FATIGUE CRACK GROWTH IN FRICTION STIR WELDS OF 6082-T6 AND 6061-T6 ALUMINIUM ALLOYS: A COMPARISON

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Abstract. Friction stir welding (FSW) is a solid-state joining process which emerged as an alternative technology to be used in high strength alloys that were difficult to join with conventional techniques. Notwithstanding the widespread interest in the possibilities offered by FSW, data concerning the fatigue behaviour of joints obtained using this process still is scarce. In this work, a comparative study between fatigue crack growth behaviours of friction stir welds of 6082-T6 and 6061-T6 aluminium alloys is carried out. Fatigue crack growth curves were determined for cracks growing in different locations of the weldments, including the base material, the heat affected zone and the welded material. Generally, friction stir material exhibited lower strength and ductility properties than the base material. However, an enhanced crack propagation resistance is observed in welded material. The 6082-T6 and 6061-T6 base materials exhibit very similar crack propagation behaviours. On the other hand the friction stir 6061-T6 material shows lower crack propagation rates than corresponding 6082-T6 friction stir material.

1. INTRODUCTION

The increasing relevance of aluminium alloys in transportation requires research on more efficient and reliable joining processes. FSW is a solid-state joining process which emerged as an alternative technology to be used in high strength alloys that were difficult to join with conventional techniques. The process was developed initially for aluminium alloys, but since then FSW has been found suitable for joining a large number of materials. In FSW the interaction of a non consumable and rotating tool with the workpieces being welded, creates a welded joint through frictional heating and plastic deformation at temperatures below the melting temperature of the alloys being joined. Notwithstanding the widespread interest in the possibilities offered by FSW, data concerning the mechanical behaviour of joints obtained using this process still is scarce. Crack growth fatigue data concerning the welded material is required to provide tools for damage tolerance analyses. These analyses can be performed using linear elastic fracture mechanics concepts where the stress intensity factor plays a fundamental role in conjunction with the Paris law**.**

In this work, a comparative study on the fatigue crack propagation behaviour of friction stir (FS) butt welds of 6082-T6 and 6061-T6 aluminium alloys is carried out. Monotonic tensile tests of welded joints and base material (BM) were performed to understand the influence of the welding process in the static mechanical properties. Microhardness profiles were measured and fatigue crack growth curves were determined for cracks growing in different locations of the weldments, including the BM, the heat affected zone (HAZ) and the welded material (WM).

2. MATERIALS AND WELDING PROCESSES

The 6061-T6 and 6082-T6 are extruded medium to high strength Al–Mg–Si alloys that contain manganese to increase ductility and toughness. The T6 condition is obtained through artificial ageing at a temperature of approximately 180°C [1].

The 6061 alloy is one of the most widely used alloys in the 6000 series. This standard structural alloy, one of the most versatile of the heat-treatable alloys, is popular for medium to high strength requirements and has good toughness characteristics. Applications range from transportation components to machinery and equipment applications to recreation products and consumer durables.

Alloy 6061 is easily welded and joined by various commercial methods. Since 6061 is a heat-treatable alloy, strength in its T6 condition can be reduced in the weld region [2].

The 6082 is intended for structural applications including rod, bar, tube and profiles. This alloy offers similar but not equivalent physical characteristics compared to 6061 alloy. Alloy 6082 is very common in Europe [3].

Table 1 summarizes the typical chemical composition of the aluminium alloys.

The friction stir welds were performed in a prototype machine with a capability of 6m weld length developed to be used in a Portuguese shipyard. For both aluminium alloys the same parameters were used: welding speed of 800mm/min; pitch angle of 2º; rotating speed of 1500rpm. The FSW process of the 6082-T6 aluminium alloy was performed using a tool with a 6mm diameter threaded pin and the shoulder had 15mm diameter. For the 6061-T6 aluminium alloy a tool with a 4mm diameter threaded pin and a shoulder of 10mm diameter were used. The optimal welding speed depends on several factors; since alloy type, penetration depth and joint type are the most relevant, these parameters were chosen by trial and error attempts until no visually detected defects could be identified. The penetration depth was adapted to fully penetrated butt joint in a material of 3mm thickness.

