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Investigation into the effect of temper condition on friction stir weldability of AA6061 Al-alloy plates

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Abstract

Although Al-alloys have been widely applied in transportation industries in recent years owing to their low density and excellent formability properties, further advancement in welding of these alloys is a very critical issue for further increasing their use in practice. These alloys, which exhibit difficulties in fusion welding processes, particularly age-hardened grades, can be successfully joined by friction stir welding.

In this study, AA6061 Al-alloy plates both in O and T6 temper conditions were joined by friction stir welding using four different sets of weld parameters. Microstructural and mechanical characterization of the joints produced was made by detailed optical microscopy investigations, extensive hardness measurements and tensile tests. The effect of temper condition on the joint performance was also determined in addition to the effect of weld parameters on the joint quality.

Key words: Al-alloys, friction stir welding, mechanical properties, joint performance, temper condition

1. Introduction

Friction stir welding (FSW), which is a relatively novel solid state joining method was developed in 1991 at The Welding Institute (TWI), U.K. [1, 2]. This joining process can be successfully used for joining difficult-to-fusion weld Al-alloys, i.e. age hardened AA7075 Al-alloy [3–7]. The problems experienced in fusion joining of Al-alloys, i.e., excessive porosity formation and cracking particularly in that of age hardened grades [8–11], are not encountered in FSW of these alloys owing to the fact that it is a solid state joining method. Several researchers have reported that sound joints were readily produced in Al-alloys by this method [3–6, 12–18]. The process has also been demonstrated to be used successfully in joining of other structural materials, i.e. Cu-alloys [19–22] and Mg-alloys [23–25].

In this method, a non-consumable rotating tool with a specially designed pin and shoulder is plunged into the abutting edges of the plates to be joined and traversed along the line of joint. The tool heats the work-piece and moves the material to produce the joint. The heating is accomplished by friction between the tool and the work-piece and plastic deformation of work-piece. The localized heating softens the material around the pin and combination of tool rotation and translation produce the joint by mixing the abutting edges of the work-pieces [2–6, 26].

The peak temperature generated during FSW is below the melting temperature of the work-piece. Thus, the mechanical properties of the joints produced by this technique in Al-alloys are usually better than those obtained by fusion joining of these materials [14–17, 26].

Although there are numerous reports on friction stir welding of 6XXX series Al-alloys plates, most of these works concentrated on the determination of friction stir weldability of this alloy in age-hardened condition and microstructural and mechanical characterization of the joints produced [14, 16–18, 27–30]. Therefore, there is still a need for further research on

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Table 1. Chemical compositions of the plates used (wt.%)

Material	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Others
AA6061-O	Bal.	0.68	0.6	0.3	0.09	1.1	0.19	0.14	0.03	0.01	0.08
AA6061-T6	Bal.	0.65	0.54	0.25	0.11	0.9	0.19	0.05	0.07	–	0.01 Ni

Table 2. Weld parameters used

Parameters		
Symbol	Rotation rate (rpm)	Travel speed ($\mathrm{mm\,min^{-1}}$)
750/150	750	150
1000/200	1000	200
1250/300	1250	300
1500/400	1500	400

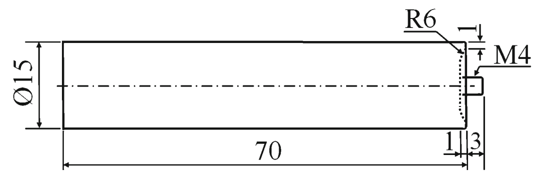

Fig. 1. Schematic illustration of the details of the stirring tool used in this study (in mm).

friction stir welding of AA6061 Al-alloy plates, particularly for works aiming at the determination of the effect of temper condition on joint quality.

In this study, AA6061 Al-alloy plates were joined by FSW both in O and T6 temper conditions using different weld parameters, i.e. rotation rate and weld speed. The effect of weld parameters on the joint quality in both temper conditions was investigated. The effect of original temper condition of the plates on the joint quality was also determined.

