Fatigue Crack Growth Rate Behaviour of TIG Aluminium Alloy 5083 Weld Joints Under Various Preheating

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Abstract

Aluminium alloy AA5083 finds broad use in welded structural members such as marine frames and truck. In general, aluminium welded structures are known for their low fatigue crack growth resistance due to the formation of residual stress. The aim of the present investigation is to improve fatigue crack growth rate (FCGR) resistance of TIG welded AA5083 using preheating.

In this investigation, AA5083 plates were joined using TIG with various preheating temperatures, namely 100, 200 and 300 ^oC. Subsequently, FCGR test was performed using a constant amplitude with stress ratio (R) of 0.1 and frequency of 11 Hz. Specimens used were in the form of centre-cracked tension (CCT) with an initial crack located at the weld centerline. To gain better understanding to the FCGR behaviour of weld joints, microstructural examination and mechanical property tests including hardness and tensile tests were also performed.

Results show that an optimum preheating temperature which produces the weld joint with the lowest FCGR is achieved at preheating temperature of 300 ^oC. This improved FCGR could be associated with microstructure and thermal gradient between the weld metal and its adjacent base metal during welding process.

Keywords: TIG, AA 5083, Preheating, FCGR

Introduction

As one of the most commonly used non heat-treatable alloys in structural members, autobody sheets and marine applications, aluminium alloy 5083 is often welded during manufacturing process. Generally, this alloy is easily welded using arc welding processes such as tungsten inert gas (TIG) or metal inert gas (MIG) welding processes [1-3]. However, welding process often produces problems such as residual stress and distortion due to local heating during welding process.

Local heating affects the temperature distribution in weld joint and it's adjacent area. Rosenthal [4,5] has proposed a model for predicting temperature distribution around the weld based on a single-point moving heat source as given by the following equation,

$$T - T_o = \frac{q/v}{h(4\pi k\rho ct)^{1/2}} e^{-r^2/4\alpha t} \qquad (1)$$

where T_o is initial temperature or preheat, q : heat generated, v : travelling welding speed, h : plate thickness, k : thermal conductivity, ρ : density, c : thermal capacity, α : diffusivity which is equal to $k/(\rho c)$ and t : time.

In engineering applications, aluminium welded structures are often subjected to repeating load leading to fatigue failure. According to Maddox [6], the fatigue crack growth rate (FCGR) of a weld joint during the period of stable crack propagation follows the well-known Paris equation [7] which relates the fatigue crack growth rate, da/dN as a function of the stress intensity range, ΔK as given by :

$$\frac{da}{dN} = C(\Delta K)^n \qquad (2)$$

where a is the crack length, N is the number of cycles, C and n are material constants. The presence of high tensile residual stress in weld joints increases FCGR because these initial stresses, when superimposed on the applied stresses, increase overall mean stress and in contrast, compressive residual stresses reduce the effect of applied tensile stress resulting in increased fatigue performance.

In recent years, there has been a number of works aimed to reduce residual stress prior to and during welding using thermal process such as preheating. Preheating is normally carried out at temperature below 300 ^oC [5,8]. The advantage of preheating is based on the fact that preheating is an in-process method, therefore from the view point of manufacturing efficiency and cost, the preheating is more desirable than other post weld treatments.

Despite preheating is well established topic in welding research, there is lack of data on FGRT of aluminium alloy 5083 under preheating treatment, therefore is the suject of the present investigation.

Experimental

Materials

Material used was aluminium alloy 5083 plates and a filler of ER5356 with their chemical compositions are given in Tables 1 and 2.

Table 1. Chemical composition of Al 5083 (wt%)

Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti
0.40	0.40	0.10	0.50	4.0	0.25	0.20	0.15

Table 2. Chemistry of ER5356 filler (wt%)

Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti
0.25	0.4	0.1	0.12	4.5	0.1	0.12	0.13

Welding Procedure

In this investigation, the 5083 aluminium alloy plates with the dimensions of 100 mm wide, 300 mm long and 3 mm thick were butt welded along 300 mm long. Welding was performed using a tungsten inert gas (TIG) welding process with alternating current (AC) mode and argon as shielding gas. Welding parameters including current, voltage and heat input were 130 A, 30 V and 0,5 kJ/mm respectively. Welding was performed without and with preheating at various temperatures of 100, 200 and 300 ^{o}C as shown in Fig.1 then microstructural examination was carried out using optical microscopy.

