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INVESTIGATION OF THE EFFECT OF TEMPER CONDITION ON THE FRICTION-STIR WELDABILITY OF AA7075 Al-ALLOY PLATES

RAZISKOVANJE UČINKA POPUŠČANJA PLOŠČE IZ ALUMINIJEVE ZLITINE AA7075 NA VARIVOST S TRENJEM

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Al-alloys are widely used in the transportation industries due to their low density and excellent formability properties. These alloys, which are problematic in fusion-welding processes, can be successfully joined by friction-stir welding. Particularly high-strength AA7075 alloy is considered to be non-weldable by fusion welding. Friction-stir welding, being a solid-state joining technique, can also be successfully used in joining other difficult-to-weld alloys. In this study, 3.17-mm-thick, AA7075 Al-alloy plates both in the O- and T6-temper conditions were joined by friction-stir welding using four different weld parameters. Microstructural and mechanical characterizations of the joints produced were obtained with detailed optical microscopy investigations, extensive hardness measurements and tensile tests. The effect of temper condition on the joint performance was determined in addition to the effect of the weld parameters on the joint quality.

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

Aluminijeve zlitine se pogosto uporabljajo v transportni industriji zaradi majhne gostote in odličnih preoblikovalnih lastnosti. Z varjenjem s trenjem se je mogoče izogniti težavam, ki nastopajo med talilnim varjenjem teh zlitin, in sicer predvsem napakam ob liniji zlitja. Predvsem visokotrdnostna aluminijeva zlitina AA7075 se šteje kot težko variva s talilnim varjenjem. Varjenje s trenjem se je izkazalo kot ustrezen postopek za spajanje te zlitine. V okviru prispevka smo s trenjem zavarili 3.17 mm debelo ploščo iz aluminijeve zlitine AA7075 v dveh stanjih: brez popuščanja (stanje O) in z njim (stanje T6). Varili smo večkrat z različnimi parametri varjenja s trenjem. Iz zavarjenih plošč smo pripravili vzorce in eksperimentalno ugotovili mehanske lastnosti. Izmerili smo trdoto in naredili natezne preizkuse ter opravili podrobne metalografske preiskave. Dodatno k učinku parametrov varjenja na kvaliteto spoja je bil določen tudi učinek popuščanja, ki se izraža pri varilnih parametrih in s tem vpliva na kakovost zavarjenega spoja.

Ključne besede: aluminijeva zlitina, varjenje s trenjem, mehanske lastnosti, lastnosti spoja, pogoji popuščanja

1 INTRODUCTION

Friction-stir welding (FSW) is a relatively new solid-state joining method developed in 1991 at the Welding Institute (TWI), UK.[1,2] This method can be successfully used for joining difficult-to-fusion-weld Al-alloys, i.e., the age-hardened AA7075 Al-alloys[3–7] as well as the other structural materials, i.e., Cu-alloys[8–11] and Mg-alloys.[12–14] Excessive porosity formation and cracking may be encountered in the fusion joining of Al-alloys, particularly in those consisting of age-hardened grades.[15–17] These problems are, on the other hand, not encountered in the FSW of these alloys due to the fact that it is a solid-state joining method. Several researchers have reported that sound joints are readily produced with this method in such alloy.[3–6,18–24]

In friction-stir welding, a non-consumable rotating tool consisting of a pin and shoulder is plunged into the abutting edges of the plates to be joined and traversed along the line of the joint. The tool heats the workpiece and moves the material to produce the joint. The heating is accomplished by the friction between the tool and the workpieces causing plastic deformation of the work-pieces. The localized heating softens the material around the pin, and the combination of the tool rotation and translation produces a joint by mixing the abutting edges of the workpieces.