2. Experimental procedure

Both AA6061-O and AA6061-T6 Al-alloy plates with a thickness of 3.17 mm (0.125 inches) were used in this study. The chemical compositions of the plates used are given in Table 1. The plates were joined perpendicular to the rolling direction by FSW using various weld parameters, which are given in Table 2, at a CNC machine with the usual clamping and steel backing plate. The welding parameters were selected considering the existing literature [28–30] and to determine the effect of temper condition on the joint quality for AA6061 Al-alloy. A stirring tool with a cylindrical pin produced from H13 tool steel was used for joining trials in this study. The shoulder diameter was 15 mm. The pin was threaded with a diameter of 4 mm (M4). The welding trials were conducted in position control mode and no tilting was employed. The other details of the stirring tool used in this study are illustrated in Fig. 1.

Microstructural evolution within the weld region was investigated in detail on the specimens extracted from the joints obtained. For that purpose, cross-sections were cut through the experimental welds, polished and etched. The etching was conducted using Keller's reagent at room temperature. Extensive microhardness measurements were also conducted across the joints using a load of 100 g (loading time is 20 s) to determine the hardness profiles. To determine the mechanical properties of the joints, four standard transverse tensile test specimens were also extracted from each joint produced. The geometry of the specimens tested was given in a previous publication [26]. Tensile testing of the base plates was also performed to determine the joint performance values of the joints. All tensile tests were conducted using a loading rate of 1 $\mathrm{mm\,min^{-1}}$.

3. Results and discussion

3.1. Microstructural aspects

Optical micrographs showing the microstructures of the base plates and the macrographs illustrating the transverse cross-sections of the joints produced are given in Figs. 2 and 3, respectively. O represents annealed material, which is heat treated in alpha phase region and possesses therefore low strength (soft), whereas T6 stands for solution heat treated and then artificially aged material, which has a significantly higher strength due to the presence of homogeneously distributed fine precipitates in the alpha matrix [31]. As seen from Fig. 2, both base plate microstructures exhibited inhomogeneously distributed iron and silicon rich particles. While the microstructure of annealed plate (i.e., AA6061-O) consists of alpha grains containing inhomogeneously distributed large rounded particles, i.e., Mg_2Si, that of the T6-treated plate consists of alpha grains containing inhomogeneously distributed script-like Fe_3SiAl_{12} particles and large rounded Mg_2Si particles [32]. The strengthening particles existing in the microstructure of age-

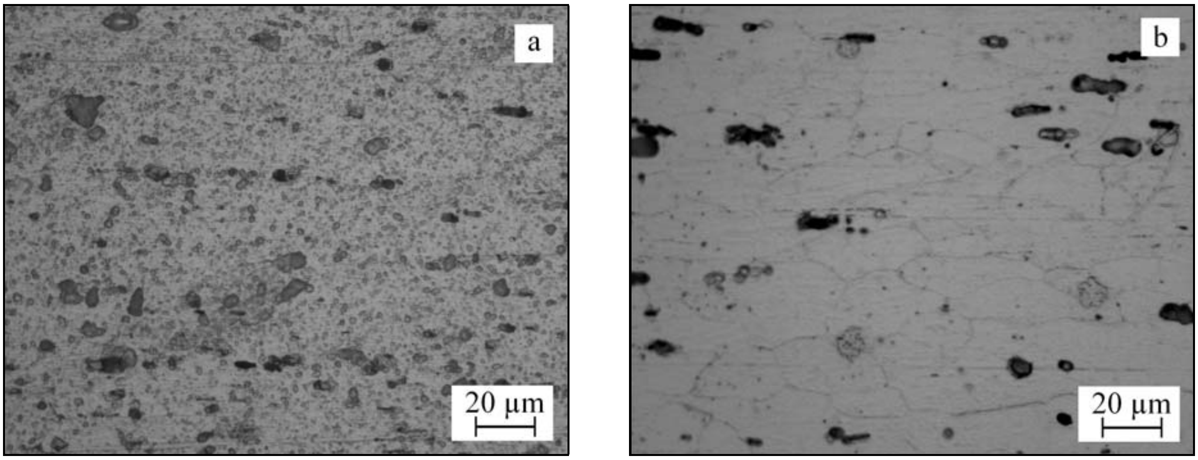

Fig. 2. Microstructures of the as-received base plates: (a) AA6061-O and (b) AA6061-T6.