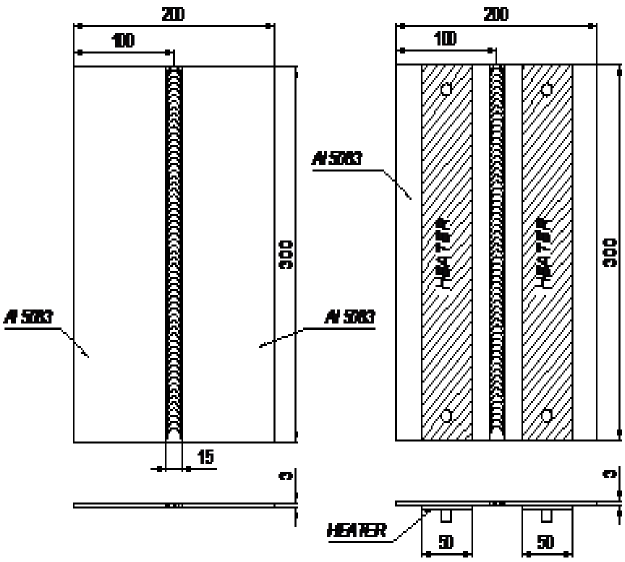

Figure 1. Welding procedure with preheating

Hardness Test

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

Tensile Test

The strength of TIG weld was assessed using tensile test with the specimens in the form of transverse weld specimen according to ASTM B557 as shown in Fig.2.

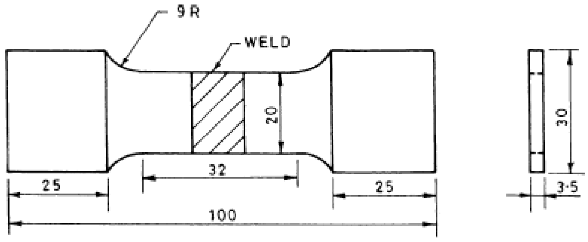

Figure 2. Transverse weld specimen (ASTM B557)

Fatigue Crack Growth Test

Specimens for fatigue crack growth rate test were prepared according to ASTM E-647 standard [9]. Centre-cracked tension (CCT) specimens were selected with initial crack were located at weld metals as shown in Fig. 3.

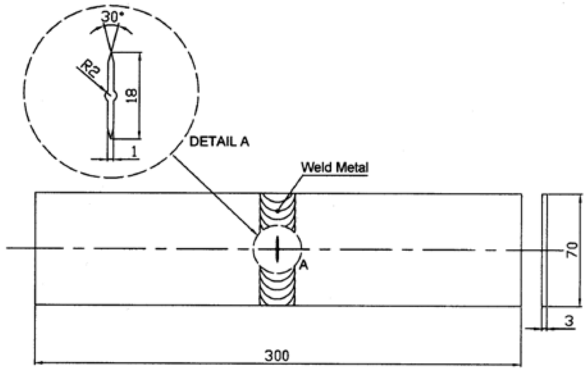

Figure 3. Centre-cracked tension (CCT) specimen

Fatigue experiment was carried out using a servo-hydraulic universal testing machine and a sinusoidal load was selected with the stress ratio, R of 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 (Eq.2) was analyzed using Secant Method as follows :

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

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

where $\bar{a}$ is average crack length and subscripts i and (i+1) represent i^{th} and $(i+1)^{th}$ cycle. The stress intensity factor range, ΔK for centre crack tension (CCT) geometry was calculated using the following equation

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

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

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

Results and Discussions

Figure 4 shows macrostructure of TIG alumium weld joint consisting of various regions, namely weld metal (WM) or fusion zone (FZ), heat affected zone (HAZ) and base metal (BM) whereas the microstructure present in each region is shown in Fig.5.