The peak temperature generated during FSW is below the melting temperature of the material to be welded. 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.[20–23,25]

The 7xxx-series aluminum alloys are precipitation-hardened Al-Zn-Mg-(Cu) alloys that have been used extensively in the aircraft structural components, mobile equipment and other highly stressed applications. Although numerous studies were conducted on friction-stir welding of AA7075 Al-alloy plates[18,19,25–32], the material-property data, particularly with respect to fatigue properties, is still limited as well as the effect of temper condition on the joinability of these alloys by FSW. The aim of this work is to demonstrate the effect of temper condition on the joinability of these alloys. Thus, AA7075 Al-alloy plates were joined by FSW in two different temper conditions, i.e., the O (annealed)-

Table 1: Chemical compositions of the plates used (in mass fractions, *w*/%)
Tabela 1: Kemijska sestava uporabljenih plošč (v masnih deležih, *w*/%)

Material	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr	Others
AA7075-O	Bal.	0.12	0.24	1.46	0.03	2.48	0.19	5.61	0.03	0.01	0.01	0.02
AA7075-T6	Bal.	0.05	0.09	1.69	0.02	2.42	0.20	5.60	0.04	0.006	0.005	0.001 B, 0.0018 Pb, 0.004 Ni, 0.0026 Sn, 0.003 Be, 0.08 H_2*

* ml H_2/100g Al

and the T6 (aged)-temper conditions, using different weld parameters, i.e., different rotation rates and weld speeds. The effect of weld parameters on the joint quality in both temper conditions was investigated. The effect of the original temper condition of the plates on the joint quality was also determined.

2 EXPERIMENTAL PROCEDURE

AA7075 Al-alloy plates with a thickness of 3.17 mm, in both annealed (softened) and aged conditions (i.e., AA7075-O and AA7075-T6, respectively), were used in this study. The chemical compositions of the plates used are given in **Table 1**. The plates of 300 mm × 130 mm were extracted from both as-received plates for weld trials. The plates were joined perpendicularly to the rolling direction (the weld length of 300 mm) by FSW using various weld parameters, **Table 2**. The welding trials were conducted using a CNC machine with the usual clamping and steel-backing plate. The tool used in this study was produced from H13 tool steel and heat treated to obtain 52 HRC hardness. The shoulder diameter was 15 mm. The cylindrical pin was threaded to a diameter of 4 mm (M4).

Table 2: Weld parameters used
Tabela 2: Parametri varjenja

Parameters		
Symbol	Rotation rate (r/min)	Travel speed (mm/min)
750/100	750	100
1000/150	1000	150
1250/200	1250	200
1500/300	1500	300

The microstructural evolution within the weld regions was investigated in detail on the specimens extracted from the joints obtained. Microhardness measurements were also conducted across the joints using a load of 100 g (the loading time was 20 s) with an interval of 1 mm to determine the hardness profiles. To determine the mechanical properties of the joints, four standard transverse tensile-test specimens (**Figure 1**) were also extracted from each joint produced. The tensile tests of the base plates were performed on these specimens to determine the performance values of the joints. All tensile tests were conducted using a loading rate of 1 mm/min.

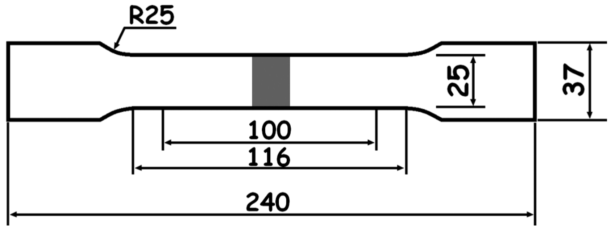

Figure 1: Geometry of the tensile specimens (dimensions are in mm)
Slika 1: Geometrija nateznih preizkušancev (dimenzije v mm)

3 RESULTS AND DISCUSSION

3.1 Microstructural aspects

The optical micrographs of the base plates and the macrographs showing the transverse cross-sections of the joints produced are given in **Figures 2** and **3**,

