Mechanical performances of friction stir welding applied to aluminium alloys

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Keywords

Aluminium alloys, friction stir welding, porosity, residual stress, mechanical performances, joint technology.

1. Introduction

Aluminium was relatively new when it was first introduced as a structural material. The variety of alloys was limited and the fabrication techniques very primitive compared with the situation today. Despite these facts, structural aluminium applications were successfully introduced into many areas, such as the ship building industry, the automotive industry and the civil engineering industry.

It is normal to look at the highest tensile properties, but additional factors must be considered when choosing the optimal alloy and temper. The desired tensile strength should always be matched with requirements for ductility, corrosion behavior under the actual working conditions, fabrication requirements, such as cold forming (bending), thermal working conditions, weldability [1].

Regarding the weldability, it is known that for many aluminium alloys this characteristic involves difficulties in obtaining the necessary quality for a proper welded connection.

To extend the application of aluminium alloys, a new welding technology - friction stir welding (FSW) - has been developed since 1991 by TWI. FSW is a solid state welding process that takes place at temperatures below the melting point of aluminium alloys. The technology is based on the heating of the materials through friction and plastic deformation realized at the interaction between the non-consumable pin tools which are rotating at the surface of the joined elements. The interactions affect the heating and cooling rates, plastic deformation and flow, dynamic re-crystallization phenomena and the mechanical integrity of the joint. Due to the combined effect of tooling [2], FSW produces five different microstructure zones: weld nugget, thermo mechanically affected zone, heat affected zone, base material (see Figure 1).

The procedure raised the interest for many industries, such as ship building, aircraft, automotive and, recently, also for constructions, because of the advantages of this technology in comparison with the fusion welding procedures. The most important advantages are lack of porosity in the welding seam, no involvement of any use of filler material, no scrap, no additional surface finishing [3]. FSW is considered to be the most significant development in metal joining in decades. It is also a "green" technology, due to its energy efficiency, environment friendliness and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding [4]. Since the development of the process, more and more research centers but also the industrial appliers extended the applications fields. The big number of the patents for FSW applications from all over the world is a confirmation of the process quality and advantages for many application fields [5].

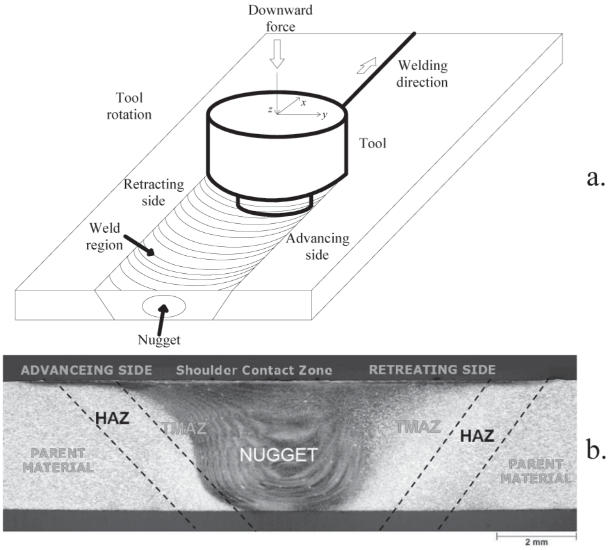

Figure 1. a) Schematic of the friction stir welding process; b) The zone distribution in the weld cross-section

This paper aims to present the advantages of FSW technology at welding of aluminium alloys elements.

2. Characterization of FS welded seams

FSW results in significant microstructural evolution within and around the stirred zone, i.e. nugget zone, TMAZ, and HAZ. This leads to substantial change in post weld properties. In the following sections, typical properties of post welded aluminium alloys are briefly reviewed.

For a basic characterization, some bending tests are carried out to see if the welding seam presents any surface defects, such as root flaws or "kissing bond" effect or tunneling defect.

2.1. Hardness

Aluminum alloys are classified into heat-treatable (precipitation-hardenable) alloys and nonheat-treatable (solid-solution-hardened) alloys. A number of investigations demonstrated that the change in hardness in the friction stir welds is different for precipitation-hardened and solid-solution-hardened aluminum alloys.

In contrast to age hardenable AA 6082-T651, where a minimum hardness occurs in the HAZ (see Figure 2a), FSW of non-hardenable AA 5083-H111 results in uniform hardness across the weld (see Figure 2b). Based on the results of hardness measurement, the evaluation of the resistance of the welded seam and also prediction of the failure under tensile tests can be made [6].

