COMPARATIVE STUDY ON FATIGUE CRACK GROWTH RATE BEHAVIOURS OF FRICTION-STIR WELDED ALUMINIUM ALLOYS 2024-T3 AND 6061-T6

Mochammad Noer Ilman

Department of Mechanical and Industrial Engineering
Gadjah Mada University
Jl. Grafika No.2, Yogyakarta, Indonesia
Phone: +62-0274-521673, FAX: +62-0274-521673, E-mail: ilman_noer@ugm.ac.id

ABSTRACT

Friction stir welding (FSW) is a solid-state joining process which enables unweldable metals to be joined without difficulty. This work presents comparative study between fatigue crack growth behaviours of friction stir welds of Al 2024-T3 and Al 6061-T6. The friction stir welds were prepared using the tool rotation speed, Rt and the plate travelling speed, V of 1450 rpm and 0.2 mm/s respectively. Subsequently, a sequence of tests was carried out including microstructural examination, hardness measurement, tensile test and fatigue crack growth rate (FCGR) test in combination with fractography. The FCGR test was carried out using constant amplitude fatigue experiments with stress ratio (R) and frequency of 0.1 and 11 Hz respectively whereas specimens used were centre crack tension type located at the weld nuggets. Results of this investigation showed that the fatigue crack growth rate (da/dN) of friction stir Al 2024-T3 welds was relatively lower compared to that of friction stir Al 6061-T6 welds especially at higher ΔK*, typically above 6* $MPa.m^{0.5}$*. The better fatigue performance of friction stir Al 2024-T3 welds was likely to be associated with fine grained weld microstructure present in the welds. However, the fatigue properties of both friction-stir Al 2024-T3 and Al 6061-T6 welds were not as good as that observed in their base plates. This may be associated with metallurgical changes and the formation of residual stress in the welds during welding process.*

Keywords: friction stir welding, fatigue crack growth rate, Al 2024-T3 and Al 6061-T6

1. Introduction

Aluminium alloys have become important materials for engineering applications in transportation such as automotive industry, aeronautics and military because the alloys have good mechanical properties, low density and high resistance to corrosion. Aluminium alloys 2024-T3 and 6061-T6 are the most common materials for structural applications in aircraft especially for fuselage skin due their extremely good damage tolerance and high resistance to fatigue crack growth [1].

Aluminium alloy 2024-T3 is Al-Cu alloy with the copper content in the range of 3.8-4.9% where T3 represents solution heat treated and naturally aged to achieve significant hardening whereas Al 6061-T6 is Al-1Mg-0.6Si alloy in T6 condition, i.e. solution heat treatment followed by artificial ageing [2,3].

Aluminium alloys are usually welded using conventional arc welding such as metal inert gas (MIG) or tungsten inert gas (TIG) welding. However, these welding processes often produce problems such as porosity, hot cracking, residual stress and distortion [4-6]. With the invention of advanced welding process such as friction stir welding (FSW), unweldable aluminium alloy such as Al 2024 can be welded without difficulty since the FSW technique is performed in solid state without melting hence avoiding hot cracking.

Figure 1 shows FSW process where weld joint is obtained by inserting a rotating pin into the adjoining edges of the plates to be welded [7].

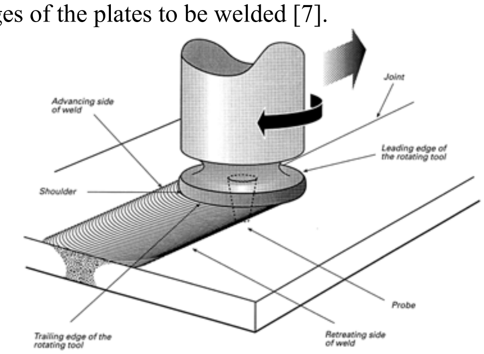

Fig.1. FSW process [7]

During welding process, heat Q is generated mainly by tool rotation speed Rt and plate travelling speed V and is given by Eq.(1) as follow [6] :

$$Q = \left(\frac{4}{3}\right)\pi^2 \mu P R_t D^3 \qquad (1)$$

where P is pressure and D is the surface radius of tool. Welding parameter R_t/V is closely related to heat input per unit length of the welded joint.

Fatigue property needs to be paid attention when FSW process is applied to structures under dynamic loads since many service failures of these structures are caused by manly fatigue failure. Fatigue crack growth rate of FSW welds seem to follow the Paris power law [8,9] which relates fatigue crack growth rate (da/dN) as a function of stress intensity range (ΔK) and is given by Eq.(2) below :

$$da/dN = C(\Delta K)^n \qquad (2)$$

where a is the crack length, N is the number of cycles, C and n are material constants. The present investigation aims to study fatigue properties of friction stir welded aluminium alloys 2024-T3 and 6061-T6.