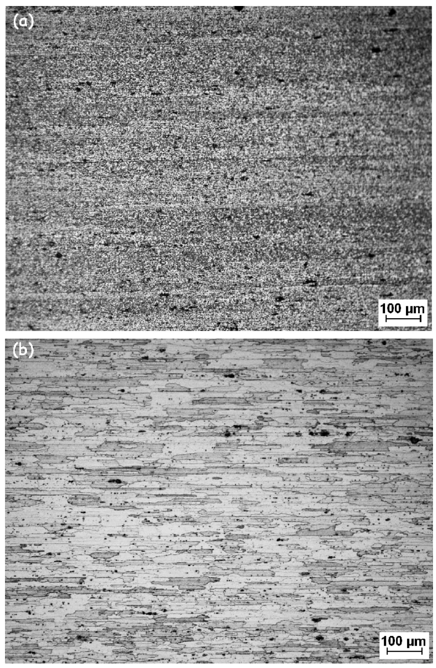

Figure 2: Microstructures of the as-received base plates: a) AA7075-O and b) AA7075-T6
Slika 2: Mikrostruktura dobavljenih plošč: a) AA7075-O in b) AA7075-T6

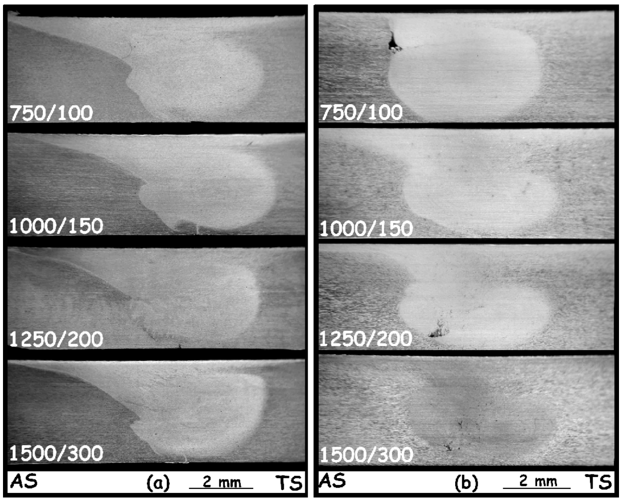

Figure 3: Macrographs of the welds showing the cross-sections of the joints: a) AA7075-O and b) AA7075-T6 (750/100: 750 r/min, 100 mm min^{-1}; 1000/150: 1000 r/min, 150 mm min^{-1}; 1250/200: 1250 r/min, 200 mm min^{-1}; 1500/300: 1500 r/min, 300 mm min^{-1})

Slika 3: Metalografski posnetek prereza skozi zvar: a) AA7075-O in b) AA7075-T6 (750/100: 750 r/min, 100 mm min^{-1}; 1000/150: 1000 r/min, 150 mm min^{-1}; 1250/200: 1250 r/min, 200 mm min^{-1}; 1500/300: 1500 r/min, 300 mm min^{-1})

respectively. The base-plate microstructures consist of alpha grains containing undesirable, inhomogeneously distributed iron- and silicon-rich particles in the form of coarse constituent particles, i.e., Al_7Cu_2Fe, $Al_{12}Fe_3Si$, and Mg_2Si.[33,34] Optical microscopy also revealed that no weld-defect formation took place in the weld regions of all the joints produced in the case of the O- temper condition, **Figure 3a**. On the other hand, a small amount of defect was detected in all the joints produced in the T6 condition except for the joint produced with a rotation rate of 1000 r/min and a travel speed of 150 mm/min, which did not display any defect in the nugget zone,

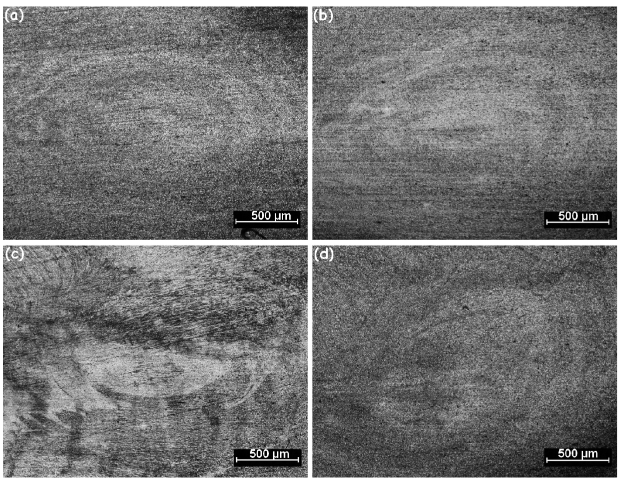

Figure 4: Dynamically recrystallized zones of the welded AA7075-O plates produced at: a) 750/100, b) 1000/150, c) 1250/200, and d) 1500/300