Figure 1 illustrates the macrostructures of the two welded materials. In Figure 1a) the macrostructure of the friction stir weld of 6061-T6 aluminium alloy is presented. At the centre is possible to identify the weld nugget (NZ). The thermo-mechanically affected zone (TMAZ) ends at the tool shoulder delimited by the dashed lines. After the TMAZ appears the HAZ. In this weld sample, particularly at the advancing side, a high penetration of the shoulder is identified creating a small notch effect that could affect mainly the fatigue lives. In Figure 1b) the macrostructure of the friction stir weld of the 6082-T6 aluminium alloy is presented. At the centre is possible to identify the NZ with its typical shape of onion rings. The weld nugget experiences high strain and is prone to recrystallization. Immediately at its side is the TMAZ which ends at the tool shoulder delimited by the dashed lines. Adjacent to the TMAZ appears the material affected by the heat generated during the welding process.

Table 1 – Typical chemical compositions of the aluminium alloys (% weight) [2,3].

Alloy		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others each	Others	Al
6082-T6	Min.	0.7	-	-	0.4	0.6	0.04	-	-	-	-	Reminder
	Max.	1.3	0.5	0.1	1.0	1.2	0.15	0.20	0.20	0.05	0.15	
6061-T6	Min.	0.4	-	0.15	-	0.8	0.04	-	-	-	-	
	Max.	0.8	0.7	0.40	0.15	1.2	0.35	0.25	0.15	0.05	0.15	

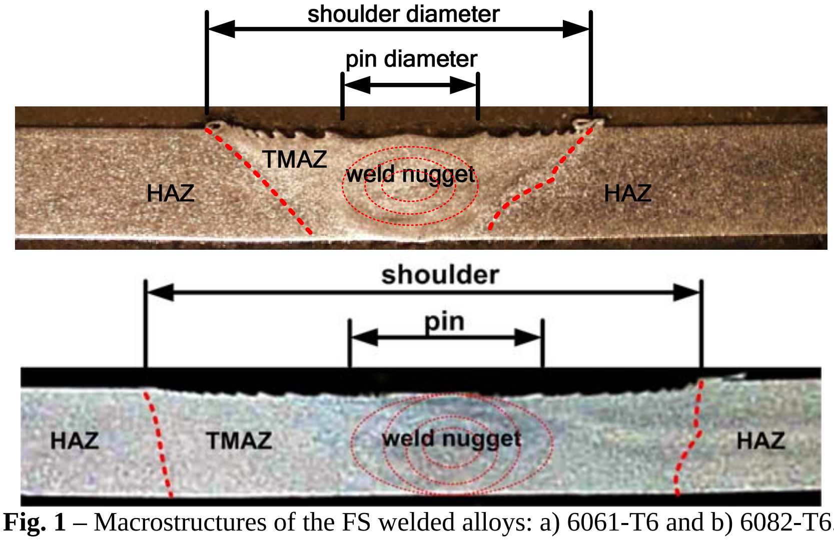


Fig. 1 – Macrostructures of the FS welded alloys: a) 6061-T6 and b) 6082-T6.

Figure 2 illustrates the microhardness profiles of the friction stir welded aluminium 6082-T6 and 6061-T6. A hardness decrease is identified in the TMAZ. The average hardness of the nugget zone was found to be significantly lower than the hardness of the base alloy. There is a zone outside the nugget zone which has the lower hardness value. The welding process softened the material reducing the hardness to 33% of the parent material, as shown in [4]. The minimum hardness values are obtained in the welding retreating side [5]. As it also suggested in [6], that variation of the microhardness values in the welded area and parent material is due to the difference between the microstructure of the base alloy and weld zone.

