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SIMILAR AND DISSIMILAR FRICTION STIR WELDING OF AA7075

M. EL-SHENNAWY[1], ADEL A. OMAR[2] & M. AYAD[3]

[1]Mechanical Engineering Department of , Engineering College, Taif University, Taif, KSA On leave from Mechanical Engineering Department, Faculty of Engineering, Helwan University, Helwan, Egypt

[2]Benha University, Benha, Egypt

[3]Menofeya University, Menofeya, Egypt

ABSTRACT

Friction stir welding (FSW) is a new solid-state joining process. It can be applied to all aluminum alloys without hot cracking, porosity or other common problems associated with fusion welding process of aluminum. Thermal effects such as contraction and distortion are also avoided due to the absence of fusion. The absence of arc results also in clean joining process with no ultraviolet or electromagnetic radiation hazards. No spatter or fumes or other pollutants in this joining process, FSW. Excellent mechanical properties of the friction stir welded joints promoted its applications in various industrial fields such as aerospace, automotive, maritime, …etc. Aluminum alloy 7075 has special importance due to its high strength properties which promoted its usage in aerospace industry. Friction stir welding of AA7075 received considerable emphasis in the literature. The possibilities of joining dissimilar metals using FSW encouraged investigators to build dissimilar joints between AA7075 and other metals including aluminum alloys, magnesium and others.

KEYWORDS: Friction Stir Butt Welding, Aluminum Alloys, Welding Research

INTRODUCTION

Friction stir welding (FSW) is a solid–state, hot–shear joining process [1-3] in which a rotating tool with a shoulder and terminating in a threaded pin, moves along the butting surfaces of two rigidly clamped plates placed on a backing plate. The shoulder makes firm contact with the top surface of the work–piece. Heat generated by friction at the shoulder and to a lesser extent at the pin surface, softens the material being welded. Severe plastic deformation and flow of this plasticized metal occurs as the tool is translated along the welding direction. Material is transported from the front of the tool to the trailing edge where it is forged into a joint. Different joint types can be friction stir welded such as butt, lap and fillet joints. This process (FSW) was invented by the TWI in 1991[4-5]. From that time research and development in FSW and associated technologies has taken great places in many companies, research institutes and universities and international conference series dedicated to its study.

The 7*xxx* aluminum alloys are age hardenable, with good combination of strength, fracture toughness, and corrosion resistance in both thick and thin wrought sections. The addition of zinc with other elements, notably copper, magnesium, and chromium, produces very high strength, including the highest strength available in any wrought aluminum alloy. Aluminum alloy 7075 is a high strength 7*xxx* alloy. Its composition limits is: 1.20 to 2.0 Cu, 2.1 to 2.9 Mg, 0.30 Mn max, 0.40 Si max, 0.50 Fe max, 0.18 to 0.28 Cr, 5.1 to 6.1 Zn, 0.20 Ti max, 0.05 max other (each), 0.15 max others (total), bal. Al [6]. This alloy is used in aircraft structural parts and other highly stressed structural applications where very high strength and good resistance to corrosion are required. The weldability of this alloy by conventional fusion welding techniques is not good. Therefore, there has been considerable research into the ability to join AA7075 by using the solid-state friction stir welding technique [7, 8, 9] due to its importance in aerospace industry.

The FSW has been focused on welding aluminum alloys. Investigations of FSW have been carried out for other alloys such as copper alloys [10-17], magnesium alloys [18-27], titanium alloys [28-32], steels [33-41], nickel alloys [42-44] and also molybdenum [45].

In addition considerable work has focused on using FSW to join dissimilar aluminum alloys [46-72] Lightweight vehicles has pushed research towards dissimilar joining of aluminum alloys to other metals, including aluminum to magnesium [73-80] aluminum to metal matrix composites [81], aluminum to steel [82-87], and aluminum to copper [88-94].

Because of the advantages FSW provides, it has found its place in many industrial applications; such as those in marine like fishing vessels [95], large steel cruise ships [96], and the Japanese fast ferry “Ogasawara” [97]. In aerospace like fuel tanks for unmanned Delta II and later Delta IV rockets [98-100], the manufacturer Boeing and large fuel tank for the Space Shuttle [101-103], and the Eclipse 500 business jet [104]. Friction stir welding has been applied in rail such as the Japanese Shinkansen [105-107], in automotive, such as Mazda Rx-8 sports car, bonnet and rear doors [108] and in lightweight armored vehicles [109-110]. Replacing copper by aluminum has potential applications since similar electric properties can be achieved at a lower price and a lower density [111]. Aiming at replacing copper with aluminum successfully, the welding of these two metals is a key problem to be solved. The welding of dissimilar materials is generally more difficult than that of homogeneous materials. High-quality Cu-Al dissimilar joint is hard to be produced by fusion welding techniques due to the large difference of melting points, brittle intermetallic compounds existence and crack formation[111-112]. Friction stir welding is the best solution for this joining [113]. Limited researches have been carried out in this field.