2. Experimental

Materials

Materials used were aluminium 2024-T3 and 6061-T6 plates with the thickness of 3 mm and their chemical compositions are given in Table 1.

Welding Process

Two aluminium plates with thickness of 3 mm were butt welded using FSW process with tool rotation speed and tool travelling speed of 1450 rpm and 0.2 mm/s respectively. The shoulder diameter of the tool was 15.5 mm whereas diameter and length of the pin were 4 mm and 2.9 mm respectively.

Microstructure

Microscopical examination was carried out using an optical microscope. The specimens were prepared using standard metallograpic procedure consisting of grinding, polishing and etching using Keller's reagent.

Hardness Test

Hardness of weld nugget, TMAZ, HAZ and base metal were assessed using microhardness Vickers.

Tensile Test

The strength of FSW weld was assessed using tensile test with the specimens in the form of transverse weld specimen as shown in Fig.2.

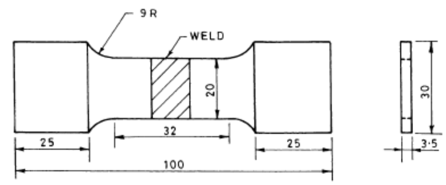

Fig.2. Tensile test specimen

Fatigue Crack Growth Test

Specimens for fatigue crack growth rate test were prepared according to ASTM E-647 standard. Center-cracked tension (CCT) specimens were selected with initial crack (a_o) of 18 mm were located at weld metals as shown in Fig.3.

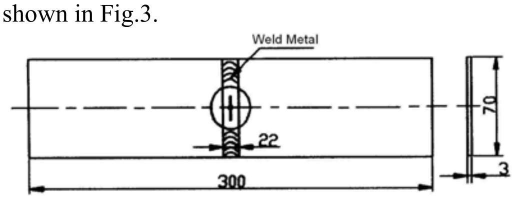

Fig. 3. Center-cracked tension (CCT) specimen

Fatigue experiments were carried out using a servo-hydraulic universal testing machine and a sinusoidal load was selected with the stress ratio, R = 0.1 and a frequency of 11 Hz. A stress level used was 20% of yield stress.

The fatigue crack growth rate (da/dN) of the Paris power law in Eq.(2) was analyzed using Secant Method by the following equations :

$$\left(\frac{da}{dN}\right)_{\bar{a}} = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \qquad (3)$$

$$\bar{a} = \left(a_{i+1} + a_i\right)/2 \qquad (4)$$

where $\bar{a}$ is average crack length and subscripts © and (i+1) represent i^{th} and $(i+1)^{th}$ cycle. The stress intensity factor range, ΔK for center crack tension (CCT) geometry was calculated by using Eq.(5) and Eq.(6) as follows :

ISBN: 978-602-97742-0-7

Table 1. Chemical composition of Al 2024-T3

Material	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti
Al 2024-T3	0.50	0.50	3.9	0.60	1.5	0.25	0.10	0.15
Al 6010-T6	0.59	0.33	0.19	0.07	0.94	0.009	0.14	0.02

$$\Delta K = \frac{\Delta P}{B}\left[\sqrt{\frac{\pi\alpha}{2W}\sec\frac{\pi\alpha}{2}}\right] \quad (5)$$

$$\Delta P = P_{max} - P_{min} \quad (6)$$

where B is the specimen thickness, W is the specimen width and $\alpha = 2a/W$

3. Results and Discussion

3.1. Microstructure

Figure 4 shows a typical FSW joint where the weld area is in the form of asymmetrically inverted trapezoid which the area extends more towards the advancing side. The advancing side is the side of the weld where there is a positive combination of the tool feed rate and the peripheral tool velocity whereas in retreating side, the vectors are opposite. As a consequence, HAZ and TMAZ regions of this advancing side are wider than that of retreating side.

Fig. 4. FSW weld joint

Based on microstructures formed, the weld area can be divided into 4 regions namely weld nugget, thermomechanically affected zone (TMAZ), heat affected zone (HAZ) and base metal. According to Fratini et al [10] these FSW microstructures are defined as follows :

a. Weld Nugget (WN) : stir zone or the dynamically recrystallized area in TMAZ
b. Thermomechanically affected zone (TMAZ) : in this region, the material has been plastically deformed by the tool and at the same time, heat flux has a significant influence on microstructure
c. Heat affected zone (HAZ) : in this region the material is thermally cycled during welding resulting in changes in microstructure and mechanical properties without plastic deformation
d. Base metal (BM) : no material deformation has occurred with microstructure and mechanical properties are not affected by heat generated during welding.