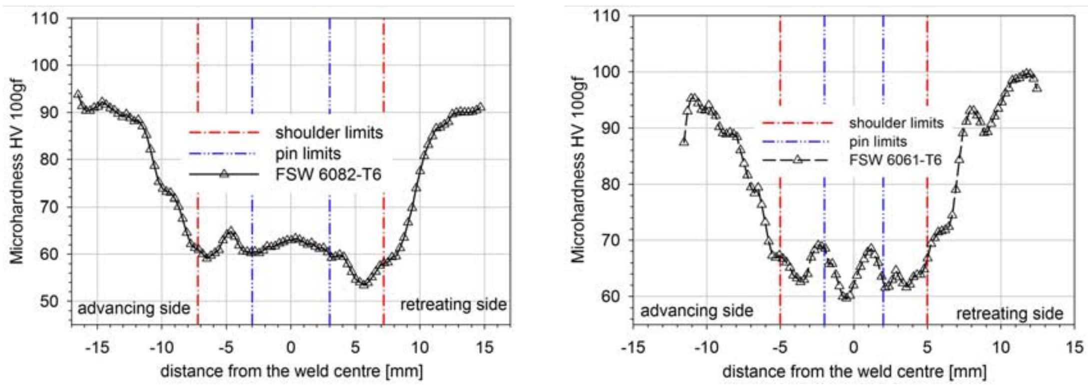


Fig. 2 – Microhardness profiles of the FS welded specimens: a) 6082-T6 aluminium alloy; b) 6061-T6 aluminium alloy.

3. MONOTONIC STRENGTH PROPERTIES OF THE BASE AND FRICTION STIR WELDED MATERIALS

Table 2 summarizes some mechanical properties of the aluminium alloys **reported** by the materials suppliers. Authors also performed tensile tests and Table 3 summarizes the measured monotonic strength properties for the two aluminium alloys under analysis. For each batch of specimens of the same material, tests presented similar results which are higher than values **given** by the material suppliers. Results show higher strength properties for the 6061-T6 aluminium **alloy: the 6061**-T6 aluminium alloy has an ultimate tensile strength about 6% higher than the 6082-T6 aluminium alloy. All specimens failed according 45º shear planes.

Table 2 – Tensile properties for base materials, data from materials suppliers.

Alloy	σ_{yield} [*MPa*]	σ_{rupt} [*MPa*]	E [*GPa*]	Elongation [*%*]
6082-T6	>260	310	69	10
6061-T6	276	310	68.9	12

Table 3 – Tensile properties for base materials, tensile tests by authors.

Alloy	Specimens	σ_{yield} [*MPa*]	σ_{rupt} [*MPa*]	E [*GPa*]	Elongation [*%*]
6082-T6	1	276.0	322.6	65.9	18.9
	2	276.0	323.4	64.7	16.4
	3	276.5	322.7	70.7	17.2
	Average	**276.2**	**322.9**	**67.1**	**17.5**
6061-T6	1	307.0	343.5	67.2	17.7
	2	301.0	337.3	73.7	16.9
	3	311.0	345.2	64.4	16.9
	Average	**306.3**	**342.0**	**68.5**	**17.1**

Tensile tests of friction stir welded specimens were also carried out. Table 4 summarizes the main results of these tests. In the case of the 6082-T6 friction stir welded specimens, fracture occurred near the weld edge, Figure 3, where a decrease of hardness occurs [4]. The fracture surface presents a 45º angle, as also presented by Svensson *et al.* [5]. In the case of the 6061-T6 friction stir welded specimens, the fracture started at the weld root indicating that a lack of penetration occurred during welding (root flaw), Figure 4. Since the fracture surface occurred at the weld middle line, it is possible to identify the different layers of material that were formed by each rotation of the welding tool. Dickerson *et al.* [7] suggested that root flaws up to 0.35*mm* deep do not cause degradation in mechanical performance when compared to flaw-free welds. The elongation of all friction stir welded specimens (4% to 5%) is approximately 25% of the base material (17%).

The aluminium 6082-T6 friction stir welded specimens present a yield stress of 51% and a rupture stress of 70% of the base material. Scialpi et al. [4] obtained also a relation of rupture stress of 76% between the base material and friction stir welded specimens. Values of the same magnitude are also reported by Ericsson [1], Harris [6], and Nicholas [8] in their literature review.

The aluminium 6061-T6 friction stir welded specimens have a yield stress of 52% and a rupture stress of 71% of the base material. Hong et al. [9] performed friction stir welds of 4mm thick aluminium 6061-T651 plates and found lower values for the yield stress and rupture stress when compared with those obtained in this study.

Table 4 – Tensile properties for FS welded specimens, tests by authors.

