Influences of Post Weld Heat Treatment on Fatigue Crack Growth Behavior of Transverse TIG Welded Al6013-T4 Aluminum Alloy Joint

횡방향 TIG 용접된 Al6013-T4알루미늄 합금 용접부의 피로균열전파거동에 미치는 PWHT의 영향

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Key Words : 용접후열처리(Post Weld Heat Treatment), 피로균열전파율(Fatigue Crack Growth Rate), TIG용접(TIG Welding), 인장강도(Tensile Strength), 미세조직(Microstructure)

Abstract : 본 연구는 횡방향 TIG 용접된 Al6013-T4 알루미늄 합금 용접부의 피로균열전파거동에 미치는 용접후열처리(PWHT)의 영향을 조사하는 것이 주목적이다. 기초적으로 인장시험, 경도 및 미세조직이 조사되었으며, 피로균열전파거동을 고찰하기 위한 피로 시험은 모두 중앙균열인장(CCT) 시험편에 대하여 수행되었다. T82열처리에 있어서 시효시간은 피로균열전파율, 인장강도 및 경도에 대단히 민감함을 나타내었으며, 모재와 열영향부재의 경우가 용접재보다 기계적 성질이 우수하였다. 횡방향 TIG 용접한 Al6013-T4 시험재의 용접후열처리 조건에 따라서 피로균열전파 저항에는 차이가 나타났으며, 본 실험의 조건하에서 24시간 인공시효 PWHT-82 시험편이 피로균열전파 저항이 가장 우수한 결과를 나타내었다.

1. 서 론

There is growing interest in the structure use of aluminum alloys, for such applications as automotive and railway vehicles, bridges, offshore structure topsides, and high-speed ships. In all cases, welding is the primary joining method and fatigue is a major design criterion. However, it is well known that welded joint can exhibit poor fatigue properties. Thus, proper design guidelines are needed to ensure that fatigue failures are avoided in welded aluminum alloy structures[1]. Apart from basic design of new structures, there is also increasing interest in methods for assessing the remaining lives of existing structures. Prompted by difficulties experienced in reaching a consensus on fatigue performance of welded aluminum alloys have been undertaken over the past 10 years[2].

Welding of aluminum is generally performed either by gas metal arc welding or tungsten inert gas (TIG) welding. Gas metal arc welding offers the advantage of high deposition rate and high welding speed besides deeper penetration because of high heat input. However, excessive heat input imposes the problems such as melt through, distortion etc. specially in welding of thin aluminum sheets. Therefore, to produce high quality weldments TIG welding is preferred over gas metal arc welding. Presently, TIG welding

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Table 1 Chemical composition of Al 6013 T4, and filler wire Al 5356.

Materials	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al 6013 T4	0.66	0.09	0.80	0.39	1.04	0.07	0.06	0.02	Bal
Al 5356	0.25	0.40	0.10	0.10	5.55	0.20	0.10	0.20	Bal

process is one of the most well established processes which can not only weld all metals of industrial use but also produces the best quality welds amongst the arc welding processes[3].

The good weldability and less demanding requirements with regard to pre-heating and interposes temperature, the weld metal (WM) and the heat affected zone (HAZ) have lower impact energy and fracture tendency than that of the base metal (BM). In general, welded structures perform less well than the base metal as the welding process results in profound microstructures changes with the formation of both harder and more fragile structures[4].

Fatigue tests are widely used to characterize the behavior of materials, though they tend to be more used for sample testing of uniform material. To determine the fatigue tendency of welded joints, the study and control of the tests is more complex, as welded joints present microstructures variations over small distances, not to mention complex distributions of residual stresses. A more detailed study of the fatigue behavior of welded joints is necessary as it provides data for determining the resistance of structures[5].

In our previous study, Gunawan et al. [6] the effect of PWHT on fatigue crack propagation of longitudinal weld-ed joints Al 6013-T4 across from the weld metal have presented TIG welding process on longitudinal welded joint of Al 6013-T4 can decrease tensile strength and yield strength.