General reviews have been introduced by many researchers about friction stir welding covering wide range of materials [114], or concentrates on heat generation and tool/material flow interaction [115], and ASM handbook which cover FSW and FSP [116]. Recently, a concentrated review on aluminum alloy FSW has been introduced [117]. The aluminum alloy 7075 has a special importance among other aluminum alloys due to its high strength and age hardenability. It is used extensively in aerospace industries and researches gave considerable interest to its weldability, either by conventional fusion welding which is difficult or by solid-state welding such as friction stir welding FSW process. Therefore, this present review will draw on a wide selection of published data dealt with friction stir welding of aluminum alloy 7075 either in as a similar joining or dissimilar joining with other aluminum alloys and materials to summarize current understanding of the complex relationship between welding parameters, microstructure and properties for AA7075. Besides, the weldability of this alloy in dissimilar manner with other materials is discussed.

Similar Friction Stir Welding of AA7075

The 7xxx aluminum alloys are age hardenable, with a good combination of strength, fracture toughness, and corrosion resistance in both thick and thin wrought sections. Weldability of the high-strength 7xxx aluminum alloy by conventional fusion welding techniques is not good in any temper. However, some investigations showed successful examples for fusion welding of 7xxx, and specifically AA7075 [118-120]. There is a considerable interest in the high-strength 7xxx aluminum alloys in aerospace industry, which encouraged many researchers to use the FSW technique instead of conventional fusion welding processes [121-124]. Examples for similar friction stir welding of AA7075 can be found in many references [7-9, 125-151]. There is a wealth of data on strain rate and super-plasticity condition [132, 134-142], corrosion and stress corrosion cracking [129-130, 152-161], mechanical properties [131, 144, 146], microstructure and compositional characterizations [all through the majority of the last mentioned researches and others [133, 143, 145], material transfer [145], the role of intermetallic compound [144], fatigue [131, 144], impact [144], failure mode [143], and temperature effect [145]. Important applications of FSW were introduced by NASA [147] and others [148]. There is no surveys were done –to the best knowledge of the author- for the friction stir welding of AA7075.

Mechanical Properties

The microstructure across a friction stir weld is non-uniform which results in considerable change in yield strength, tensile strength, and ductility over very short distances [152]. Therefore, the results can be very different according to whether the welds have been tested in the longitudinal or transverse direction according to the weld as shown in Table 1. Width and length of the test piece will also change the stress-strain response because of their effects on residual stresses and average ductility, respectively [117].

A study of the deformation on AA7075-T7541 [149] has demonstrated the variability in strain across transverse tensile samples. Tensile properties of FSW AA7075-T651 in longitudinal and transverse directions have been recorded at room temperature [146] as shown in Table 1. Table 1 indicates a decrease in strength and ductility in transverse directions compared to longitudinal direction and greater decrease when compared to base metal values. HAZ represents the low-strength zone due to the precipitate coarsening and the development of precipitate-free zones PFZs. Figure 1 shows the high strain level (12-14%) at HAZ compared to weld zone (2-5%), therefore, fracture occurs in the HAZ. Transverse direction of the weld always exhibit low strength and ductility allover its long. Other studies have been conducted using mini tensile specimens in order to determine the tensile properties at different locations of the FSW welds of AA7075. Similar results were obtained where a typical variation of tensile properties with the position across the weld of FSW AA7075 is shown in Figure 2.

Table 1: Longitudinal and Transverse Tensile Properties of FSW AA7075-T651 at Room Temperature [146]

Condition	UTS (MPa)		YS (MPa)		Elongation (%)	
	Long.	Trans.	Long.	Trans.	Long.	Trans.
Base metal, T651	622	622	571	571	14.5	14.5
As-FSW	525	468	365	312	15	7.5
Postweld age treatment T6	469	447	455	312	3.5	3.5