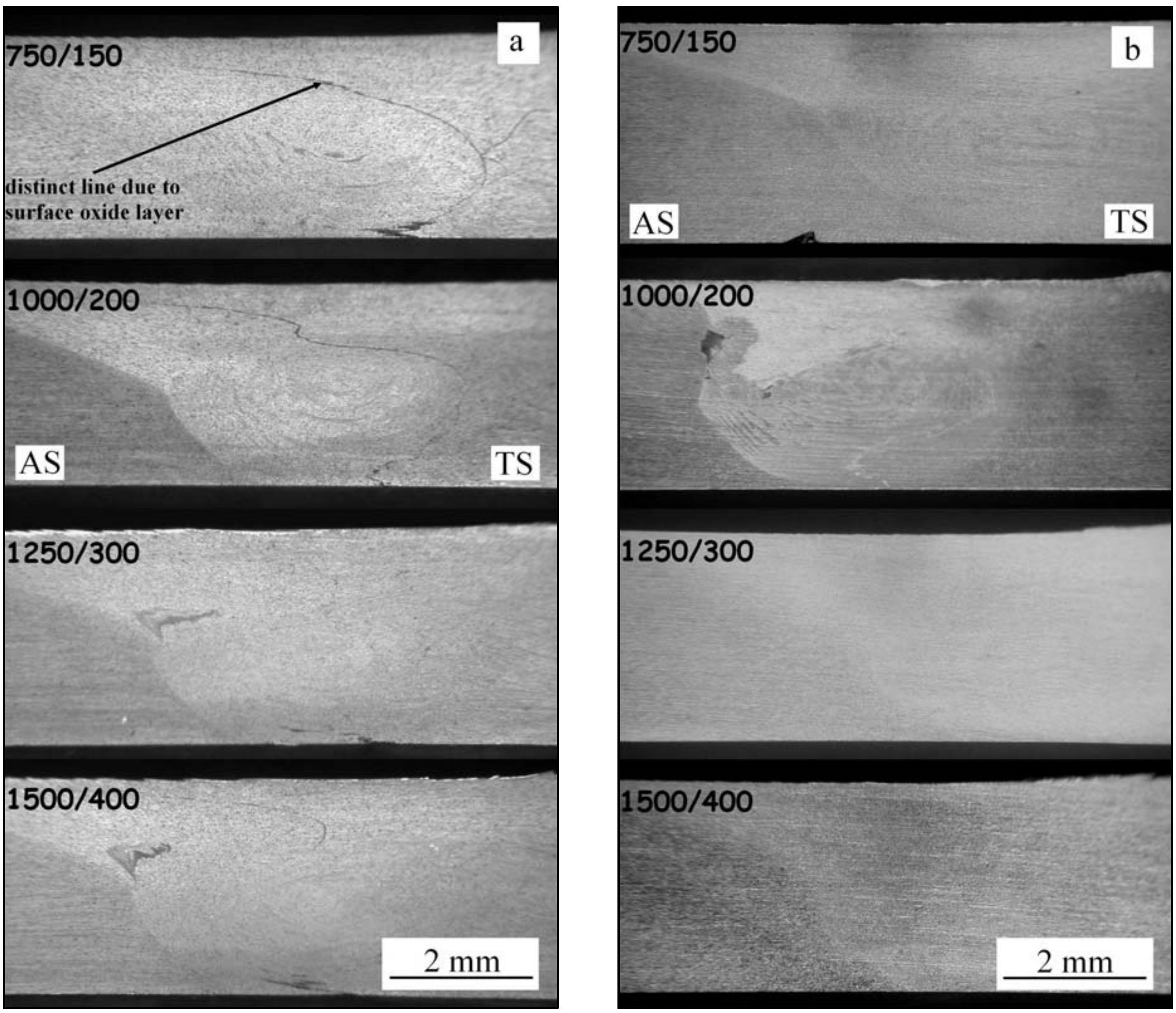

Fig. 3. Optical macrographs showing the transverse cross-sections of the joints: (a) AA6061-O, (b) AA6061-T6.

