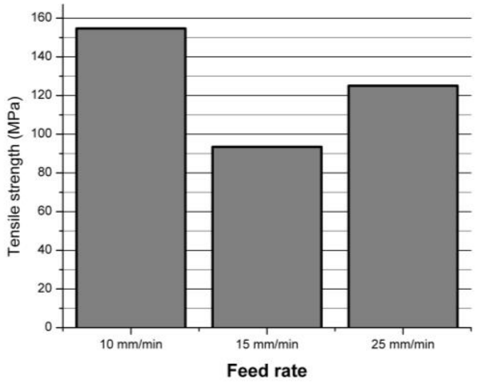

Fig. 6. Tensile test results.

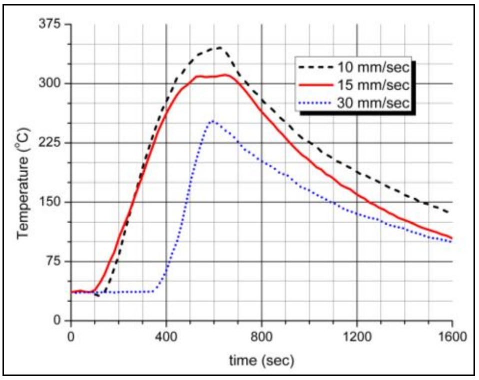

Fig. 7. Temperature histories of thermocouple 11.

It was hoped with a lower feed rate, which also means higher heat input and intensive mixing forces, the higher tensile strength will be obtained, but Figure 6 showed that the lowest tensile strength is shown by feed rate equal to 15 mm/sec. The hardness profile as shown in Figure 8, also confirmed the tensile test result. The distance between nodes in Figure 8 is 500 μm.

From X-Ray diffraction in Figure 9, it can be shown that MgO is formed while FSW was applied. The content of the MgO is shown in Table 2. From the table it can be said that with the lower feed rate, more MgO is produced. MgO is formed when the Mg is exposed to temperature above 265°C [9, 10]. From Figure 7 it can be concluded that the slower the feed rate, the material will be exposed in temperature above 265°C in the longer period.
It should be noted that the thermocouple is embedded at a certain distance from the higher temperature in a FSW process (under probe or in nugget zone). However, the Figure describes that with the lower feed rate, a certain point will experience higher peak temperature and will be exposed to temperature above 265°C in the longer period. While they are exposed to temperature above 265°C the MgO will be formed and since the lower feed rate exposed a certain point above 265°C in longer period, the MgO content will be higher which is confirmed by table 2. The method used to obtain the Table 2 is atomic absorption spectroscopy.

The Mg alloy in aluminum alloy increases the strength, including tensile strength [11, 12]. Since the total Mg in a certain aluminum plate is constant, increasing MgO means decreasing Mg content in the aluminum alloy. This depleting Mg in the alloy in turn decreases the tensile strength which reverse to the expectation that with the slower feed rate it is expected higher tensile strength will be obtained.