Alloy	**Specimens**	σ_{yield} **[*MPa*]**	σ_{rupt} **[*MPa*]**	**E [*GPa*]**	**Elongation [%]**
6082-T6	1	138,5	225,1	46,3	5,9
	2	137,5	222,9	40,7	5,3
	3	145,5	230,4	61,3	5,4
	Average	**140,5**	**226,1**	**49,4**	**5,5**
6061-T6	1	161,0	240,8	53,0	3,4
	2	158,0	241,2	48,6	4,0
	3	157,0	242,4	48,8	4,6
	Average	**158,7**	**241,5**	**50,1**	**4,0**

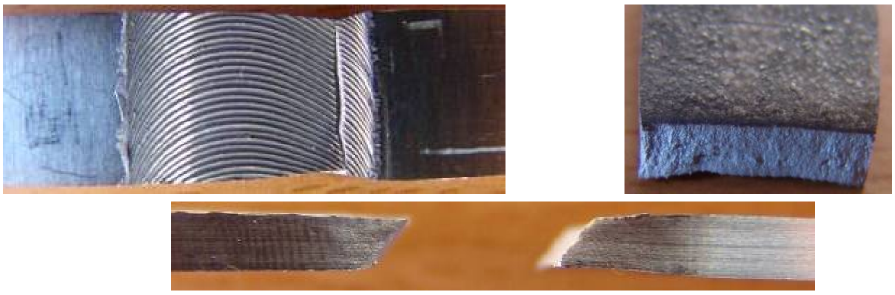


Fig. 3 – Fracture surface of the 6082-T6 FS welded specimen.

Fig. 4 – Fracture surface of 6061-T6 FS welded specimen.

4. CRACK PROPAGATION DATA

This paper presents a study on fatigue crack growth data of FS butt welds made of 3mm thick age hardenable 6082-T6 and 6061-T6 aluminium alloys. Both BM, HAZ and FS welded material materials are investigated. All fatigue experiments were carried out under constant load amplitude, at room temperature and in laboratory air on a computer controlled servo-hydraulic INSTRON 8801 testing machine, following the ASTM E647 standard [10]. Crack propagation was monitored through visual measurements using a travelling microscope. “As-welded” 40mm wide compact tension (CT) specimens were tested for a 20Hz load frequency. Figure 5 illustrates the geometry and dimensions of the tested specimens. Figure 6 illustrates the tested crack path orientations, in relation to the weld location. Table 5 summarizes crack propagation test program. A total of 29 CT specimens were tested, namely 18 specimens from the 6082-T6 aluminium alloy and 11 specimens from the 6061-T6 aluminium alloy. Several stress ratios were tested, namely R=0.0, R=0.1 and R=0.5 for the 6082-T6 alloy and R=0.1 and R=0.5 for the 6061-T6 alloy. For the base material, some tests were conducted according the rolling direction and others according the transverse to the rolling direction.

Table 3 – Program of crack propagation tests.

Specimens	Direction	Stress ratio, R	Material
MB-00-L-1	Rolling	0.0	6082-T6 (BM)
MB-00-L-2			
MB-00-L-3			
MB-01-L-1	Rolling	0.1	
MB-01-L-2			
MB-01-T-1	Transverse to Rolling	0.1	
MB-01-T-2			
MB-05-L-1	Rolling	0.5	
MB-05-T-1	Transverse to Rolling	0.5	
MB-05-T-2			
MD-01-1	-	0.1	6082-T6 (WM)
MD-01-2			
HAZ-01-1	-	0.1	6082-T6 (HAZ)
HAZ-01-2			
HAZ-01-3			
T-01-1	-	0.1	6082-T6 (BM+HAZ+WM)
T-01-2			
T-01-3			
MB-01-L-1	Rolling	0.1	6061-T6 (BM)
MB-01-L-2			
MB-01-L-3			
MB-05-L-1	Rolling	0.5	6061-T6 (BM)
MB-05-L-2			
MB-05-L-3			
MB-01-T-1	Transverse to Rolling	0.1	6061-T6 (BM)
MD-01-1	-	0.1	6061-T6 (WM)
MD-01-2			
T-01-1	-	0.1	6061-T6 (BM+HAZ+WM)
T-01-2			