-hardened (T6 treated) plate, i.e., finely distributed Mg_2Si precipitates, are not clearly visible at this magnification (Fig. 2b). No significant differences in microstructures of the stir zones of AA6061-O plates produced with different sets of weld parameters were observed. On the other hand, the microstructures of the nugget zones of AA6061-T6 joints produced are shown in Fig. 4. As seen from this figure, a fine grain

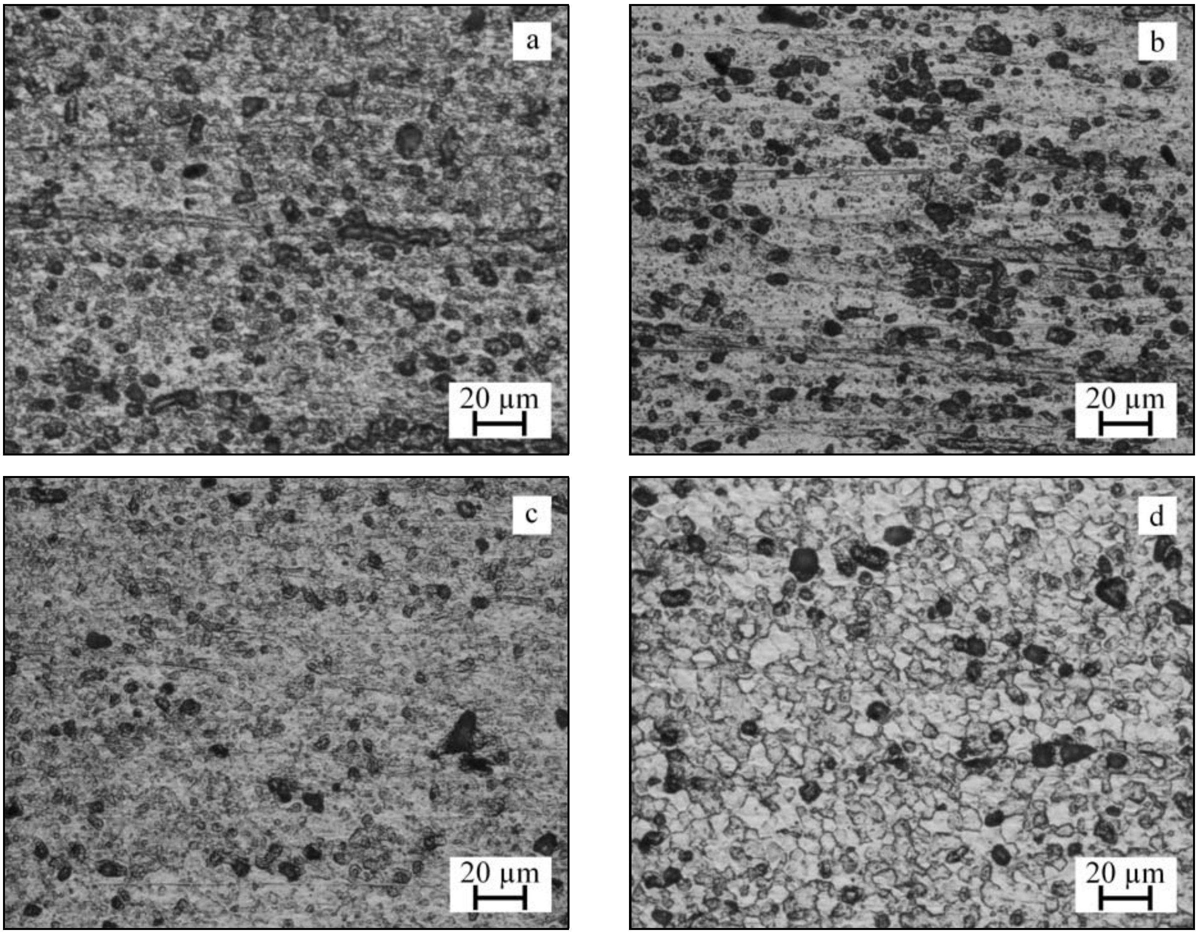

Fig. 4. Optical micrographs of the nugget zones of AA6061-T6 joints produced at: (a) 750 rpm/150 mm min^{-1}, (b) 1000 rpm/200 mm min^{-1}, (c) 1250 rpm/300 mm min^{-1}, and (d) 1500 rpm/400 mm min^{-1}.

structure was evolved in the stir zone of the joints in T6 temper condition, which was also the case in O temper condition. Furthermore, distinct lines have been observed in the nugget zones of the AA6061-O joints, Fig. 3a. However, liquid penetrant examination revealed that no defects existed within the weld zone of these joints, Fig. 5. The plate surfaces were not cleaned mechanically or chemically following laser beam cutting prior to joining. Thus, the reason for the existence of these distinct lines is attributed to the presence of surface oxide layers, which is currently observed in friction stir welded Al-alloys.