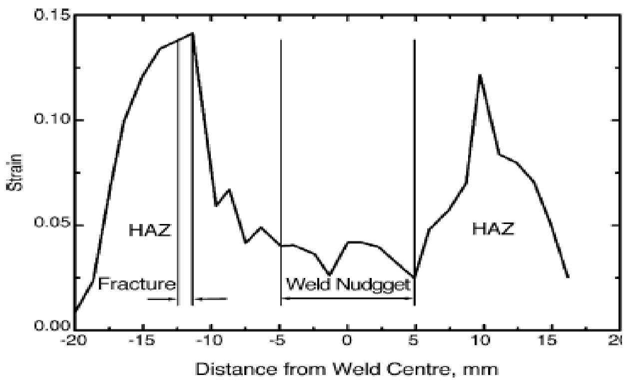

Figure 1: Tensile Strain Distribution within the HAZS and Weld Nugget of FSW 7075al-t651 Weld [146]

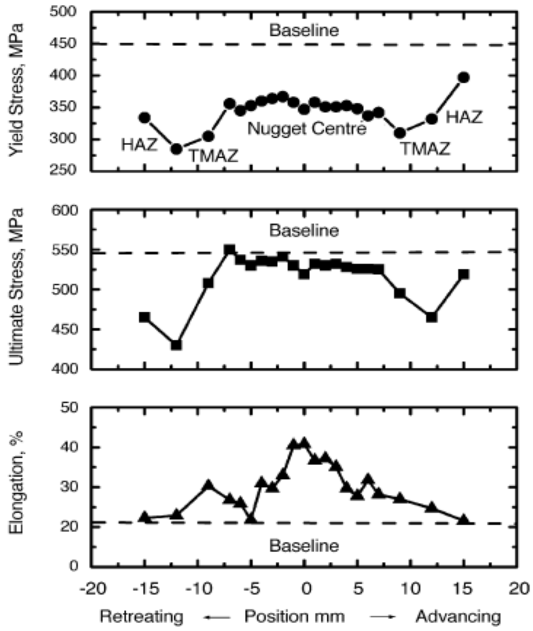

Figure 2: Variation of Tensile Properties with the Position across the Weld in an FSW 7075al Alloy [152]

Table 2 illustrates transverse tensile properties of FSWed AA7075 at different conditions; as welded and after postweld aged. Joint efficiency for each case is calculated and put in the table. FSWed AA7075 joint efficiency ranges from 74% for AA7075-T651 [146] to 96% for AA7075- T7351 [153]. It is worth noting that these values are for transverse tensile strength which is the lowest value as discussed in the above paragraphs. These values are high when compared with conventional welding processes, especially that there are difficulties when welding this high strength heat treatable alloy 7075.

Table 2: Transverse Tensile Properties of FSWed Aa7075 [116]

Condition		UTS (MPa)	Efficiency (%)	YS (MPa)	Ref
7075-T6	Base metal	553	-	486	128
	As-FSW	410	74	333	
7075-T651	Base metal	622	-	571	127
	As-FSW	468	75	312	
		485	78	340	126
	T6	447	72	312	127
7075-T73	Base metal	515	-	-	9
	As-FSW	416	81	-	
7075-T7351	Base metal	472	-	-	186
	As-FSW	455	96	-	

Dissimilar Friction Stir Welding of Aa7075

One of the most advantages of friction stir welding is its ability to join dissimilar materials. For metals, aluminum is the most common metal to be joined by FSW in a dissimilar joint. Friction stir welding had been used to join different aluminum alloys, copper alloys or aluminum alloys to other metals [150, 151, 154-169]. Many dissimilar joints of various aluminum alloys were made to fulfill many application requirements. Aluminum alloy 7075 had been joined with AA2024 in many applications which can be considered as one of the most common aluminum alloys joined with AA7075 due to its importance in aerospace applications [170-188]. Aluminum alloy 7075 was also joined with AA6061 [189-195], AA5754 [196-197], AA2219 [57, 60, 198], AA6262 [199], AA2017 [151, 165], and AA1100 [151]. AA7075 was joined also with magnesium alloy [176].

Various parameters and topics have been studied for dissimilar joining of AA7075 with other aluminum alloys and metals. These parameters include: mechanical properties [170-171, 173- 178, 182, 189, 191, 196-197, 199], bending strength [191], fatigue life [171-172, 174, 179-182, 193], microstructural characterization [170-171, 175-176, 192-193, 199], tool position [172], defects [173], effect of process parameters [174, 190], weld temperature effect [189], failure mode [197], and repair weld [198]. Joints were butt joints [170-172, 175-176, 189-192, 196-199], [57, 60] and lap joints [173-174, 177, 187].