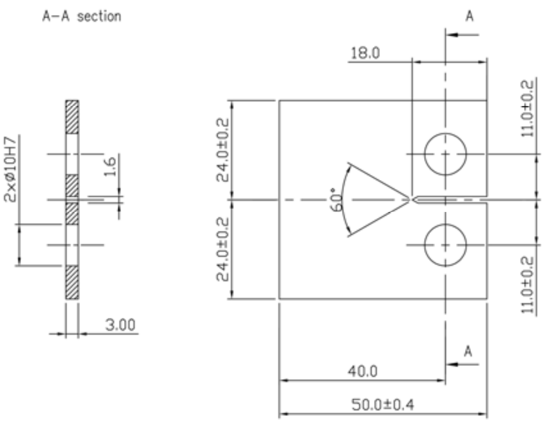
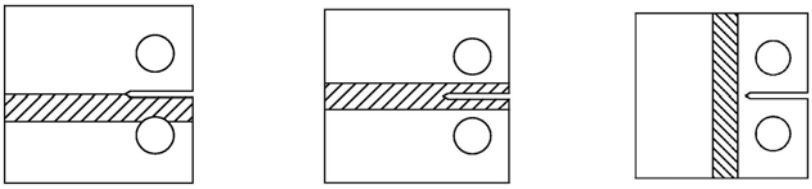


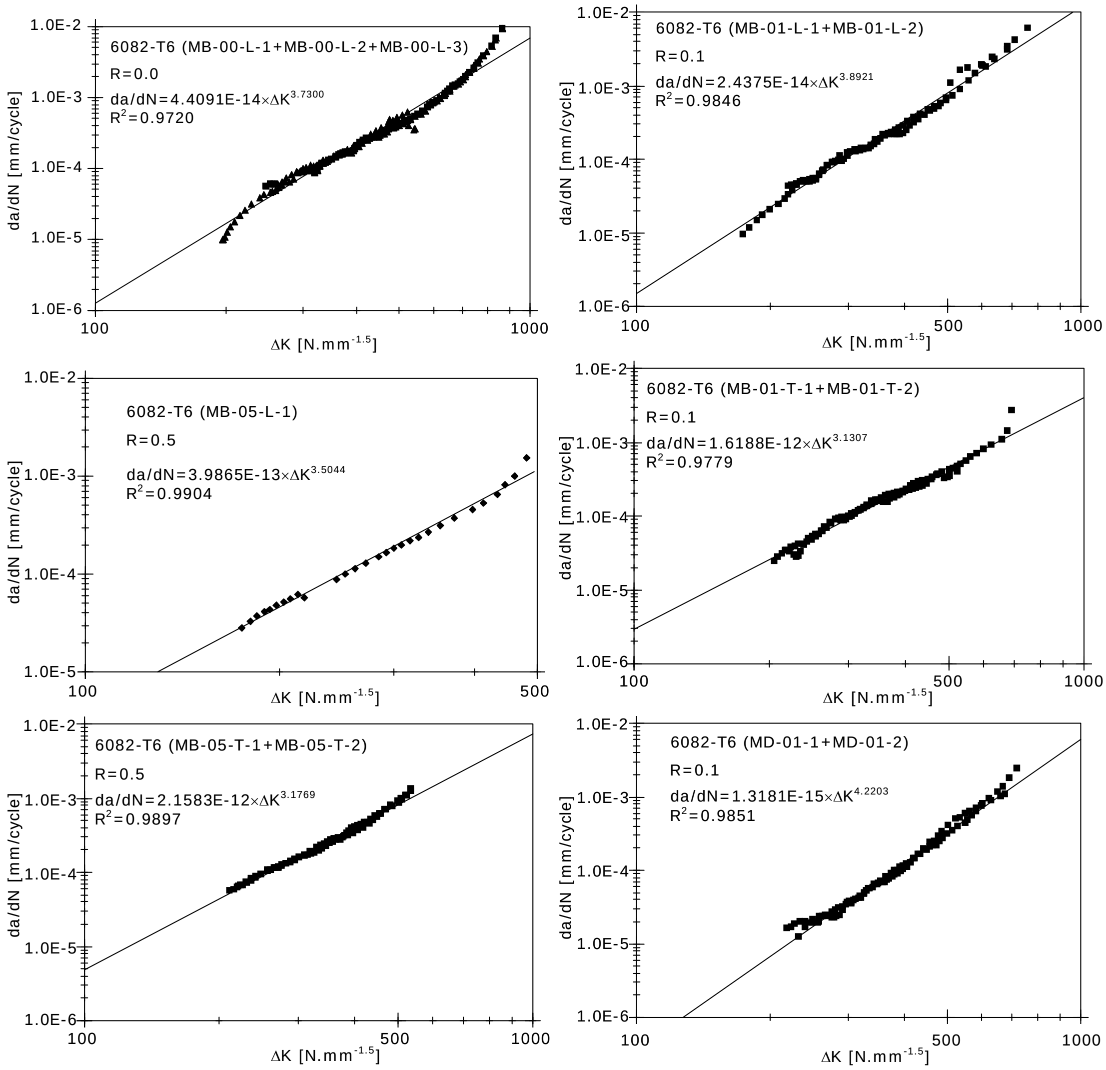
Fig. 5 – Compact tension specimens (dimensions in mm).



a) HAZ – parallel to weld b) WM – parallel to weld c) transverse to weld

Fig. 6 – Crack path orientations.

