Study of Process Parameters and Joint Properties in Friction Stir Welding of Thin and Ultra-thin Aluminium Alloy 6061-T6 Sheets

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Abstract

On downscaling the process of friction stir welding (FSW) to workpieces of thickness less than 1 mm (termed as µFSW), the application areas such as electronic packaging and joining of micro-mechanical assemblies can be benefited. To study the effect of reducing sheet thickness on process parameters and on weld strength, in this work, aluminium alloy 6061-T6 sheets of thickness 0.5 mm and 1 mm were welded, using a specially developed fixture for µFSW, and on optimization of the weld strength, the best set of process parameters in case of each thickness was obtained. Similar tool geometry were used for welding sheets in both thicknesses. The process parameters studied were tool rotational speed, tool travel speed and shoulder penetration. Wider set of process parameter window was observed in case of 1 mm sheets which also showed comparatively better ductility. 0.5 mm sheets' welds were found to perform best at comparatively higher tool rotation and travel speed, and lower plunge depth.

Keywords: Friction Stir Welding, Thin Sheets, Downscaling, Ultra-thin Sheets. Process Parameters

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1. INTRODUCTION

Friction stir welding is now a days a well established technique for joining aluminium alloys. As a solid state technique, it has many advantages to its credit and therefore used in aerospace and automotive industries [1]. It can, in fact, also be used in applications areas of electronic packaging and in joining micro-mechanical assemblies where sheets less than 1 mm are joined [2]. The work done so far on thin sheets joining [3-5] has widened the scale (thickness) of workpieces that can be joined by friction stir welding. However, some challenges are present that need to be overcome when the sheet thickness being welded is reduced. Selecting appropriate process parameters is one of them [2]. The available work on ultra-thin sheets welding shows that the set of process parameters used in this case is different from the one used in case of thicker workpieces [2-5]. It is anticipated that this different set of process parameters could affect the joint properties and/or process physics. Also, the trend of variation in the set of process parameters, if any, is necessary to be understood. This paper aims at finding answers to these questions.

In this work, two different thickness of sheets were joined separately using the same sets of process parameters and the weld strength and percentage elongations were measured for all welds. Analysis of the suitable process parameters in case of each sheet thickness was done. Effect of sheet thickness on joint properties were also examined.

2. EXPERIMENTATION

Welding was performed on aluminium alloy 6061-T6 sheets in two different thicknesses: 0.5 mm and 1.0 mm. Table 1 presents some important mechanical properties of the workpiece material used. Aluminum alloy 6061-T6 is the most commonly used aluminium alloy and has excellent corrosion resistance, high strength and good formability. It can be readily welded using conventional fusion welding processes such as GTAW [6]. However, in fusion welding processes, there is presence of high heat input, shielding gases, fluxes, etc. which are undesirable in electronic packaging and therefore use of conventional welding methods for such applications is not preferable. Alternatively, FSW of this alloy can prove beneficial in above applications and is therefore chosen as the workpiece material in the present work. The tool used was H13 tool steel whose geometry for both the thicknesses were as follows: Equal shoulder diameter (6.4 mm) and, pin top and bottom diameter (2.4 and 2.0 mm) were used . Equal tool geometry was used because the difference in sheet thickness was not too large. Same tool geometry have also been used in other works for different workpiece thicknesses [7]. The aim of this work was to see the effect of sheet thickness reduction on process parameters, in particular, and not on other process variables, in general. The pin length in case of 0.5 and 1 mm sheets were kept as 0.33 and 0.83 mm, respectively so as to get penetration throughout the workpiece thickness in each case.