Microstructures present in weld nuggets of aluminium alloys 2024-T3 and 6061-T6 are shown in Fig.5(a)-(b). Both microstructures show equiaxed grains as a result of recrystallization under high temperature and large deformation in the weld center due to stirring process. However, they are different in term of grain size, i.e. the weld nugget in Al 2024-T3 is marked by fine grained microstructure whereas the grain size of weld nugget in Al 6061-T6 is relatively coarser.

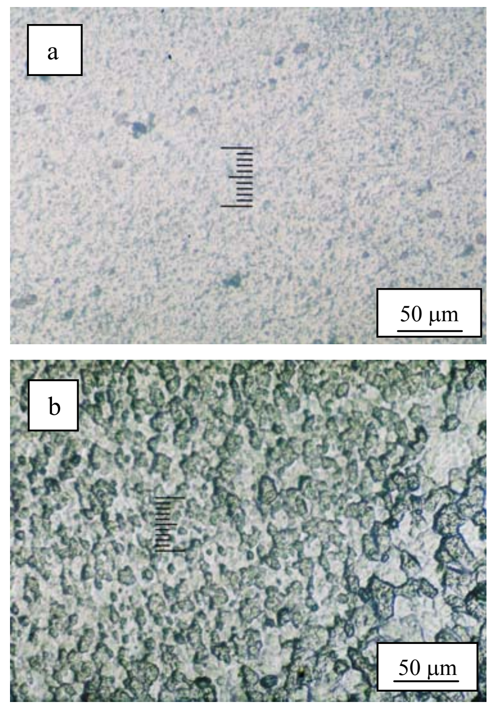

Fig.5. Weld nugget microstructure in : (a) Al 2024-T3 and (b) Al 6061-T6

3.2. Mechanical Properties

Results of tensile test given in yield stress (S_y) and maximum stress (S_{max}) are shown in Fig.6. It can be seen that S_y and S_{max} of the weld nugget are lower than those of the base metal for both Al 2024-T3 and Al 6061-T6. In Al 2024-T3, the strength of weld nugget is around 50% the strength of its base metal whereas strength reduction in Al 6061-T6 is much lower. In comparison with Al 6061-T6, the strength of weld nugget in Al 2024-T3 is relatively higher. This may be explained based on the fact that the weld grain size of Al 2024-T3 is smaller and it has been known that the smaller grain size may increase strength according to the Hall-Petch relationship [11] as given in Eq.(7).

$$\sigma_y = \sigma_f + kd^{-1/2} \tag{7}$$

where σ_y is yield stress, σ_f is friction stress, k is constant and d is grain size.

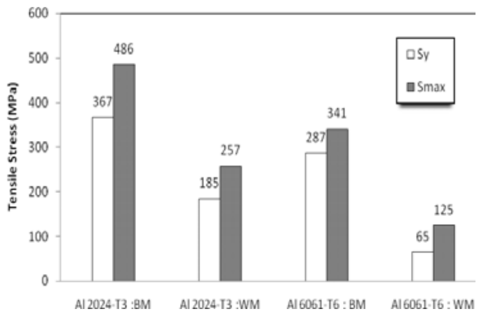

Fig.6. Tensile tests

Results of microhardness measurement for both Al 2024-T3 and Al 6061-T6 are shown in Fig.7. The hardness of weld nugget is lower than that of its base metal for both the aluminium alloys under study. These microhardness results have similar trend to that obtained in the tensile tests suggesting that the strength is linearly proportional to the hardness.

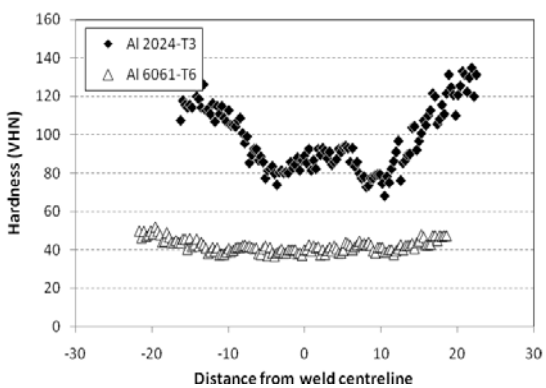

Fig. 7 Hardness distribution in FSW joints

3.3. Fatigue Crack Growth Rate

Figure 8 shows results of fatigue crack growth measurements given in crack length (a) as a function of number of cycles (N) where their fatigue life are given in Table 2. It can be seen that fatigue life of weld nugget is lower than that of its base metal, typically 26 % the base metal strength for both Al 2024-T3 and Al 6061-T6. This suggests that fatigue failure is likely to occur at FSW weld nugget when it is applied to structures which are subjected to dynamic loads.