In post welding heat treatment T82 process can decrease the value of elongation and elasticity on longitudinal welded joint. On the fatigue crack propagation testing, crack growth starts from the base metal into heat affected zone and weld metal.

On the PWHT techniques, PWHT-T82 with variation of aging time produces in different form of grain structure. The PWHT-T82 for 18 hour of aging produces fine grains in the base metal, heat affected zone and weld metal region compared to the other PWHT-T82 for 6 and 24 hour aging. However, the postweld heat treatment applied to joints caused noticeable change in the formation of precipitates and their distribution[6].

From the literature review, it is understood that there is no reported research work on the effect of post weld aging treatment on fatigue crack growth behaviour of TIG welded 6013 T4 aluminum alloy transverse welded joint. Hence, the present aimed to study the fatigue crack growth behavior of Al 6013-T4 on the transverse welded butt joint across from the weld metal through the heat affected zone and the base metal. The fatigue crack growth of the welded joints were measured and the results were compared with those the parent plate. The influence of postweld heat treatment (PWHT) on the resistance to crack growth was also evaluated in this work, and tensile test and the hardness testing were employed as supporting data.

2. Material and Experiment Work

The material used in this study is Aluminum Alloy Al 6013 T4 sheets with thickness of 2.5 mm. The chemical composition of the material is given in Table 1. Specimens used for testing are base material Al 6013 T4, and welded materials with and without heat treatment T82.

The welding process on specimens using Al 5356 filler with 3.2 mm diameter, the welding done in elongated direction. The welding is done by using TIG method with resources Voltage 10-15 Volts. The current is 60-70 Amperes, the position of the positive electrode output (+). Using argon shielding gas, welding grade is 99.95%, and the melting point is 543℃-640℃. Speed the process of welding the direction perpendicular (200 mm) is approximately 60 seconds. The welding conditions and process parameters of TIG welding can be seen in Table 2.

Table 2 The conditions and parameters the TIG welding

Parameter	values
Welding machine	Miller
Tungsten electrode diameter	3.0 mm
Filler rod/wire diameter	3.2 mm
Heat input	2.5 kJ/mm
Peak current	70 Amps
Base current	60 Amps
Peak voltage	15 Volts
Base voltage	10 Volts
Welding Speed	3.3 mm/sec
Welding grade	99.95%
Melting point	543^0C-640^0C
Pulse frequency	6 Hz
Pulse on time	50 %
Shielding gas	argon
Gas flow rate	15 lit/min

Table 3 The amount of the tensile test specimens of transverse welded joint.

Specimens	With no PWHT	PWHT/Aging (h)		
		6	18	24
BM	3	-	-	-
Transverse welded joint	3	3	3	3

T82 heat treatment on the specimen is described as the specimen experienced the process of solution treatment (the specimen is heated until it reaches the temperature of 425 ℃) followed by a process of strain hardening of 2%, and the final process is artificial aging temperature of 175 ℃ and aging time of each 6 hours, 18 hours, and 24 hours[7)].

Tensile test specimens are made with dimensions of objects determined by a standard test ASTM B-557 (American Standard Testing Materials) as showed in Fig. 1, and crack propagation tests specimens according to standard test ASTM E-647-08. The amount of transverse welded tensile test specimens can be seen in Table 3. These specimens were grouped into three kinds of fracture conditions, i.e. cracks in the influence without of heat treatment, cracks in the welding simulation, and cracks in the welding simulation is continued with the T82 various of artificial aging.

Initial cracks on the specimen fatigue crack propagation test were made by using EDM (Electric Discharge Machine). Initial crack length is 12 mm and 0.9 mm width. Initial crack was made on Centre Cracked Tension (CCT) specimens. CCT fatigue crack growth test specimen were prepared to the dimensions as showed in Fig. 1.