Table 1

Mechanical properties of the workpiece material AA6061-T6

Mechanical properties	0.5 mm sheet	1.0 mm sheet
Yield strength	276 MPa	278 MPa
Ultimate tensile strength	312 MPa	316 MPa
Elongation	18 %	18 %

Samples were welded parallel to the rolling direction on CNC milling machine (model: FLEXMILL; make: MTAB). A specially developed fixture best suited for joining of thin sheets was used. The fixture was capable of holding thin sheets with precision, uniform pressure and close to the weld line at the same time reducing heat loss from the sheets [8]. Both the thickness of sheets were exposed to the same set of process parameters (tool rotation speed, tool travel speed and plunge depth) so as to find the suitable parameters for each thickness in a fair manner. The levels of the parameters were selected after numerous trial experiments. After welding, the welded specimens were cut on wire-cut EDM (model: SPRINTCUT; make: ELECTRONICA) as per ASTM E8 standard of subsize specimen for transverse tensile tests. Uniaxial tensile tests were conducted on UTM machine (ZWICK/ROELL; model: Z050) at a strain rate of 0.001 per second, carried for two test samples

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for each weld. Table 2 gives the details of the parameters used, experiment design formed using Taguchi orthogonal array and the joint properties measured.

3. RESULTS AND DISCUSSION

3.1. EFFECT OF REDUCING SHEET THICKNESS ON PROCESS PARAMETERS

With reduction in sheet thickness, a smaller plunge depth was found to be more suitable. Loss of workpiece material (in the form of weld flash) due to higher plunge depth led to thinning of the welds which deteriorated the weld strength in case of 0.5 mm sheets. However, with 1 mm sheets, plunge depth was comparatively insignificant (see Table 3 and 4). For 1 mm sheets, even at lower plunge depth, more amount of heat would be generated due to bigger pin length, higher plastic work and lower heat dissipation from workpiece due to conduction.

On reducing sheet thickness, comparatively higher tool travel speed was observed to be more suitable as shown in Figure 1 and 2. The heat produced from friction between tool and workpiece corresponding to a particular tool rotation speed in case of thinner sheet would lead to a rise of temperature more quickly because of its lower thermal capacity. If this heat flux was not quickly distributed to other areas along the weld line, it could have led to melting, defects or excessive thinning in case of thinner sheets. These were possibly the reasons for this higher tool travel speed in case of thinner sheets. However, in case of thicker sheets, lower tool travel speed was observed to be more suitable. This can be attributed to the fact that comparatively more heat input per unit weld length was required in case of thicker sheets because of its higher thermal capacity. Higher tool travel speed, in fact, may lead to defects such as voids.

A tool rotation speed of 1900 rpm or higher was suitable in case of thinner sheets and in case of thicker sheets 1750 rpm or higher tool rotation speed was observed more suitable. The total heat input in FSW comes from the friction between the tool and the workpiece interface and from the plastic deformation of the workpiece material. In case of thicker sheets, both these heat sources increased and hence even at a lower tool rotation speed (which is a source of heat input) satisfactory welds were obtained. On the other hand, lower plunge depth and hence lower tool-workpiece contact led to lower heat source in case of thinner sheets. Thus, the heat requirement had to be fulfilled from a higher tool rotation speed in this case.

In addition to the above observations, it was also interestingly noted that the most suitable process parameters window for obtaining a weld strength of 200 MPa or higher was more wide in case of 1 mm sheets than in case of 0.5 mm sheets as can be seen in Figure 1 and 2. This observation goes well with the present understanding of the challenge present in process parameters selection in joining of ultra-thin sheets which is mainly due to the fact that adverse effect of process parameters gets more dominant when we downscale the FSW process. Higher tool rotation has risk of tearing, higher tool penetration has risk of excessive thinning and higher tool travel speed has risk of defects [2,8]. On the other hand, lower values of tool rotation speed in case of thinner sheets is not justified because relatively more energy is required in case of thinner sheets and much of that should come from shoullder friction [2].