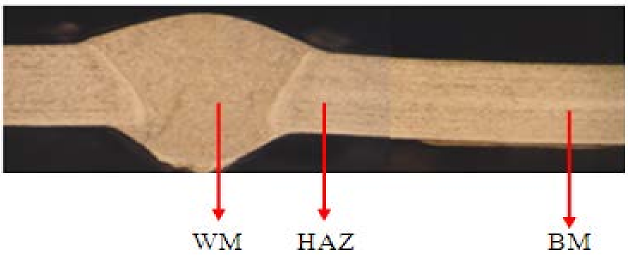

Figure 4. TIG aluminium weld joint profile

Referring to Fig.5, it can be seen that a significant variation in the microstructure from weld metal to base metal is observed. The weld metal region as shown in Fig.5(a) is marked by the presence of fine equiaxed grain structure consisting of grains of aluminium solid solution designated α (light etched) and eutectic (Al-Mg-Si) mixture (dark etched) along the grain boundaries. Based on phase diagram as shown in Fig.6, this Al-Mg-Si phase could be in the form of Al+Mg_2Si [10-13]. Coarse HAZ grains along fusion line as shown in Fig.5(b) seem to act as nucleation sites for α phase and the epitaxial growth during solidification is evident. Epitaxial growth occurs when the solidification moves towards region with maximum temperature gradient, i.e. weld centerline.

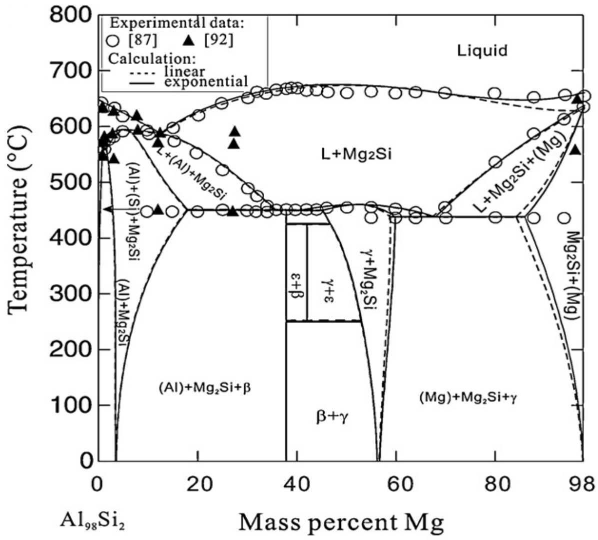

Figure 6. Phase diagram of Al-Mg-2Si system [10]

Heat affected zone (HAZ) is region adjacent to weld metal where its microstructure changes without melting as a result of heat during welding process. HAZ region shown in Fig.5(c), consists of coarse grains compared to the grains in base metal (Fig.5(d)). This is because the grain growth in HAZ have already occurred. Microstructure of base metal is characterized by fine and elongated grains along rolling direction known as texture.

The effect of preheating temperature on weld metal microstructure is shown in Fig.7. It can be seen that two microstructural changes are observed, coarsening microstructure and the amount of eutectic Al-Mg phase is reduced in favour of aluminium solid solution (α). These microstructural changes are associated with cooling rate where an increase in preheating temperarature lowers cooling rate.