AA7075-AA2024 Butt Joints

Dissimilar friction stir welding of AA7075-AA2024 received considerable interest in the literatures [170-173, 175-178, 182-188]. These joints have been designed to be butt or lap configurations depending on the application.

In case of butt joint configuration [170-172, 175-176, 178, 182], the main parameters investigated were mechanical properties including tensile and hardness measurements, and microstructural investigation. Fatigue life and fatigue crack propagation was mainly investigated for the 7075/2024 joints. As shown in Table 3 the efficiency approached for this type of joint was considerably high ranging from 85 to 95% of AA2024 base material in average. Some specimens showed less and some showed higher but the majority was in the above mentioned range. The investigations showed that the joint gives better efficiency when AA2024 (the softer material) is put in the advancing side and AA7075 in the retreating side. Meanwhile the fracture location after tensile test was always at the HAZ of AA2024. Reduced ductility of the joints AA7075/AA2024 was attributed to localized deformation in the low-strength HAZs. The plate thicknesses of both alloys were mainly ranging from 3 to 4 mm. It was found that the optimum process condition is 1200 rpm for the rotational speed and 120 mm/min as welding or traverse speed especially for 3.0 mm. thick plate. The fatigue test for FSWed AA7075/AA2024 joints showed a fatigue life of 2x106 cycles which corresponds to 44 MPa which is a satisfactory level compared to the base metal AA2024 [290]. When FSWed AA7075/AA2024 joints were examined under axial total stress control mode under fully in tension conditions (*R=0.1*) the fatigue life recorded was 3x106 cycles corresponding to 105 MPa when the tool had been displaced from the center of weld line towards AA2024 by 1.0 mm [172, 182]. Microstructural examinations for various FSWed specimens for AA7075/AA2024 showed the common onion rings at the WZ/SZ as clearly shown in Figure 3 (a), and especially at high rotational speed, Figure 3 (b). The microstructure at WZ/SZ is a mixed structure of equiaxed fine grains. With increasing the heat input which results from increasing the rotational speed and with severe plastic deformation remarkable smaller grains compared to base metal is obtained with estimated length $3 \sim 5\ \mu m$ [171, 178]. Grain size increases in with moving away from the WZ/SZ up to the HAZ where the grain size is almost the same as the base metal. Also, there are large amount of resident base metal start to appear. The precipitates at this region are coarsened. In the region adjacent to the WZ/SZ which is TMAZ, there are deformed grains with size nearly similar to that of base metal [171]. Analysis of WZ/SZ using EDS showed nearly similar mass percentages of Cu, Mg, and Mn in positions 1, 3, and 5 (Figure 3 (a)) to their contents of AA2024 while the concentrations of Zn, Mg, and Mn at positions 2, 4, and 6 were close to AA7075 plate [170].

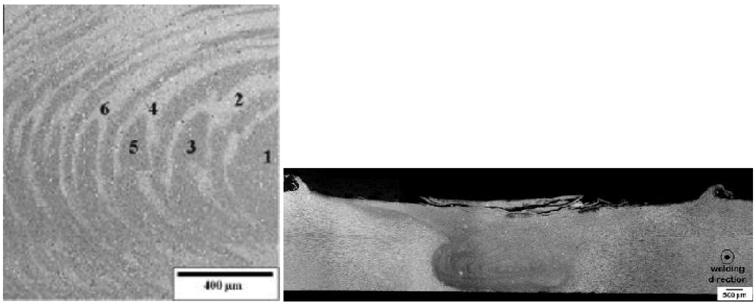

Figure 3: (a) SEM Image of SZ for FSW 7075/2024 at 1200 rpm [289] and (b) OM Macrograph of the Cross-Section of Condition FSW 7075/2024 At 200 Rpm [178]

Table 3: Summary for FSWAA7075/AA2024 – BUTT Joints

Joint	T, mm	rpm	mm/ min	YS, MPa	UTS, MPa	Elong., %	Failure Location	Efficiency	Ref.
2024-T3	-	-	-	327	461	29.5	-	-	170
7075-T6	-	-	-	498	593	17.7	-	-	
2024-T3/7075-T6	3	1200	42	275	395	13.6	HAZ-2024	86	
				270	392	12.1		85	
			72	282	404	14.5	HAZ-2024	88	
				264	394	12.5		85	
			102	290	423	14.9	HAZ-2024	92	
				280	381	9	WZ	83	
			198	287	398	11.4	WZ	86	
7075-T6/2024-T3				283	340	7.5		74	
2024-T3	-	-	-	380	490	17	-	-	171
7075-T6	-	-	-	503	572	11	-	-	
2024-T3/7075-T6	2.5	-	160	325	424	6	HAZ-2024	87	
2024-T3	-	-	-	380	490	17	-	-	172,182
7075-T6	-	-	-	503	572	11	-	-	
2024-T3/7075-T6 0*	4	1600	120	325	424	6	HAZ-2024+	87	
2024-T3/7075-T6 0.5*				340	435	7	HAZ-2024+	89	
2024-T3/7075-T6 1.0*				395	460	4.5	HAZ-2024+	94	
2024-T3/7075-T6 1.5*				285	390	2.5	HAZ-2024+	80	