Optical microscopy also revealed that no weld defect formation took place in the weld regions of the joints of AA6061-T6 plates, except the joint produced with a parameter set of 1000 rpm and 200 mm min^{-1}. As seen from Fig. 3b, there is a weld defect in the upper part of this joint, which is believed to occur due to the insufficient plasticization of the alloy during joining resulting from the insufficient weld parameters.

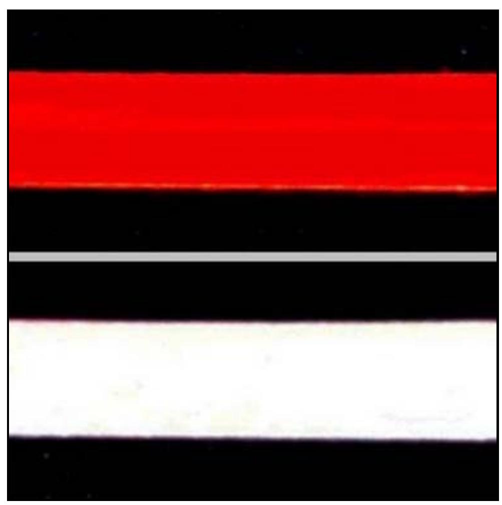

Fig. 5. Liquid penetrant examination result of an AA6061--O joint.

3.2. Hardness

Figure 6 shows the hardness profiles obtained from all the joints produced. The joints produced in the O and T6 temper conditions exhibit different hardness values in the weld region, namely hardness in-

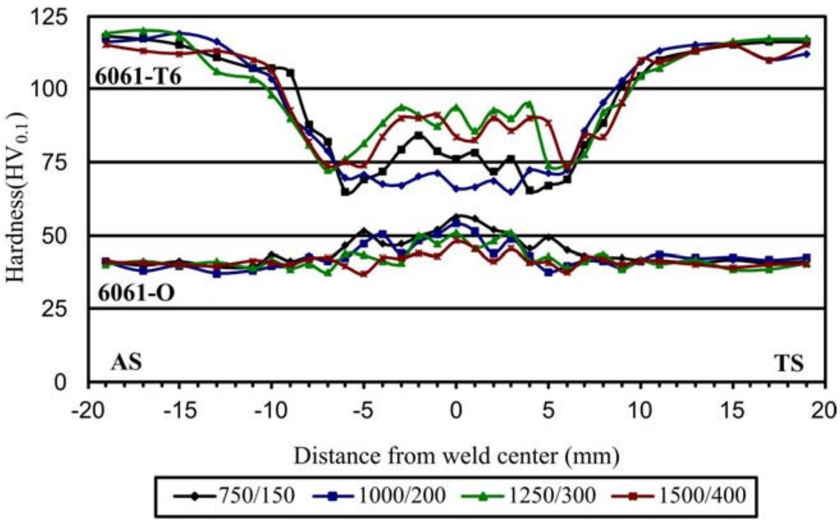

Fig. 6. Hardness profiles of the joints produced.

crease and hardness loss, respectively. This is due to the difference in their original microstructures prior to joining, the microstructure of material with O temper consisting of alpha grains without homogeneously distributed fine precipitates while that of the material with T6 temper consists of alpha grains containing homogeneously distributed fine precipitates, which significantly increase the strength of the material [31].

As seen from Fig. 6, there is a hardness increase in the weld regions of all the joints produced in the O temper condition. Similar results were also reported for other age hardenable Al-alloys FSWed in O temper condition by [33–35]. The reason for this hardness increase is the fact that the as-received base material (O-temper condition) was in the homogenized condition wherein all strengthening precipitates are dissolved, thus, the material has a low strength (is soft) prior to joining and the grain refinement takes place in the stir zones of the joints produced in this temper condition. The evolution of some fine precipitates in the weld nugget of the joints produced in the O temper condition was also reported to be the reason for this hardness increase although it was not supported by a detailed TEM investigation [33]. The increase in hardness decreases slightly with the increase in the rotation rate and weld speed. While the highest hardness value (i.e., 56 HV) in the weld region was displayed by the joint produced with the weld parameters of 750 rpm and 150 mm $\min^{-1}$, the joint produced at 1500 rpm with a travel speed of 400 mm $\min^{-1}$ exhibited the lowest hardness value, i.e., 48 HV, in the weld region. This is believed to be due to the difference in the grain size within weld region resulting from different heat inputs involved. A more significant hardness increase in the weld regions has been reported for friction stir welded AA7075 Al-alloy plates in O temper condition [26].