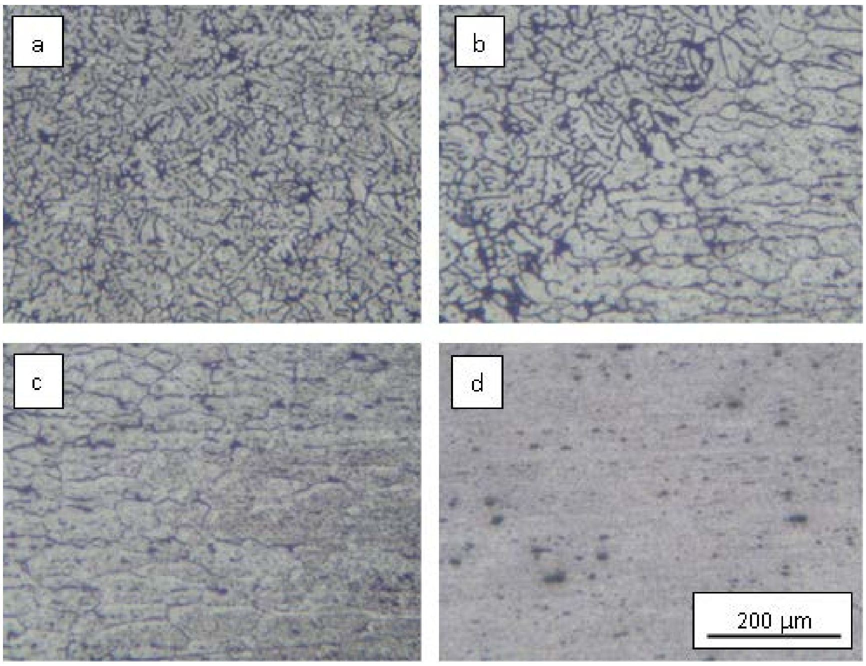

Figure 5. Microstructure present in : (a) weld metal, (b) fusion line, (c) HAZ region and (d) base metal

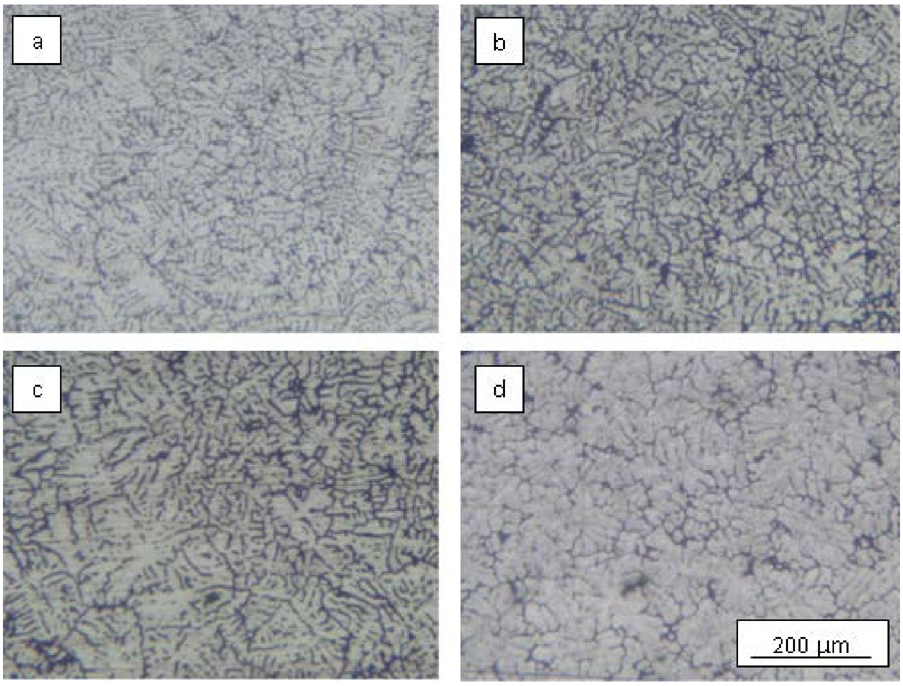

Figure 7. TIG aluminium weld metal microstructures : (a) as welded, and preheating temperature of (b) 100 ^{o}C, (b) 200 ^{o}C, (b) 300 ^{o}C

Results of microhardness measurements starting from base metal, HAZ region up to weld metal are shown in Fig.8. In general, welding process causes softening in the fine grained HAZ region where this region is located near base metal-HAZ boundary. During welding process, this region had nucleated allowing recrystallization to occur but it did not sufficient time to grow. Sharp increase in hardness is observed in HAZ region. The formation of Mg_2Si could be responsible for increasing hardness in HAZ. Variation in hardness is closely link to microstructure present in these regions. The effect of preheating temperature seems to decrease the hardness due to low cooling rate during welding process.