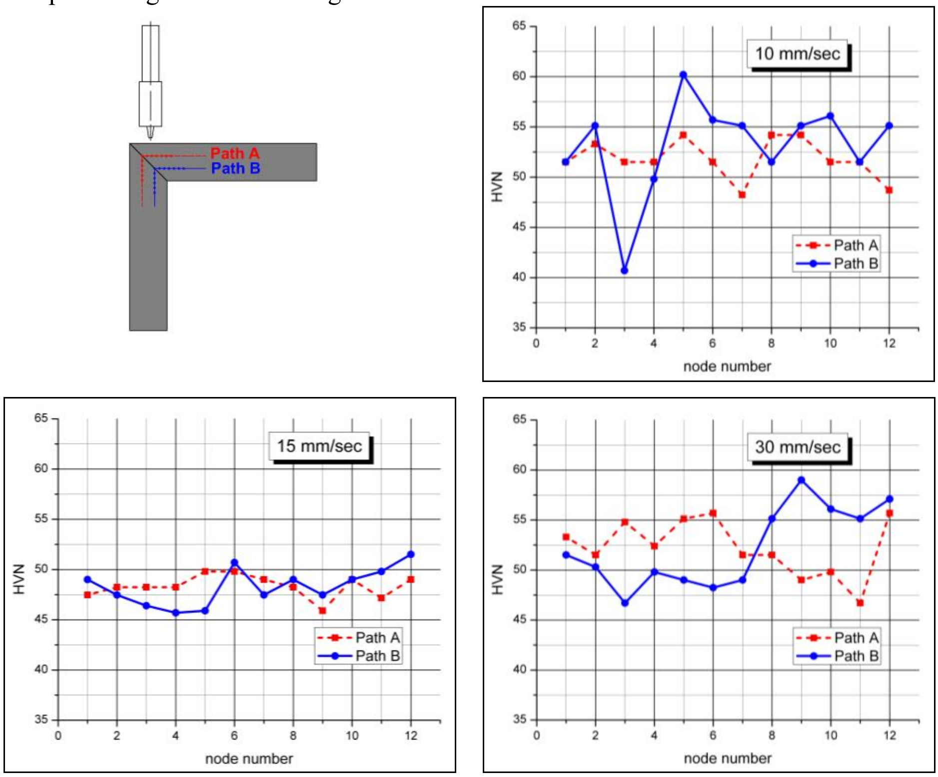

Fig. 8. Hardness profile for varied feed rate.

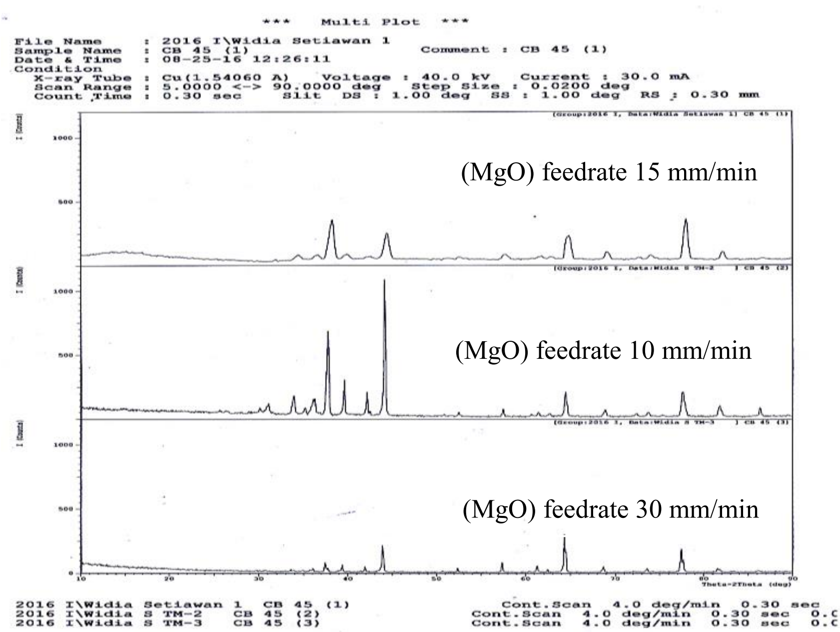

Fig. 9. X-ray defraction.

Table 2. The Mg and MgO contents

No.	Sample Code	Content	Metrology result (ppm)		
			I	II	III
1.	CL-45 (1) 30mm/min	Mg	1868.412	1868.412	1868.825
2.		MgO	3097.828	3097.828	3128.355
3.	CL-45 (2) 15mm/min	Mg	1997.299	1978.886	3097.828
4.		MgO	3311.521	3280.993	3280.993
5.	CL-45 (3) 10mm/min	Mg	1960.474	1960.474	1997.299
6.		MgO	3250.466	3250.466	3311.521

The final result of slower feed rate is the compromise between the increasing strength due to higher temperature and intensive mixing force and the decreasing strength due to the lower Mg content in the aluminum alloy. The final results are as it is shown in Figure 6, the 15 mm/sec feed rate provides the lowest tensile strength which also supported by micro hardness profiles as shown in Figure 8.

4 Conclusion

Although the principle of mechanical bonding in the FSW process has been established, the contribution of each parameter still needs further study to describe the process comprehensively. The effect of feed rate on the resulted tensile strength was demonstrated here. It was expected that with the lower feed rate the tensile strength will be higher as the result of high temperature and intensive mixing forces, but the high input also oxidizes the Mg alloys which in turn decrease the tensile strength.

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