On the other hand, a hardness loss occurred within the weld zones of all the joints produced in the T6 temper condition, Fig. 6. This is not surprising since the T6 treated material has originally a high strength and overaging (coarsening of finely distributed precipitates) takes place in the HAZ and dissolution of precipitates occurs in the stir zone during friction stir welding of aged Al-alloy plates giving rise to hardness decrease in these regions [28, 35]. Although the hardness loss taking place in the HAZs of the joints produced with different weld parameters is similar, a larger scatter in the hardness of stir zones of AA6061-T6 joints was observed in contrast to a much lower scatter in hardness of the stir zones of AA6061-O joints. As seen from Fig. 6, the hardness loss is lower in the joints produced with the lower welding speeds (i.e., 150 and 200 mm $\min^{-1}$), whereas it is more significant for the joints produced with higher weld speeds (i.e., 300 and 400 mm $\min^{-1}$). The reason for this is the higher heat inputs involved in the joints produced with lower weld speeds resulting in a higher degree of precipitate dissolution and the difference in the amount of coarse particles in the weld zones of the joints produced with higher and lower heat inputs. Similar results were also reported for FSWed AA6061-T651 and T4 alloys [30, 36]. Similar hardness loss in the weld area has also been reported for friction stir welded AA7075-T6 Al-alloy plates [26]. The lowest hardness value within the weld region (i.e., 65 HV) was displayed by the joint produced with the weld parameters of 1000 rpm and 200 mm $\min^{-1}$.

3.3. Tensile properties

Table 3 gives the summary of the tensile test results obtained from all the joints produced, and Fig. 7 gives a column graphic summarizing average values of

T a b l e 3. Summary of tensile test results

Weld parameters (rpm/mm min^{-1})	Tensile strength (MPa) Elongation (%)											
	AA6061-O						AA6061-T6					
	1	2	3	4	Ave.*	JP (%)**	1	2	3	4	Ave.*	JP (%)**
Base Metal	–	–	–	–	**123**	–	–	–	–	–	**345**	–
					28.2	–					**11.7**	–
750/150	123.8	123.5	122.8	123.2	**123.3**	**100**	228.4	234.6	235.6	228.6	**231.8**	**67.2**
	23.8	24.5	24.6	24.7	**24.4**	**86.5**	2.7	2.6	3	3.4	**2.9**	**24.8**
1000/200	122.5	122.9	122.8	123.2	**122.9**	**100**	188.2	191.2	198.2	189.5	**191.8**	**55.6**
	24.8	24.4	23.9	23.9	**24.3**	**86.2**	1.2	1.1	1.3	1	**1.2**	**10.3**
1250/300	122.3	122.9	123.2	123.2	**123.2**	**100**	243.6	244.4	226	247	**240.3**	**69.7**
	24.1	24.6	24.2	23.6	**23.9**	**84.8**	1.6	1.3	1.5	2.2	**1.7**	**14.5**
1500/400	123.4	122.7	123.8	123.7	**123.4**	**100**	264.3	235	261.7	264.7	**256.4**	**74.3**
	26	21	23	23.9	**23.5**	**83.3**	2.5	2.1	2.6	2.4	**2.4**	**20.5**