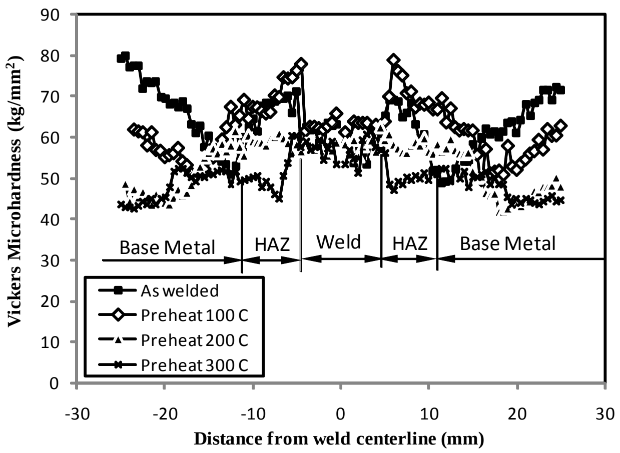

Figure 8. Hardness distribution of the weld joints

Results of tensile test are shown in Fig.9. As expected, all transverse weld specimens were fractured at fine grained HAZ-base metal boundary where softening occurs in this region. An increase in preheating temperature decreases the strength of TIG weld joint.

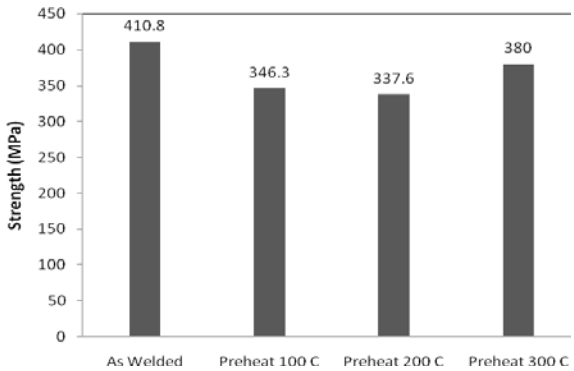

Figure 9. Strength of the weld joints

Apart from HAZ-base metal region, another region which needs to be paid attention when dynamic loads occur during service is weld metal region. This is because weld metal shape cause high stress concentration which allow crack initiation. In addition, weld metal produces residual stress which promotes fatigue crack growth rate (FCGR).

Results of fatigue test given in crack length vs the number of cycles are shown in Fig.10 whereas %increase where as welded used as refference is given Table 3. It can be seen that preheating temperature of 100 ^{o}C does not give significant effect on fatigue life. However a sharp increase, i.e. 115.5% is achieved when the preheating temperature is increased up to 200 ^{o}C. Further increase in preheating temperature to 300 ^{o}C, increase fatigue life close to that of the base metal.

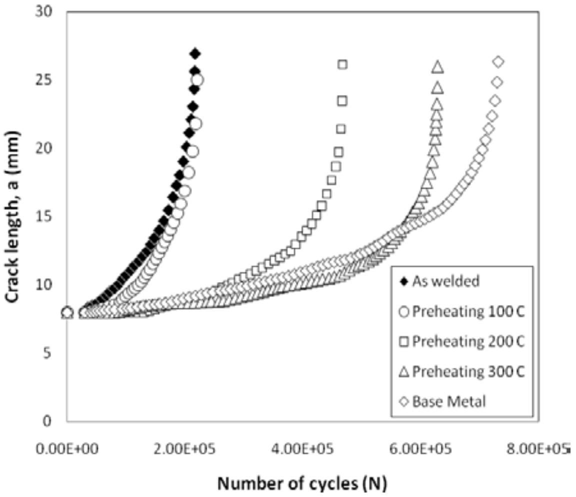

Figure 10. Fatigue life of the welds under study

Table 3. Fatigue life of welds under study

Specimen	Number of cycles (N)	% Increase
As welded	217000	-
Preheat 100 ^oC	221540	2.1%
Preheat 200 ^oC	467600	115.5%
Preheat 300 ^oC	629370	190.0%
Base Metal	731600	

The fatigue test can be better analyzed by plotting fatigue crack growth rate (da/dN) as a function of stress intensity factor (ΔK) in logarithmic scale as shown in Fig.11.