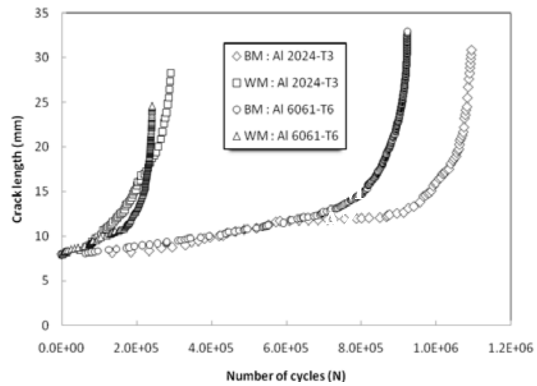

Fig.8. Fatigue life of the weld nuggets and their base metals

Table 2. Fatigue life

Material	Fatigue Life (cycles)	% decrease
Al 2024-T6 : BM	1.093.469	-
Al 2024-T6 : WM	289.905	26.5%
Al 6061-T6 : BM	922.102	-
Al 6061-T6 : WM	241.343	26.2%

Fatigue crack growth rate behaviour of FSW joints can be presented by plotting (da/dN) as a function of stress intensity factor range (ΔK) as shown in Fig.9. It can be seen that the curves are in the form of sigmoidal with three regions, namely crack initiation (region I), stable fatigue crack growth (region II) and finally, unstable crack growth leading to fracture (region III). In fatigue design, region II plays an important role especially for predicting fatigue life. The da/dN-ΔK curves of this region are linear where fatigue crack growth rate (da/dN) is linearly proportional to stress intensity factor range (ΔK) and this relationship can be represented by a power-law relation $da/dN = C(\Delta K)^n$ where C is constant and n is a power law exponent. By taking trendlines in this region (as shown in Fig.10) then the n and C values can be determined as given in Table 3. Referring to Table3, the n values are in the range of 2-5 consistent with the works reported previously [9,12].

ISBN: 978-602-97742-0-7

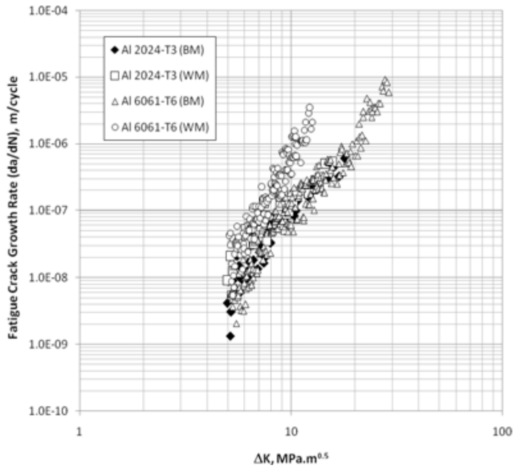

Fig.9. da/dN-ΔK curves for weld nugget and base metal for Al 2024-T3 and Al 6061-T6

Referring to Fig.9, Fig.10 and Table 3, it can be seen that both base metal Al 2024-T3 and Al 6061-T6 have excellent fatigue performance, i.e. lower fatigue crack growth rate compared to the base metal. In addition, at higher ΔK typically above 6 $MPa.m^{0.5}$ the fatigue crack growth rate of the Al 2024-T3 weld nugget is lower than that of 6 weld nugget in Al 6061-T6. This suggests that in the weld nugget of Al 6061-T6, crack inhibition occurs at the early stage of crack propagation then followed by rapid crack growth after a certain crack length is reached. In contrast, the weld nugget of Al 2024-T3 shows stable crack growth with n value is lower than that of the Al 6061-T6. It seems that from the view point of fatigue performance, Al 2024-T3 is better than that of Al 6061-T6 for both base metal and weld nugget.