* average value of four specimens; ** joint performance value

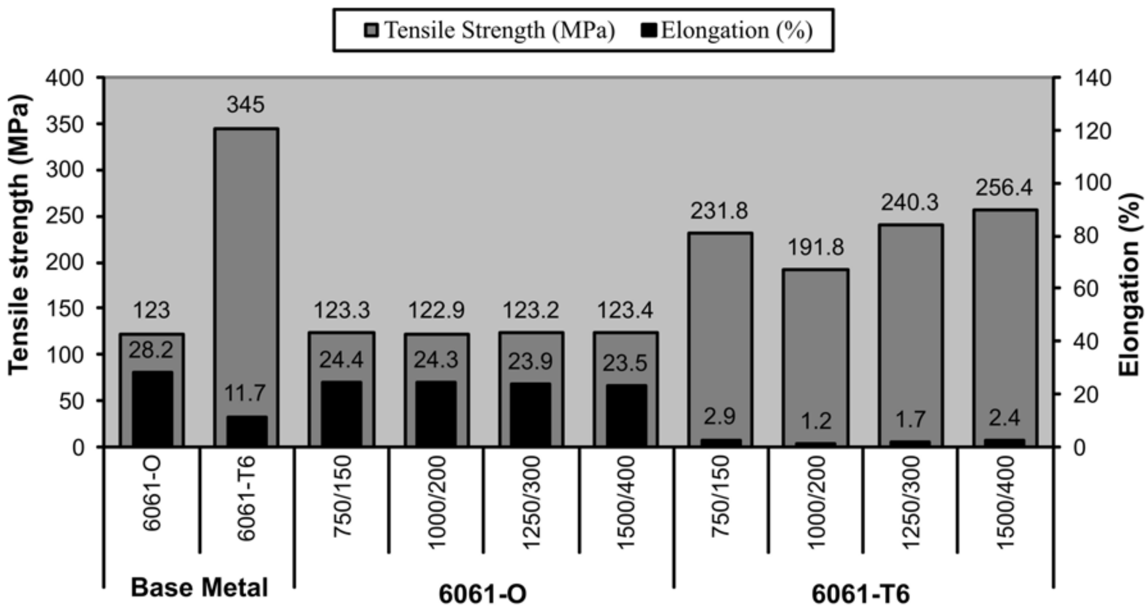

Fig. 7. Summary of average values of the tensile test results.

the tensile test results obtained. All tensile test specimens extracted from the joints produced in O temper condition failed in the base metal away from the joint area, Fig. 8. These results are in good agreement with the hardness measurements conducted on these joints, which exhibited a hardness increase in the weld area as seen from Fig. 6. The tensile strength values obtained from these joints are comparable to those of the base plate, i.e. AA6061-O. Thus, the joints exhibited about 100 % joint efficiency as seen from Table 3 and Fig. 7. Similar results were also reported in [26, 33, 35]. These results also indicate that sound FSWed AA6061 joints can be produced within a large window of weld parameters in O temper condition. While these joints exhibited comparable strength values to that of the base plate, they displayed somewhat lower ductility than the base plate. The elongation of these joints was about 24 % whereas that of the base plate is 28 %. This slight decrease in the elongation is also due to the hardness increase in the weld region, which does not yield during testing thus reducing the overall elongation of the specimen. Similarly, lower elongation

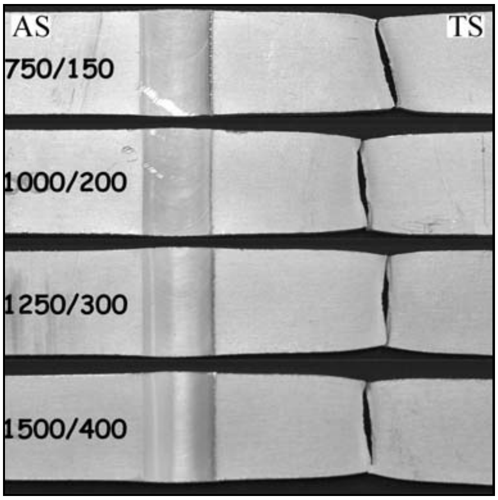

Fig. 8. Tensile test specimens extracted from the joints welded in O temper condition failing in the base plate away from the joint area.

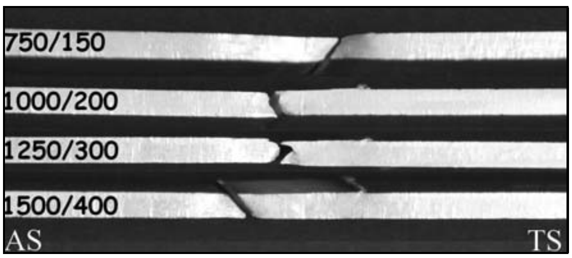

Fig. 9. Tensile specimens extracted from the joints welded in T6 temper condition failing in the joint area.

values were also reported for strength overmatching friction stir welds of AA7075-O Al-alloy plates [26] and strength overmatching laser beam welded steel joints than those of the respective base material [37, 38].