Slika 4: Dinamično rekristalizirano območje zvara AA7075-O: a) 750/100, b) 1000/150, c) 1250/200 in d) 1500/300

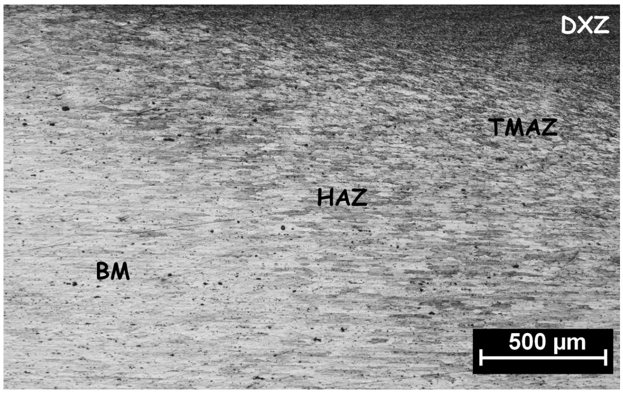

Figure 5: Advancing side of the AA7075-T6 welded plate produced at 1000 r/min and 150mm/min

Slika 5: Zgornja stran plošče AA7075-T6, ki je bila varjena s 1000 r/min in hitrostjo 150 mm/min

Figure 3b. This indicates that the weld-parameter window is larger in the O-temper condition than in the T6 condition. Thus, sound joints can be produced in the O-temper condition with a wide range of weld parameters. This is not surprising due to the fact that the alloy is much harder in the age-hardened condition.

The microstructures of the dynamically recrystallized zones (DXZs) of the joints produced in the O-temper condition are shown in **Figure 4**. As seen from this figure, a typical onion-ring structure with fine grains was evolved in the DXZs of these joints. The grains are finer in the DXZs than in the base plates due to the forging effect and recrystallization. As seen from **Figure 5**, a texture formation is also visible, in which the grains in the TMAZ region are oriented in line with the material flow resulting from the movement of the stirring pin. Moreover, the joint region consists of three distinct regions: the nugget zone (NZ), the heat-affected zone (HAZ) and the base material (BM).[5–6] The nugget zone consisted of two regions, the thermomechanically affected zone (TMAZ) and the dynamically recrystallized zone (DXZ). The presence of TMAZ indicates that the recrystallization is incomplete.[6]

3.2 Hardness

Figure 6 shows the hardness profiles obtained from all the joints produced. As seen from the figure, there is a hardness increase in the weld regions of all the joints produced in the O-temper condition. The increase in hardness in this case is very similar in all the joints produced with different rotation rates, i.e., between 153 HV and 159 HV. Similar hardness increase in the weld regions has been reported for the AA6061 Al-alloy plates that were friction-stir welded in the O-temper condition.[35]

On the other hand, a hardness loss occurred within the weld zones of all the joints produced in the T6-temper condition, **Figure 6**. This is not surprising since overaging takes place during the friction-stir

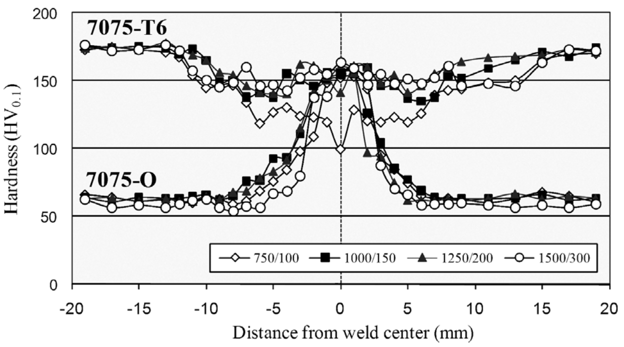

Figure 6: Hardness profiles of the welded plates
Slika 6: Profil izmerjene trdote zvara