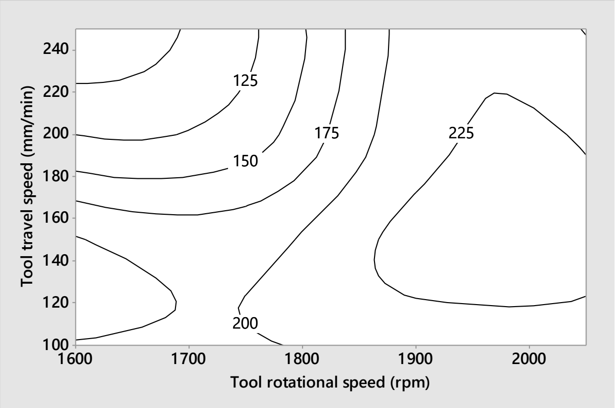

Figure 1 Contour plot for 0.5 mm sheet on UTS

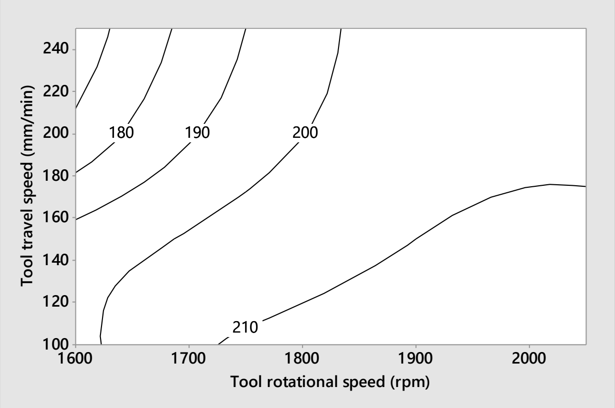

Figure 2 Contour plot for 1 mm sheet on UTS

3.2. EFFECT OF REDUCING SHEET THICKNESS ON JOINT PROPERTIES

From previous section, it can be concluded that there are separate set of process parameters which are best suited in case of thin and in case of ultra-thin sheets. It can be anticipated that these separate set of process parameters would affect the joint properties in case of each thickness. The best set of process parameters in case of 0.5 mm and 1 mm sheets were observed to be 1900 and 2050 rpm of tool rotation speed, 150 and 100 mm/min of tool travel speed and 0.10 mm of plunge depth, respectively. The best weld strength observed in case of 0.5 mm sheets was 232 MPa and that in case of 1 mm sheet it was 213 MPa. This can be attributed to the fact that the tool travel speed in case of 1 mm sheets was still too high leading to a lower heat input in this case which restricted the achievement of the best weld strength. Moreover, the stirring effect of the welding tool becomes weaker in FSW of thicker sheets [9]. So, as far as material deformation is considered, FSW of thinner sheets were advantageous.

Lower sheet thickness had comparatively poor ductility compared to thicker sheet welds. The best ductility in case of 0.5 mm sheets was 6.7 % and that in case of 1 mm sheets it was 7.7 %. Ductility in welds is dependent upon the temperature generated during welding. In case of thicker sheets, both the contribution from frictional heat and that from the plastic deformation was higher. At the same time there was comparatively lower heat loss in 1 mm sheets and hence a higher value of ductility was obtained at a particular set of process parameter.

3.3. EFFECT OF PROCESS PARAMETERS ON JOINT PROPERTIES IN DIFFERENT SHEET THICKNESS WELDS

In case of 0.5 mm sheets, an increase in plunge depth reduced the weld strength as well as percentage elongation, as can be seen from Figure 3 and 5. Excessive thinning in case of thinner sheets led to this effect on joint's strength. However in case of 1 mm sheets, plunge depth was not that significant (Figure 4 and 6). In fact, higher plunge depths were also favourable. This can be attributed to the fact that more heat input was present at higher plunge depth which was indeed required in 1 mm sheets.