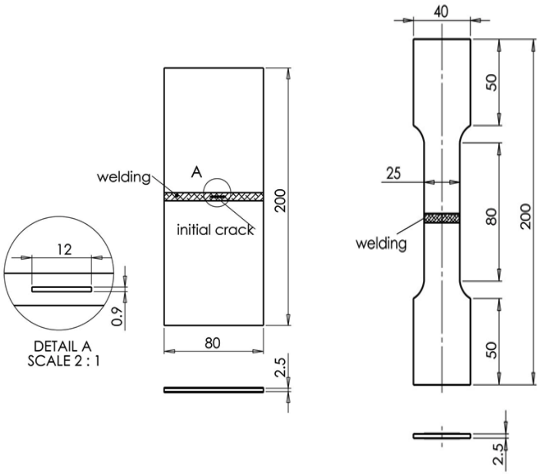

Fig. 1 CCT specimen and tensile test specimen.

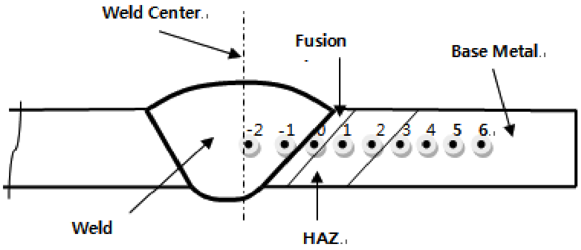

Fig. 2 Hardness distribution testing

FCG experiments were conducted using a close loop servo hydraulic controlled (Make: Shimadzu, Japan; type of machine: servo purser, capacity 30 tons static load, 20 tons dynamic load). FCG experiments were carried out at 170-346 MPa for each PWHT conditions, the servo test machine was operated at a frequency of 5-11 Hz, 15-20% stress levels and stress ratio R = 0.3. A travelling microscope (Make: MITUTOYA; Model: 5010) was used to monitor the crack growth.

Microhardness measurements across the fusion boundaries between the deposit and BM were made using a Vickers microhardness tester. Vickers's hardness measurement was carried out by using a load of 0.2 kgf and time of loaded 5 seconds. The indentations were set at an interval of 1 mm along the weld center, transverse to the direction of base metal (Fig. 2).

3. Results and Discussion

3.1 Tensile Properties Results

Fig. 3 shows the transverse tensile properties of welded Al 6013-T4 and Al 6013-T82 all joints with variety aging of PWHT. All the values are obtained from the average of 3 specimens.

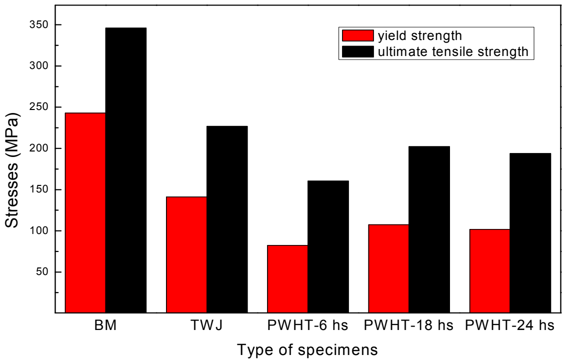

Fig. 3 Transverse tensile properties of as welded and PWHT T82 joints

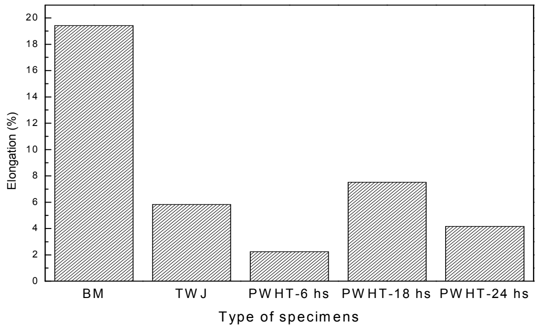

Fig. 4 Elongation of transverse as welded and PWHT T82 joints

From the above results can be discussed that the transverse welded butt joint with aging 18 hours are higher compared to aging 6 hours and 24 hours. The reason for this could be the aging 18 hours possesses is more brittle compared to the aging 6 hours and 24 hours, and also the aging 18 hours have relatively lower ductility properties.

Failure of weld joints in this case took place from the HAZ. Poor strength of HAZ compared to weld metal can be attributed to coarse grained (brittle) as cast structure of base metal compared to that of weld metal[8)]. The reduced section and notched tensile specimens were used to ensure the failure from the weld metal, as mechanical characteristics of heat treatable aluminum alloy[9)].