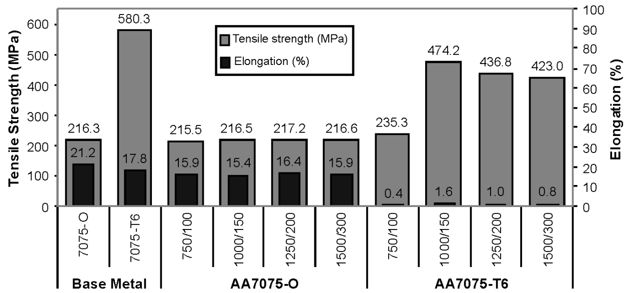

Figure 7: Summary of the average values of the tensile-test results
Slika 7: Povprečne vrednosti nateznih preizkusov

welding of aged Al-alloy plates giving rise to a hardness decrease.[15–17,35] A similar hardness loss was also reported in the weld regions of FSWed non-heat treatable Al-alloy plates provided that the plates were cold worked prior to joining.[24] The lowest hardness value within a weld region (i.e., 100 HV) was displayed by the joint produced with the weld parameters of 750 r/min and 100 mm/min. The other joints exhibited similar hardness profiles.

3.3 Tensile properties

Table 3 gives a summary of the tensile-test results obtained from the base plates and all the joints produced. It also gives the joint-efficiency values for all the joints produced in terms of both tensile strength and ductility. At least four specimens were tested for each case. **Figure 7** also gives a column graph summarizing the tensile-test results obtained.

All the tensile-test specimens extracted from the joints produced in the O-temper condition failed in the base metal away from the joint area, **Figure 8a**. All these specimens exhibited a shear fracture with a shear-fracture path at an angle of 45 degrees to the axis of tension as seen from **Figure 8a**. These results are in good agreement with the hardness measurements conducted on these joints, which exhibited a hardness increase in the weld areas (**Figure 6**). The tensile-strength values obtained from these joints are comparable to the value for the base plate (AA7075-O), i.e., 216 MPa. Thus, the joints exhibited about a 100 % joint efficiency as seen from **Table 3** and **Figure 7**. These results also indicated that sound FSWed AA7075 joints can be produced within a large window of weld parameters in the O-temper condition. While these joints exhibited strength values comparable to that of the base plate, they displayed a somewhat lower ductility than the base plate. The elongation of these joints was about 16 % whereas that of the base plate was 21 % (**Table 3** and **Figure 7**). This slight decrease in the elongation is also due to the hardness increase in the weld regions, which does not yield during the testing, thus reducing the overall elongation of the specimens. Similarly, lower elongation values were also reported for the friction-stir-welded, strength overmatching, AA6061 Al-alloy plates that were joined in the O-temper condition[35] and for the laser-beam-welded, strength overmatching steel joints.[36,37]

On the other hand, all the tensile-test specimens extracted from the joints produced in the T6-temper condition failed within the joint area, **Figure 8b**. The failure took place perpendicularly to the axis of tension. The presence of defect in the nugget zones of the joints

Table 3: Summary of tensile-test results
Tabela 3: Povzetek nateznih rezultatov

Weld parameters (r/min ; mm min^{-1})	Tensile strength (MPa) Elongation (%)											
	AA7075-O						AA7075-T6					
	1	2	3	4	Ave.*	JP (%)**	1	2	3	4	Ave.*	JP (%)**
Base metal	–	–	–	–	216.3 21.2	– –	–	–	–	–	580.3 17.8	– –
750/100	215.5 15	216.1 16.8	215.4 14.9	215.1 16.9	215.5 15.9	99.6 75.0	236.2 0.38	235.4 0.4	252.4 0.46	217 0.38	235.3 0.41	40.5 2.3
1000/150	216 14.6	216.6 16	217.1 16.45	216.4 14.4	216.5 15.4	100.1 72.6	489.9 2.13	470.4 1.54	466.7 1.45	469.7 1.41	474.2 1.63	81.7 9.2
1250/200	217.9 17.7	217.5 16.2	217.1 14.75	216.4 16.9	217.2 16.4	100.4 77.4	437.1 1.02	436.4 1.14	444.4 1.05	429.1 0.91	436.8 1.03	75.3 5.8
1500/300	216.4 17	215.8 16	216.9 15	217.1 15.5	216.6 15.9	100.1 75.0	382.7 0.7	441.3 0.84	430 0.75	437.7 0.83	423.0 0.78	72.9 4.4