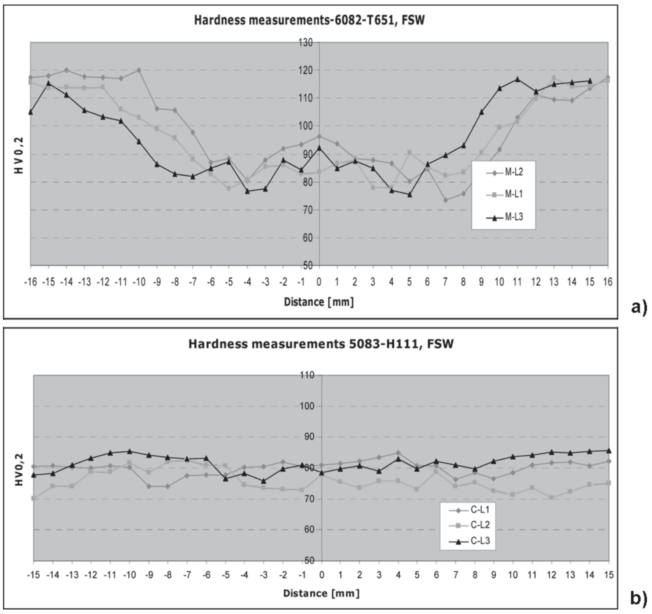

Figure 2. a) Hardness measurements of AA 6082-T651 with FSW; b) Hardness measurements of AA 5083 -H111 with FSW

Table 2. Characteristic values of 0.2% proof strength fo, tensile strength fu of some aluminium alloys, welded with FSW

Aluminium Alloy	Thickness, t	f_u	f_o	f_u^{FSW}	f_o^{FSW}	ρ_o^{FSW}	ρ_u^{FSW}
	[mm]	[N/mm^2]					
5083-H111	6	326	190.2	302	135	0.81	0.92
6082-T651	6	317	255	248	148	0.58	0.78

Vickers hardness results indicated reductions in the hardness values of the weld metal and the HAZ as compared to the hardness (about 100HV5) of the parent material. The width of the zone of reduced hardness was about 30-40mm for the welds made in this work. The lowest hardness value (about 45HV5) for the Al-Si filler welded joints was in the weld metal. The hardness value (about 60HV5) of the weld metal was similar to that of the HAZ for the Al-Mg filler welded joints [7].

2.2. Tensile performances

Tensile tests are necessary to determine yield strength f0, tensile stress fu. If failure takes place in weld, this may reveal the presence of defects in the test sample. Tensile tests on FS welds are compared with the same tests on fusion welds. For instance, the tensile properties of AA 5083 and AA 6082, welded with MIG weld, are plotted in Table 1.

For comparison, the tests results on the same aluminium alloy, welded with FSW, are presented in Table 2.

The results of tensile tests can be also evaluated from the hardness measurement. The hardness drop in the HAZ to AA 6082 indicated also a reduction of the resistance. In case of AA 6082-T651, the breakage of the samples took place in the region with lower hardness. In case of AA 5083-H111, the breakage took place in base material, under an angle of approximately 45° [3].

Table 1. Characteristic values of 0,2% proof strength fo, ultimate tensile strength fu (unwelded and for HAZ), minimum elongation of some aluminium alloys

Alloy EN-EW	Product form	Temper.	Thickness, $t^{1)3)}$	$f_o^{1)}$	$f_u^{1)}$	$A^{5)\,2)}$	$f_{o,haz}^{4)}$	$f_{u,haz}^{4)}$	HAZ factor$^{4)}$	
			[mm]	[N/mm^2]		%	[N/mm^2]		$\rho_{o,haz}$	$\rho_{u,haz}$
5083	ET, EP, ER/B	O/111, F, H112	$t \leq 200$	110	270	12	110	270	1	1
	DT	H12/22/23	$t \leq 10$	200	280	6	135	270	0.68	0.96
		H14/24/34	≤ 5	235	300	4			0.57	0.90
6082	ET, EP, ER/B	T4	≤ 25	110	205	14	100	185	0.91	0.78
	EP/O, EP/H	T5	≤ 5	230	270	8	125	185	0.54	0.69
	EP/O, EP/H, ET	T6	$t \leq 5$	250	290	8	125	185	0.50	0.64
			$5 < t \leq 15$	260	310	10			0.48	0.60
	ER/B	T6	$t \leq 20$	250	295	8			0.50	0.63
			$20 < t \leq 150$	260	310	8			0.48	0.60
	DT	T6	$t \leq 5$	255	310	8			0.49	0.60
			$5 < t \leq 20$	240	310	10			0.52	0.60