The experimental da/dN *versus* ΔK data was derived using the seven point polynomial incremental technique [10]. The experimental data was correlated using the Paris law [11]. Figure 7 illustrates the crack propagation data derived for the 6082-T6 aluminium alloy and respective welded material. The Paris law was fitted, for all cases, with high correlation coefficient. Crack propagation data for the base material concerning the rolling direction (R=0.0, R=0.1, R=0.5) and transverse to rolling direction (R=0.1 and R=0.5) is presented. Also, crack propagation is given for the FS material and HAZ under R=0.1. Finally, crack propagation data is proposed for a crack propagating transversely to the weld, crossing the BM, HAZ and FS materials.



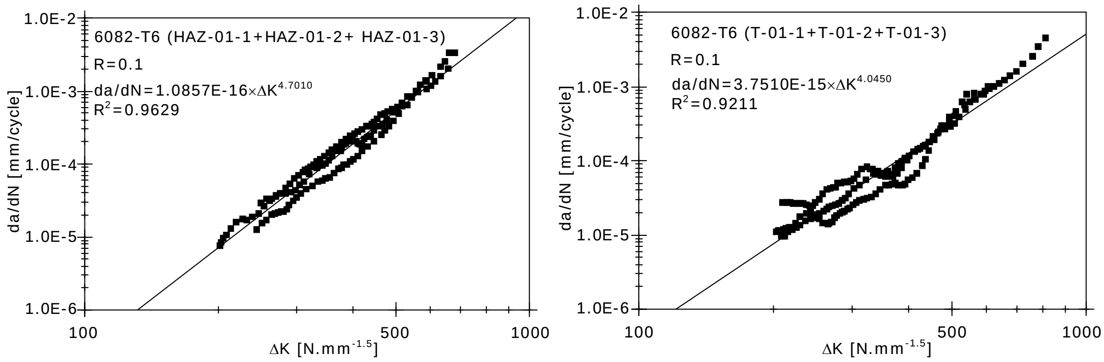


Fig. 7 – Crack propagation data obtained with the 6082-T6 aluminium alloy.

Figure 8 shows the crack propagation data obtained for the 6061-T6 aluminium alloy. The Paris law was also fitted with a high correlation coefficient. Data for the base material for a crack growing along the rolling direction (R=0.1 and R=0.5) and along transverse direction (R=0.1) is presented. Data for the friction stir welded material and for the crack growing transverse to weld path is also given.