On the other hand, all tensile test specimens extracted from the joints produced in T6 temper condition failed within the joint area, Fig. 9. These results are also in good agreement with the hardness measurements conducted on these joints, which exhibited a significant hardness decrease in the weld area as seen from Fig. 6. It is also worth noting that the scatter in the strength values of these joints is significantly large. The joint produced with the weld parameters of 1500 rpm and 400 mm min^{-1} (i.e., 1500/400) displayed the highest tensile strength value, i.e. 256 MPa, the joint performance value being about 75 %. It was also observed that the specimens extracted from the joints produced with the weld parameters of 750/150 and 1500/400 exhibited a shear fracture with the shear fracture path at an angle of 45 degrees to the axis of tension, Fig. 9. While the specimens extracted from the joint produced with the weld parameters of 750/150 failed within the TMAZ region, the specimens extracted from the joint produced with the weld parameters of 1500/400 failed along the interface between HAZ and the weld region. The specimens extracted from the joint produced with the parameters of 1000/200, which contain weld defect in the joint area, failed perpendicular to the axis of tension around the defect and then in a shear fracture mode. On the other hand, the specimens extracted from the joint produced with the parameters of 1250/300 exhibited a cup and cone type failure. These results are in good agreement with the results reported by Ren et al. [30]. They reported that the failure took place along the weakest path in terms of hardness distributions in FSWed AA6061-T651 Al-alloy plates. They also reported that the weakest path lay perpendicular to the tensile axis in the joints produced at a lower travel speed of 100 mm min^{-1} whereas it lay at an angle of 45 degrees to the tensile axis in the joints produced at a higher travel speed, i.e. 400 mm min^{-1}. They also pointed out that the heat indexes could be used as the parameters to describe the thermal input, tensile properties and fracture behaviour of FSWed AA6061-T651 Al-alloy plates and suggested that the travel speed and the direction of lowest hardness profiles appear to be the dominating factor in determining the tensile properties and the fracture mode of the welds. The results of the present work are in good agreement with this. Thus, it can be pointed out that the hardness distribution determines the failure path and the fracture paths correspond well with the lowest hardness profiles in these joints.

The specimens extracted from the joints produced in T6 temper condition exhibited much lower elongation values (i.e. between 1 and 3 %) than that of the base plate, i.e. 12 %. This can also be attributed to the significant hardness decrease in the weld region of these joints, leading to confined plasticity. The soft weld region only plastically deforms in the tensile testing of these specimens due to the much higher strength of base plate, e.g. highly strength undermatching nature of the joint. Similarly, very low elongation values were also reported for FSWed cold worked Al-alloy plates [12, 35, 36] and laser or electron beam welded highly strength undermatched Al-alloys joints [8–11].

4. Conclusions

The following conclusions have been drawn from the present study:

– Sound joints can be produced by FSW of AA6061 Al-alloy plates both in O and T6 temper conditions.

– The joints produced in the O temper condition displayed a hardness increase in the weld region due to grain refinement whereas those produced in T6 temper condition exhibited a significant hardness drop in the weld region resulting from overaging.

– The specimens extracted from the joints produced in O temper condition failed in the base plate away from the joint area due to strength overmatching while the specimens extracted from the joints produced in T6 temper condition fractured in the joint area due to the existence of a high strength undermatching in these joints.

– The failure in tensile testing takes place along the weakest path in terms of hardness, in other words, the fracture paths correspond well with the lowest hardness distribution profiles.

– All the joints produced in O temper condition displayed comparable strength values to that of the base plate (the joint performance value of all the joints produced in O temper condition being about 100 %).

– All the joints produced in T6 temper condition exhibited lower strength values than that of the base plate (the maximum tensile strength performance in T6 condition, i.e. 75 %, was obtained from the joint produced at a rotation rate of 1500 rpm with a travel speed of 400 mm min^{-1}, which exhibited a 45° shear fracture).

– AA6061 plates can be satisfactorily FSWed within a large window of weld parameters in O temper condition whereas the weld parameters play a significant role on the joint quality in T6 condition.

– The optimum rotation rate for FSW of AA6061 plates was found to be 1500 rpm for both temper conditions as it allows a higher welding speed, i.e., 400 mm min^{-1}.

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