2024-T3	-	-	-	327	461	29.5	-	-	175, 176
7075-T6	-	-	-	498	593	17.7	-	-	
2024-T3/7075-T6	3	400	100	291	399	14	HAZ-2024	87	
				275	392	11.4	HAZ-2024	85	
		800		286	407	14.3	HAZ-2024	88	
				292	395	13.4	HAZ-2024	86	
		1200		290	423	14.9	HAZ-2024	92	
				280	381	9	WZ	83	
		1600		283	392	12.5	WZ	85	
				280	386	11.5	WZ	84	
		2000		274	363	7.5	WZ	79	
7075-T6/2024-T3				234	293	7.5	WZ	64	
2024-T3	-	-	-	305	458	18	-	-	178
7075-T6	-	-	-	491	565	13	-	-	
7075-T6/2024-T3	3	400	254	269	438	7.1	HAZ-2024	96	
		1000		224	447	8	HAZ-2024	98	
		2000		253	445	7.8	HAZ-2024	97	

Colored cells are for AA2024 positioned at AS.

*Tool position from center of weld line towards AA2024

+Expected from microhardness readings

CONCLUSIONS

Aluminum alloys 7*xxx* is age hardenable, with good combination of strength, fracture toughness, and corrosion resistance in both thick and thin wrought sections. The addition of zinc with other elements, notably copper, magnesium, and chromium, produces very high strength, including the highest strength available in any wrought aluminum alloy. Aluminum alloy 7075 is a high strength 7*xxx* alloy. This alloy is used in aircraft structural parts and other highly stressed structural applications where very high strength and good resistance to corrosion are required. The weldability of this alloy by conventional fusion welding techniques is not good. Therefore, there has been considerable research into the ability to join AA7075 by using the solid-state friction stir welding technique due to its importance in aerospace industry.

Similar joint of this alloy 7075 received considerable interest from investigators from various point of views. Process parameters -including the tool profile- effect on microstructural and mechanical properties were among the major topics investigated. The main concluding remarks are:

- Most friction stir welds of AA7075 and heat-treatable aluminum alloys in general, welded in the peak aged or overaged conditions (T6/T7 tempers), exhibit a characteristic hardness profile; W-shape. This alloy (7075) spontaneously age at room temperature, continuing to harden essentially forever even at a decreasing rate.

- Strength and ductility in transverse directions have lower values compared to longitudinal direction. HAZ represents the low-strength zone due to the precipitate coarsening and the development of precipitate-free zones PFZs.
- Fatigue fracture location is usually located between TMAZ and HAZ in the advancing side in the welds of 7075-T6 at lower welding speed and in the nugget zone at a higher welding speed. Fatigue strengths of welds are nearly the same as those of the parent material of 7075- T6.
- Dissolution of larger precipitates and reprecipitation in the weld center during FSW of AA7075-T651 indicates that the maximum process temperatures are 400-480 oC.
- Aluminum alloy 7075 spontaneously age at room temperature, continuing to harden essentially forever even at a decreasing rate. Softening occurs in the HAZ with a rapid drop in hardness as the TMAZ is approached. The greatest strength recovery occurs in the nugget. Both coarsening and dissolution lead to a drop in hardness, but strength recovery only occurs following dissolution.
- Aluminum alloy 2024 is one of the most common aluminum alloys joined using FSW with AA7075 due to its importance in aerospace applications.
- Dissimilar FSW between AA7075 and other aluminum alloys including AA2024 reaches efficiency ranges between 74-95% which considered high compared with conventional fusion welding processes.
- It is recommended in dissimilar FSW of aluminum alloys to place the weaker alloy in the AS and the stronger one in the RS to ensure better mix at stir zone.
- Failure of dissimilar joint usually occurs at the HAZ of the softer alloy with low hardness.
- In both similar and dissimilar FSW of AA7075, the process conditions namely; rotational speed, travel speed, tool profile have great effect on microstructure evolution, tensile properties, and fatigue life.

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