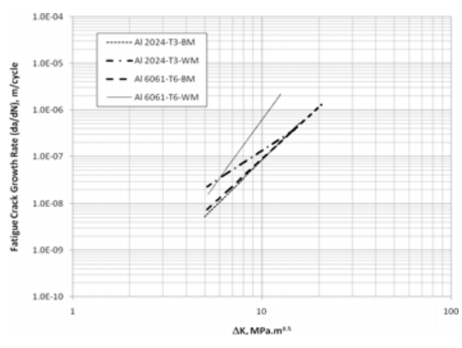

Fig.10. Trendlines taken from da/dN-ΔK curves

Table 3. The n and C values for FSW joints

Material	C	n
Al 2024-T6 : BM	1.6444E-12	3.9890
Al 2024-T6 : WM	3.1783E-10	2.6248
Al 6061-T6 : BM	1.7050E-11	3.7103
Al 6061-T6 : WM	8.5893E-12	5.5681

An example of scanning electron microscopy (SEM) fractography taken from fractured surfaces of the weld nugget in Al 2024-T3 is shown in Fig.11. It can be seen that the fractured surfaces are marked by the presence of transgranular cleavage fracture with no striations observed suggesting this type of fracture is brittle fracture.

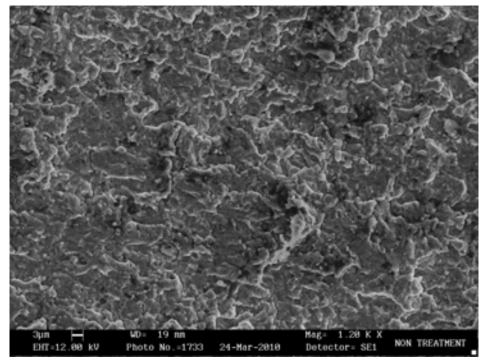

Fig.11. An example of SEM fractography of the Al 6061-T6 fractography

The present investigation has endeavoured to study fatigue crack growth rate (FCGR) behaviour of FSW joints. However, further work needs to be carried out to gain better understanding to other factors affecting FCGR such as residual stresses and precipitation in both Al 2024-T3 and Al 6061-T6.

4. Conclusions

The conclusions that can be drawn from this investigation are as follows :

1. Friction stir welding causes softening in weld nugget marked by a decrease in strength and hardness
2. Fatigue crack growth rate of FS weld in Al 2024-T3 is relatively lower (hence better fatigue performance) than that of FS weld in Al 6061-T6 at higher ΔK, typically above 6 $MPa.m^{0.5}$ due to probably its fine grains present in the weld nugget
3. In comparison with their base metals, the weld nuggets show lower fatigue performance for both Al 2024-T3 and Al 6061-T6.

Acknowledgements

This work was carried out under Hibah Penelitian Multi Tahun, Penelitian Fundamental (Contract No. LPPM-UGM/649/2009). The author acknowledge funding of LPPM UGM and DIKTI.

ISBN: 978-602-97742-0-7

References

[1] Staley,J.T. and Lege,D.J., *Advances in aluminium alloy products for structural applications in transportation,* Journal De Physique IV, 3 (1993) 179-190

[2] Polmear,I.J., *Light Alloys*, 3rd edition, Arnold, London, UK, 1981

[3] Mandal, N.R, *Aluminium Welding*, 2nd edition, Narosa Publishing House Pvt.Ltd, New Delhi, India, 2005.

[4] Huang,C. and Kou,S., *Liquation cracking in full-penetration Al-Cu welds*, Welding Research Supplement, (2004) 50s-58s

[5] Cao,G. and Kou,S., *Friction stir welding of 2219 aluminium : behaviour of θ (Al_2Cu) particles*, Welding Research Supplement, (2005) 1s-7s

[6] Nakata,K., Kim,Y.G., Ushio,M., Hashimoto,T. and Jyogan,S., *Weldability of high strength aluminium alloys by friction stir welding*, ISIJ International, 40 (2000) S15-S19

[7] Thomas,W.M. and Nicholas,E.D., *Friction stir welding for the transportation industries*, Materials & Design, 18 (1997) 269-273

[8] Paris,P.C., *Fatigue-An Interdisciplinary Approach, Proceeding of the 10th Sagamore Army Materials Research Conference*, Eds. J.J. Burke, N.L. Reed and V.Weiss, (1964) 107-132,

[9] Broek, D., *Elementary Engineering Fracture Mechanics*, Martinus Nijhoff Publisher, The Hague, Netherlands, 1983

[10] Fratini,L., Buffa,G., Palmeri,D., Hua,J. and Shivpuri,R., *Material flow in FSW of AA7075-T6 butt joints : continuous dynamic recrystallization phenomena*, Journal of Engineering Materials and Technology, Transcation of the ASME, 128 (2006) 428-435

[11] R.E. Reed-Hill and R. Abbaschian : *Physical Metallurgy Principles*, PWS publishing company, 3rd edition, Boston, 1991

[12] Lancaster, J.F., *Metallurgy of Welding*, Abington Publishing, Cambridge, UK, 1999