2.3. Fatigue properties

For many applications, like aerospace structures, transport vehicles, platforms, and bridge constructions, fatigue properties are critical. In the last years, several investigations were conducted on the S-N behavior of FSW aluminium alloys. These studies resulted in the following important observations: the fatigue strength of the FSW weld at 107 cycles was lower than that of the base metal, i.e., the FSW welds are susceptible to fatigue crack initiation; the fatigue strength of the FSW weld was higher than that of MIG and laser welds (typical S-N curves for FSW weld, laser weld, MIG weld, and base metal of 6005Al-T5 are shown in Figure 3). The finer and uniform microstructure after FSW leads to better properties compared to fusion (laser and MIG) welds; surface quality of the FSW welds exerted a significant effect on the fatigue strength of the welds.

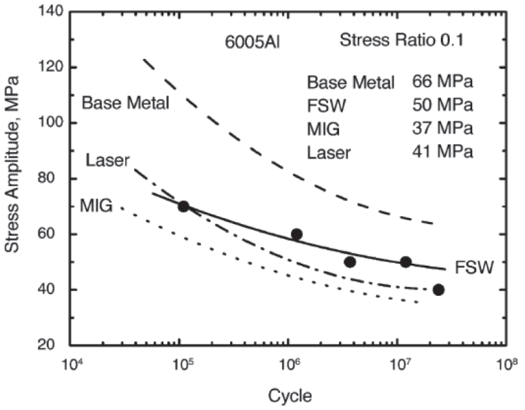

Figure 3. S-N curves of base material, FSW weld, laser and MIG weld for 6005-T5 alloy [8]

2.4. Residual stresses

Residual stresses in welds are of great significance in evaluation of the weld performance, in particular fatigue and fracture toughness. In fusion welding, residual stress levels are often large, close to parent material or weld metal yield strength. In solid state welds, the residual stresses can be substantially lower, although this is not necessarily true. In comparing residual stress levels in friction stir welds, care must be taken in interpretation of the results, as there are several techniques which are commonly used. During fusion welding, complex thermal and mechanical stresses develop in the weld and surrounding region due to the localized application of heat and accompanying constraint. Following fusion welding, residual stresses commonly approach the yield strength of the base material. It is generally believed that residual stresses are low in friction stir welds due to low temperature solid-state process of FSW. However, compared to more compliant clamps used for fixing the parts in conventional welding processes, the rigid clamping used in FSW exerts a much higher restraint on the welded plates. These restraints impede the contraction of the weld nugget and heat-affected zone during cooling in both longitudinal and transverse directions, thereby resulting in generation of longitudinal and transverse stresses. The existence of high value of residual stress exerts a significant effect on the post-weld mechanical properties, particularly the fatigue properties. Therefore, it is of practical importance to investigate the residual stress distribution in the FSW welds [9].

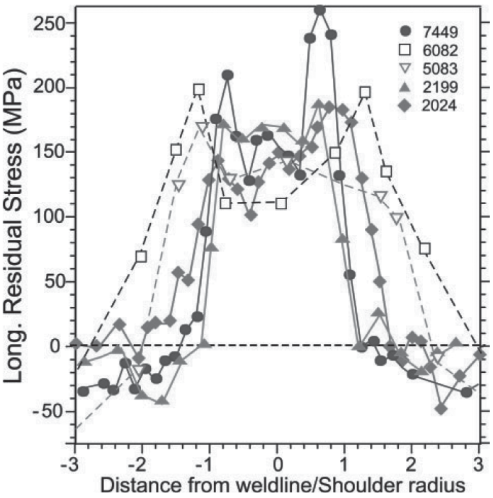

Figure 4. Longitudinal residual stress distribution normalized by pin shoulder diameter for friction stir welds in 7449, 2199, 6082, 2024 and 5083 alloy [9]

A higher welding speed increases the longitudinal residual stress but reduces it along the lateral direction. The analysis also showed that the maximum temperature gradients in the sample are located just beyond the edge of the tool-shoulder. As might be expected, the residual stress distribution is dramatically altered on unclamping the samples after friction stir welding and this must be taken into account in any modeling effort [10]. The role of plasticity during the friction stir welding process is known to be important in the calculation of residual stress; a large overestimation of the magnitudes of the residual stress can result when this effect is ignored [11].