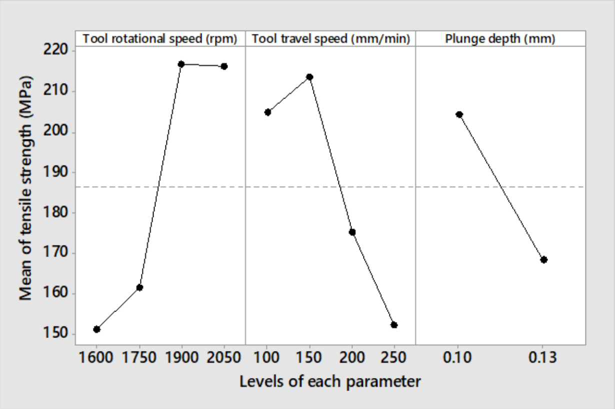

Figure 3 Main effect plot for means of tensile strength in 0.5 mm sheets

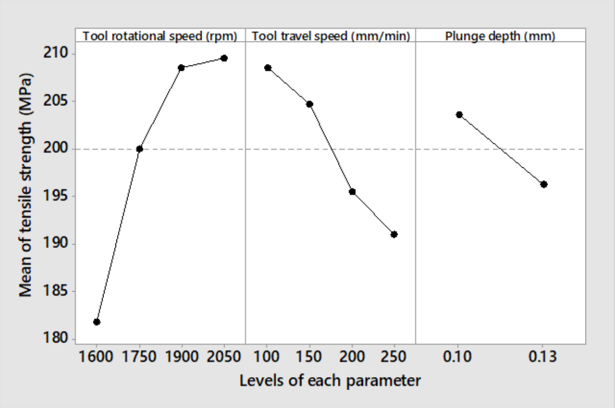

Figure 4 Main effect plot for means of tensile strength in 1 mm sheets

Lower tool travel speeds resulted in higher value of percentage elongation in case of each sheet thickness as can be seen from Figures 5 and 6. A tool travel speed of 150 mm/min was found to be the most suitable in case of 0.5 mm sheets for obtaining best weld strength as well as percentage elongation. At this feed, the heat input was appropriate enough which avoided problem of excessive heating or too less heating. In case of 1 mm sheets, the best joint properties were observed at 100 mm//min. It was also observed that the tool travel speed was most significant factor in deciding the weld ductility (more than the tool rpm). This was because travel speed was responsible in distributing heat all along the weld line (the source of heat being tool rotation).

Increasing tool rotational speed in each thickness led to more heat flux into workpieces. However in case of 0.5 mm sheets, speeds lower than 1900 rpm did not yield satisfactory weld strength. The heat input at those speeds, corresponding to the plunge depth of 0.1 mm was not sufficient for complete plastic deformation of the workpieces. In case of 1 mm sheets, speeds lower than 1750 rpm had this effect. For 1 mm sheets, even at 1750 rpm, proper plastic deformation was possible because of additional frictional heating and heating from the work of plastic deformation. However elongations in both sheet thickness were found to deteriorate below 1900 rpm.