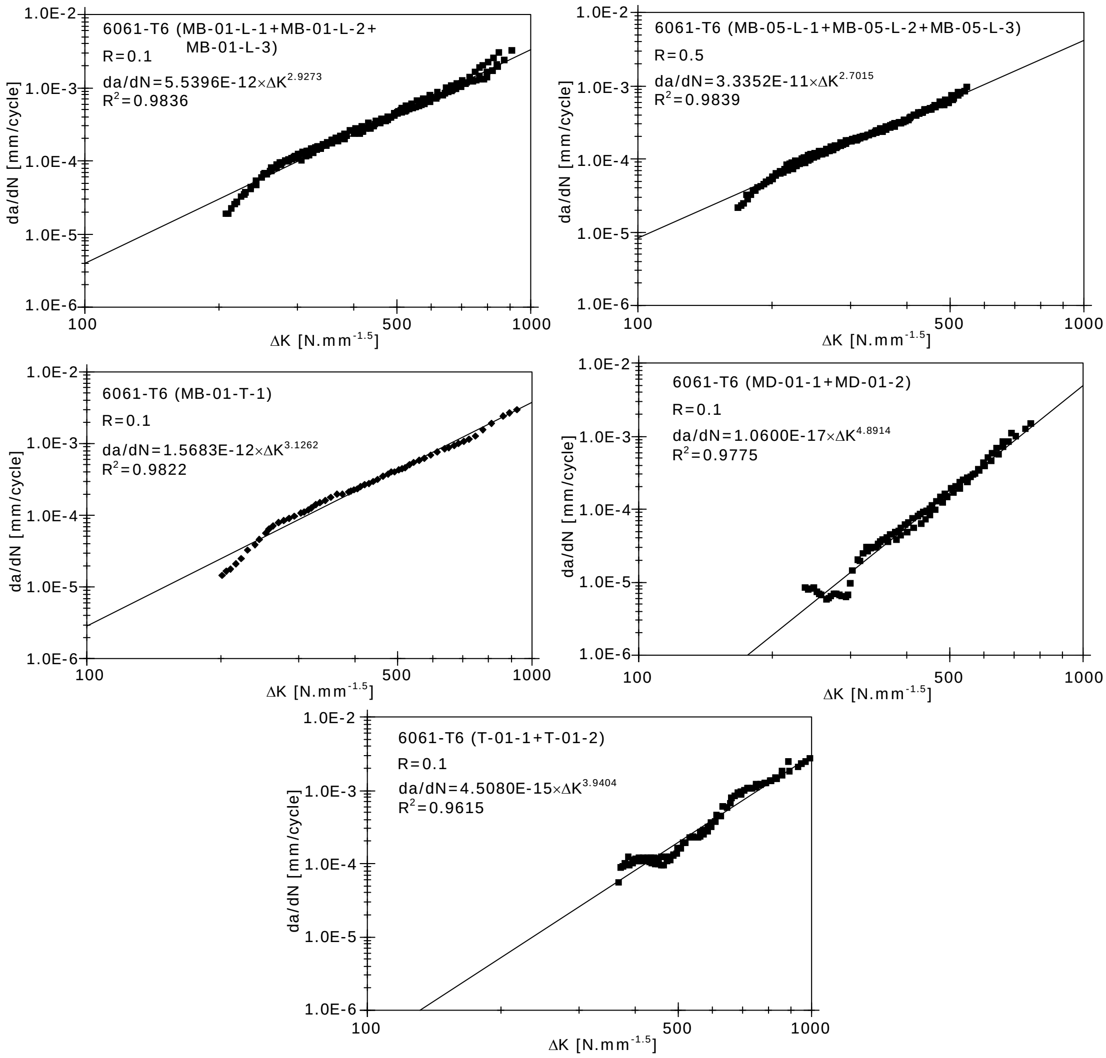


Fig. 8 – Crack propagation data obtained with the 6061-T6 aluminium alloy.

Figures 9, 10 and 11 perform comparisons between crack growth regression lines for several comparison scenarios. Figure 9 compares the crack propagation rates for several locations and stress ratios obtained with the 6082-T6 alloy. Comparisons made for the 6061-T6 base material shows that stress ratio influences the crack propagation rates – the crack propagation increases with the stress ratio, as expected. Test performed according the rolling direction shows smaller crack propagation rates for low stress intensity factor ranges; for medium-high stress intensity factor rages, smaller crack propagation rates are observed in the transverse to rolling direction. The crack growth rates are significantly lower for the FS welded material and HAZ. This difference is attenuated as the stress intensity factor range increases, at least for the HAZ.

Figure 10 compares the crack propagation data obtained for the 6061-T6 alloy. The crack propagation for this material also shows a dependency with the stress ratio – similar tendency as 6082-T6 alloy. The rolling and transverse directions show the same crack propagation rates. Again, a significant difference is encountered between the base material and the welded/HAZ materials. The FS welded material and HAZ shows remarkably lower crack propagation rates that the base material, being the welded material the most favourable.