The characteristic magnitude and profile of the longitudinal stresses across a friction stir weld are shown in Figure 4 for a range of alloys. The longitudinal stresses are typically much greater than the transversal ones. As it is clear from the figure, the stresses tend to be positive over a region extending just beyond the diameter of the tool shoulder. The tensile region tends to encompass the nugget and TMAZ and reflects the extent of the hot region beneath the shoulder. The peak stresses are often found just inside or just beyond the shoulder radius. Often the peak stress lies within the HAZ despite the lower hardness often found there. Lower level compressive residual stresses are typically found in the parent plate beyond the HAZ. The depth of the tensile plateau below the tensile peaks and the presence of a subsidiary peak on the weld centre line appear to be alloys specific. It should also be noted that the breadth of the tensile region and the magnitude of the stresses vary greatly according to the processing conditions [12].

3. Conclusions and discussion

Even Friction Stir Welding is considered today as a "young process", not entirely developed and confirmed, its application being in continuous expansion. Based on the good experimental testing results and the high resistance under the cycling loading, this new welding procedure is recommended to be used for aluminium alloys and also to be extended to other materials due to manufacture advantages, no need for supplementary preparation of the elements and also for the resulting weld seam and full automatization. A unique feature of FSW is the additional stress caused by the rotational and translational components of the tool so that the welding parameters of FSW affect the final state of stress. The stirring action of the tool is believed to relieve some of the stresses within the thermo-mechanically affected zone. Nevertheless, the outcome that the longitudinal stress along the weld centre line is positive and larger than all the other component stresses seems to be correct.

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Calendar of international and national events

Calendarul manifestărilor ştiinţifice şi tehnice internaţionale şi naţionale

2011			
06-08 Apr.	ASR Conference "Welding 2011" - Traditions and art in energy equipment	Reşiţa, Romania	Romanian Welding Society, 30, Bd. Mihai Viteazu, 300222 Timişoara - ROMANIA; tel. / fax: +40 256 - 200041; e-mail: asr@asr.ro; http://www.asr.ro
10-13 May	16th International Conference on the Joining of Materials & 7th International Conference on Education in Welding	Helsingør, Denmark	JOM. Gilleleje Strandvej 28. DK - 3250 Gilleleje. DENMARK; tel.: +45 48355458; e-mail jom_aws@post10.tele.dk
18-20 May	I IIW European-South American School of Welding and Correlated Processes	Ouro Preto, Brazil	EWF - European Welding Federation, Contact person: Heliana Bibas, e-mail: hgbibas@isq.pt; http://www.weldingschool2011.org
25-27 May	International Conference "Modern Technologies in Machine Manufacturing Technology-TMCM"	Vadul lui Mihai, Republic of Moldova	"Gheorghe Asachi" Technical University of Iaşi, Romania, Department of Machine Manufacturing Technologies, Bd Dimitrie Mangeron 59A, Iaşi 700050, ROMANIA, tel.: +40 232 21 72 90; fax: +40 232 21 72 90; e-mail: modtech@tcm.tuiasi.ro; http://www.modtech.ro/
16-17 Jun.	5th International Conference "Innovative technologies for joining advanced materials - tima11"	Timişoara, Romania	ISIM Timişoara, Bv. Mihai Viteazul nr. 30, 300222 Timişoara, ROMÂNIA; tel.: +40 256 200222; fax: +40 256 492797; e-mail: centa@isim.ro; http://www.isim.ro
17-22 Jul.	64th IIW Annual Assembly & International Conference	Chennai, India	The Indian Institute of Welding, Registered Office, 3A Dr.U.N. Brahmachari Street, Kolkata 700017, INDIA , tel.: +91-33-2281 3208; fax: +91-33-2287 1350; e-mail: iiw2011india@iiwindia.com; http://www.iiw2011.com
25-28 Sept.	6th IIW Asian Pacific International Congress	Cairns, Queensland, Australia	Welding Technology Institute of Australia (WTIA); ABN 69 003 696 526, Unit 50, 8 Avenue of the Americas, Newington, NSW 2127, PO Box 6165, Silverwater, NSW, 1811, AUSTRALIA; tel.: + 61 (0)2 9748 4443; fax: + 61 (0)2 9748 2858; e-mail: info@wtia.com.au; http://www.wtia.com.au
12-14 Oct.	AWST 2011 - IIW International Congress on Advances in Welding Science & Technology	Antalya, Turkey	Ankara Caddesi No:306 Seyhli 34913, Istanbul, TURKEY; tel.: (90 216) 378 50 00 (Pbx); fax: (90216) 378 20 44, e-mail: gedik@gedik.com.tr; http://www.gedikwelding.com