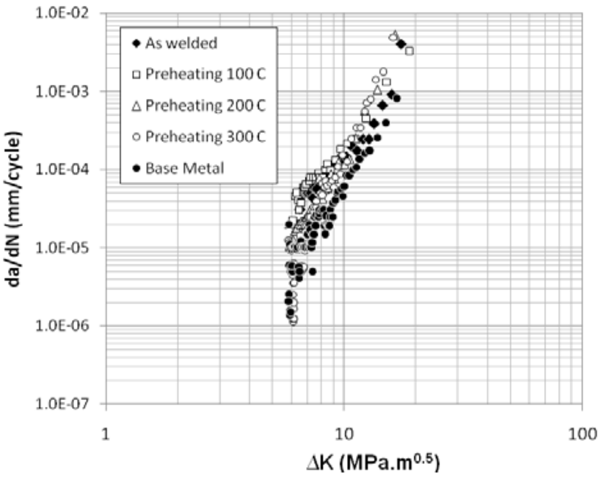

Figure 11. Plots of (da/dN)-ΔK

In general, (da/dN)-ΔK curves in Fig.11. form sigmoidal curves and these curved can be divided into three regions, namely region I, II and III [14,15]. Region I is controlled by many factors such as stress concentration, microstructure and environment. Region II is known as stable crack growth which follows Paris law according to Eq.2 hence forming linear curve in (da/dN)-ΔK curves. Finally, region III leads to fatigue failure.

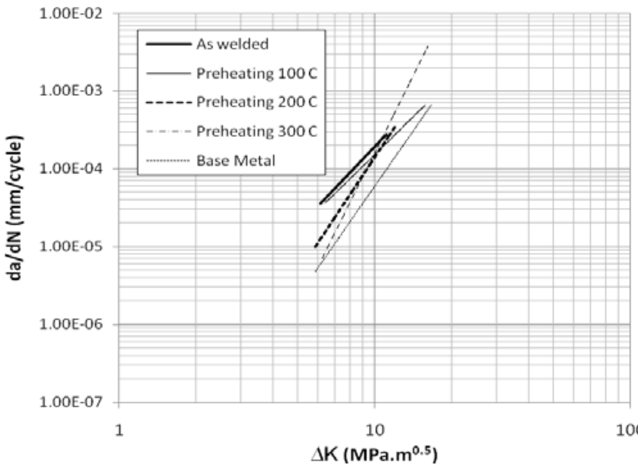

Figure 12. Trendlines taken from region II of (da/dN)-ΔK curves

Figure 12 shows trendlines taken from region II of (da/dN)-ΔK curves in Fig.11 with n and C values are given in Table 4. The FCGR depends on n and C values where n represents the slope of the linear curves whereas C at ΔK = 1 $MPa.m^{0.5}$ determines position of the curves.

Table 4. Paris constants

Specimens	Paris Constants	
	C	n
As welded	7.2107E-08	3.4212
Preheating 100 ^oC	8.6998E-08	3.2414
Preheating 200 ^oC	1.1420E-09	5.1133
Preheating 300 ^oC	4.4610E-11	6.5587
Base Metal	1.1775E-09	4.7106

Referring to Fig.11 and Table 4 and by using as welded as reference fatigue, it can be seen that at low ΔK, typically below 10 $MPa.m^{0.5}$, a slightly decrease in FCGR is observed when preheating at temperature of 100 ^oC is applied. As preheating temperature is increased up to 200 ^oC, a remarkable decrease in FCGR is evident. Again, a similar trend is observed with a higher preheating temperature, i.e. 300 ^oC.

The mechanism in which preheating temperature influences FCGR can be explained by considering thermal stress which develops during welding leading to residual stress formation. Thermal stress (σ_T) is given by [5] :

$$\sigma_T = \frac{-\alpha E \Delta T}{1-2\upsilon} \qquad (7)$$

where ΔT is thermal gradient and is given by ΔT=T–To according to eq. (1), α : coefficient of thermal expansion, υ : Poisson's ratio and E : Young's modulus of elasticity. According to eq. (1), increasing preheating temperature (To) tends to lower ΔT and as a consequence, residual stress is expected to decrease.

Conclusions

Conclusions that can be drawn from the present investigation are summarized as follows :

1. An increase in preheating temperature tends to reduce FCGR of TIG aluminium weld metals and optimum preheating temperature is achieved at 300 ^{o}C.
2. The improvement of fatigue crack growth performance due to preheating treatment is likely associated with a reduction of thermal stress.
3. Static strength of TIG aluminium weld joints are controlled by microstructural changes where softening occurs at fine grained HAZ.

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