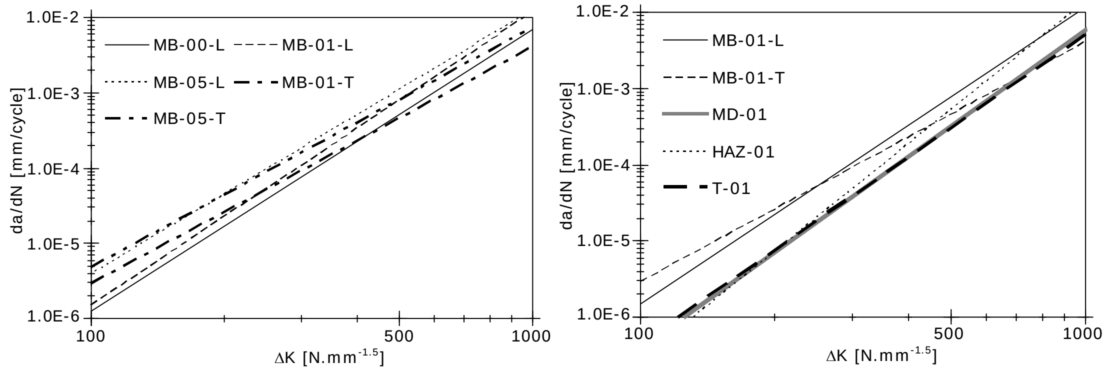


Fig. 9 – Comparison of crack propagation data obtained with the 6082-T6 alloy.

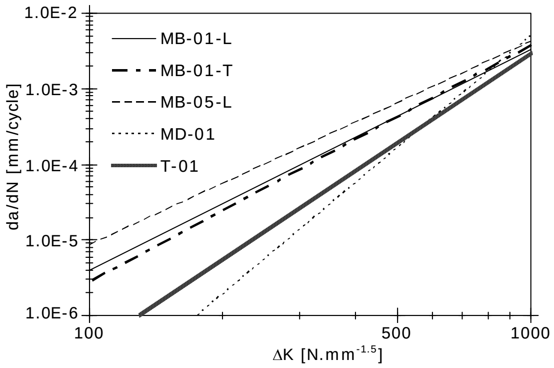


Fig. 10 – Comparison of crack propagation data obtained for the 6061-T6 alloy.

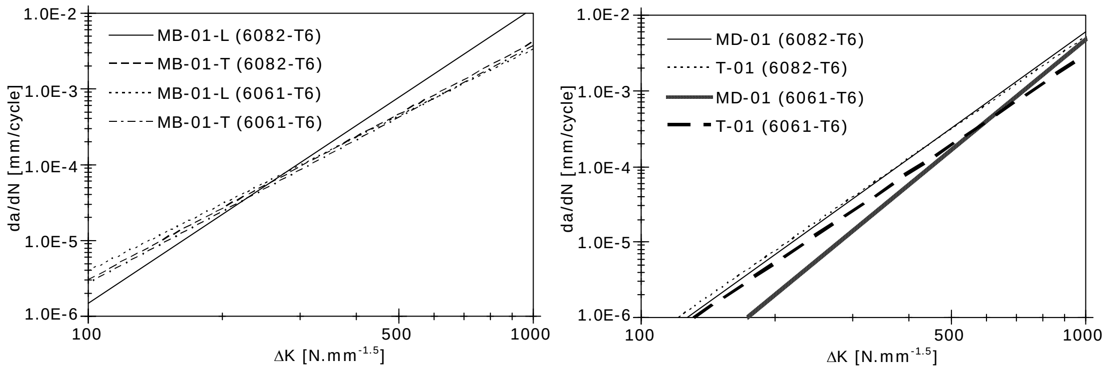


Fig. 11 – Comparison of crack propagation data obtained for the 6061-T6 and 6082-T6 alloys.

Figure 11 compares the crack propagation behaviours between the two aluminium alloys under investigation. BM's show identical crack propagation rates in the transverse direction. The FS welded material from the 6061-T6 material exhibits lower crack propagation rates than the corresponding 6082-T6 material.

6061-T6 and 6082-T6 aluminium alloys exhibit higher crack propagation rates than FS materials and HAZ. This behaviour seems contradictory with the observed lower monotonic strength properties for the FS materials and HAZ but may be explained by compressive residual stresses developed at crack vicinity when propagating in FS material, as suggested in [12].

5. CONCLUSIONS

Fatigue crack growth data for the aluminium alloys, 6061-T6 and 6082-T6 and corresponding FS materials and HAZ is presented. These two aluminium alloys exhibit higher crack propagation rates than FS materials and HAZ. This behaviour seems contradictory with the observed lower monotonic strength properties for the FS materials and HAZ, but may be explained by compressive residual stresses developed at crack vicinity when propagating in FS material. The two base materials show very similar crack propagation rates; however 6061-T6 FS material is more resistant to crack propagation than 6082-T6 FS material.

6. ACKNOWLEDGMENTS

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