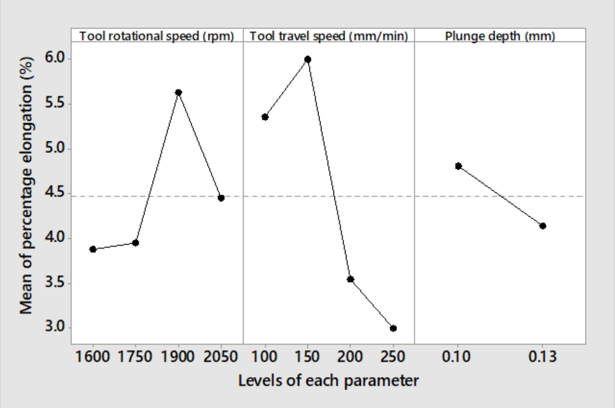

Figure 5 Main effect plot for means of percentage elongation in 0.5 mm sheets

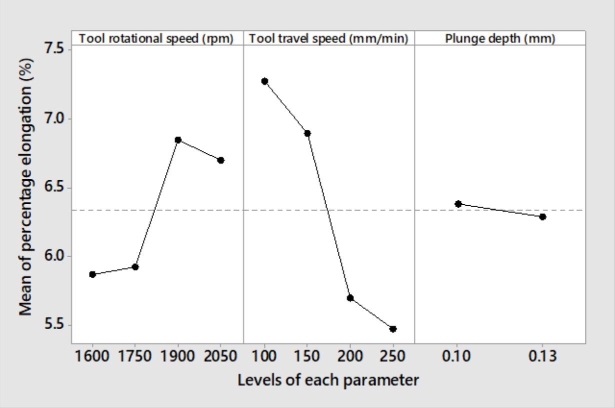

Figure 6 Main effect plot for means of percentage elongation in 1 mm sheets

Tables 3 and 4 shows the results of ANOVA for welds in case of each sheet thickness. Tool rotational speed was found to be the most significant factor on deciding the weld strength followed by the tool travel speed and, tool plunge depth was the least significant factor in case of both the thicknesses.

4. CONCLUSIONS

In this work, effect of reducing workpiece thickness from 1 mm to 0.5 mm, on process parameters and weld strength have been studied for friction stir welding of AA6061-T6 sheets. The work led to the following conclusions:

- The process window for 1 mm sheets was wider than 0.5 mm sheets for obtaining an ultimate strength of 200 MPa or more.
- Comapartively higher tool travel speed and lower shoulder penetration were more suitable for thinner sheets.
- Comparatively better ductility in terms of percentage elongation was observed for 1 mm sheets.

- Tool rotational speed was found to be the most significant factor affecting the weld strength and shoulder plunge depth the least significant factor, independent of sheet thickness.

Table 2

Process parameters, their levels and experimental results for FSW of 0.5 and 1 mm sheets

Exp. No.	Tool rotational speed (rpm)	Tool travel speed (mm/min)	Plunge depth (mm)	Mean UTS (0.5 mm)	Mean % Elongation (0.5 mm)	Mean UTS (1.0 mm)	Mean % Elongation (1.0 mm)
1	1600	100	0.10	198	5.3	197	7.1
2	1600	150	0.10	202	5.8	193	6.0
3	1600	200	0.13	125	2.5	173	5.3
4	1600	250	0.13	80	1.9	164	5.1
5	1750	100	0.10	198	5.1	211	6.7
6	1750	150	0.10	190	5.6	204	7.0
7	1750	200	0.13	138	3.0	195	5.1
8	1750	250	0.13	120	2.1	190	4.9
9	1900	100	0.13	208	6.0	213	7.6
10	1900	150	0.13	232	6.7	210	7.2
11	1900	200	0.10	216	4.7	206	6.7
12	1900	250	0.10	211	5.1	205	5.9
13	2050	100	0.13	215	5.0	213	7.7
14	2050	150	0.13	230	5.9	212	7.4
15	2050	200	0.10	222	4.0	208	5.7
16	2050	250	0.10	198	2.9	205	6.0

Table 3

Results of ANOVA for tensile strength in 0.5 mm sheets

Source	DF	Seq SS	% Contribution	Adj SS	Adj MS	F-value
Tool rotational speed	3	14671	48.08	14671	4890.2	31.28
Tool travel speed	3	9447	30.96	9447	3148.9	20.14
Plunge depth	1	5148	16.87	5148	5148.1	32.93
Error	8	1250	4.10	1250	156.3	
Total	15	30516	100			

Table 4

Result of ANOVA for tensile strength in 1 mm sheets

Source	DF	Seq SS	% Contribution	Adj SS	Adj MS	F-value
Tool rotational speed	3	1982.19	64.42	1982.19	660.73	56.84
Tool travel speed	3	784.19	25.49	784.19	261.40	22.49
Plunge depth	1	217.56	7.07	217.56	217.56	18.72
Error	8	93.00	3.02	93.00	11.63	
Total	15	3076.94	100			

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