* average values; ** joint-performance values

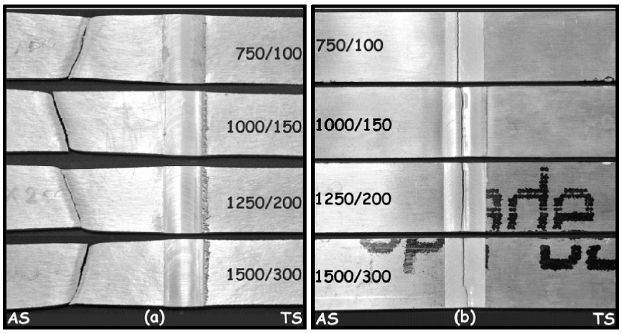

Figure 8: Tensile-test specimens: a) AA7075-O and b) AA7075-T6
Slika 8: Natezna preizkušanca: a) AA7075-O in b) AA7075-T6

produced with the parameters of 750/100, 1250/200 and 1500/300 is considered to play an important role in determining the fracture location as well as the hardness loss in this region. However, the joint produced with the weld parameters of 1000 r/min and 150 mm/min, which did not exhibit any weld defect, also failed within the weld region. This indicates that the other factor determining the fracture location is the strength undermatching. The joint produced with these weld parameters (i.e., 1000 r/min and 150 mm/min) displayed the highest tensile-strength value, i.e., 474 MPa, with the joint-performance value being about 82 %.

Moreover, the specimens extracted from the joints produced in the T6-temper condition exhibited much lower elongation values (i.e., between 0.4 % and 2.1 %) than that of the base plate, i.e., 17.8 % (**Table 3** and **Figure 7**). This can also be attributed to the significant hardness decrease in the weld regions of these joints. This hardness loss leads to confined plasticity as well as to the presence of weld defects in the joints with the exception of the one produced with the parameter set of 1000/150, which exhibited the highest ductility-performance value, i.e., 9 % of the base plate. The soft-weld region only plastically deforms during the tensile testing of these specimens due to a much higher strength of the base plate, e.g., due to the highly strength-undermatching nature of the joint. Similarly, very low elongation values were also reported for the laser- or electron-beam-welded, highly strength-undermatched Al-alloy joints,[15–17] friction-stir-welded AA6061-T6 Al-alloy plates[35] and AA5083 Al-alloy plates.[38]

4 CONCLUSIONS

Sound joints of AA7075 Al-alloy plates both in the O- and T6-temper conditions can be produced by FSW. However, unsuitable weld parameters lead to a formation of weld defects in the nugget zone of the alloy in the T6 condition. Moreover, AA7075 plates can be satisfactorily friction-stir welded within a large window of weld parameters in the O-temper condition whereas the weld parameters have a significant effect on the joint quality in the T6 condition.

The joints produced in the O-temper condition displayed a hardness increase in the weld region whereas those produced in the T6-temper condition exhibited a hardness drop in the weld region.

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

All the joints produced in the O-temper condition displayed strength values comparable to that of the base plate, the joint-performance value being about 100 %. On the other hand, all the joints produced in the T6-temper condition exhibited lower strength values than that of the base plate, the maximum tensile-strength performance being 82 % obtained from the joint produced at a rotation rate of 1000 r/min and with a travel speed of 150 mm/min.

The results suggest that this alloy can be readily joined in the O-temper condition and T6-heat treated after welding wherever possible.

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