Fig. 4 shows the percentage of elongation in cross sectional area (c.s.a) of base metal and transverse welded joint. The elongation in cross sectional area (c.s.a) of base metal (19.42%) is higher than transverse welded joint without PWHT (5.83%). This suggests that there is a reduction in ductility due to the transverse welded joint. In the transverse welded joint after heat treatment of 18 hours (7.51%) is higher than 6 hours (2.24%) and 24 hours (4.16%). From the above results can be concluded that the PWHT of T82 can increase the elongation and there by improve in ductility.

3.2 Hardness

Fig. 5 shows the hardness distribution profiles across from the welded metal zone in this investigation. From the results can be concluded that the mechanical properties of the transverse welded butt joint for aging of 18 hours are the he highest compared all those of the joint for 6 hours and 24 hours aging.

The reason for this could be the aging of 18 hours yielded the joint with more brittle, and also the aging of 18 hours yielded the joint relatively lower ductility. PWHT T82 in this case could reduce the value of tensile strength and, but the PWHT T82 can increase the value of the elongation. Precipitates and second phase particles act as barrier to the movement of dislocation which in turn increases hardness and strength[10].

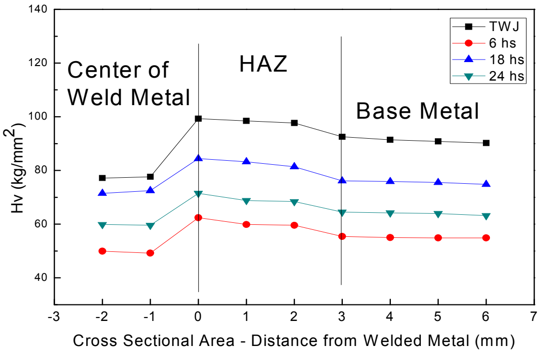

Fig. 5 Hardness distribution testing

3.3 Fatigue Crack Growth Results

Fig. 6 shows the *a-N* curves for all joints. As shown in the figure, the fatigue crack growth resistance is revealed the differences according to the aging times variety.

Fig. 7 shows the relationship between *ΔK* and *da/dN* for BM and transverse welded joint. And also, Fig. 8 shows the relationship between *ΔK* and *da/dN* for the transverse welded joint Al 6013 after PWHT-T82. The data points plotted in the graph mostly correspond to the second stage of Paris sigmoidal relationship. The exponent '*m*', which is the slope of the line on log - log plot and the intercept '*C*' of the line, were determined and are presented in Table 4. It is an important parameter to evaluate the fatigue crack growth behavior of materials since it decides the fatigue crack propagation life of the materials[11].

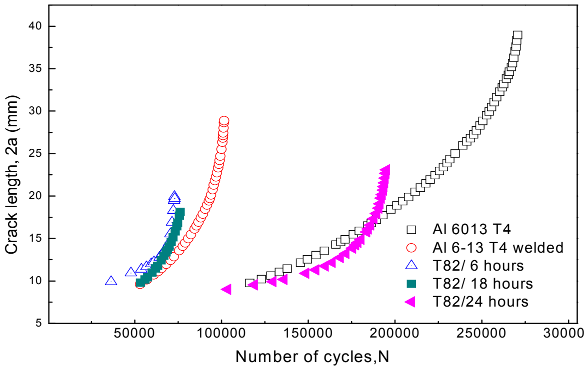

Fig. 6 Effect of PWHT-T82 on fatigue crack growth rate of transverse welded joint

Table 4 Fatigue crack growth parameters of transverse welded joints

Specimens	Crack growth parameters	
	Exponent 'm'	Intercept 'C'
BM	3.09	8.80×10^{-11}
Transverse welded	4.81	9.44×10^{-13}
PWHT T82/6h	10.36	9.18×10^{-23}
PWHT T82/18h	5.55	9.86×10^{-16}
PWHT T82/24h	6.74	9.44×10^{-19}

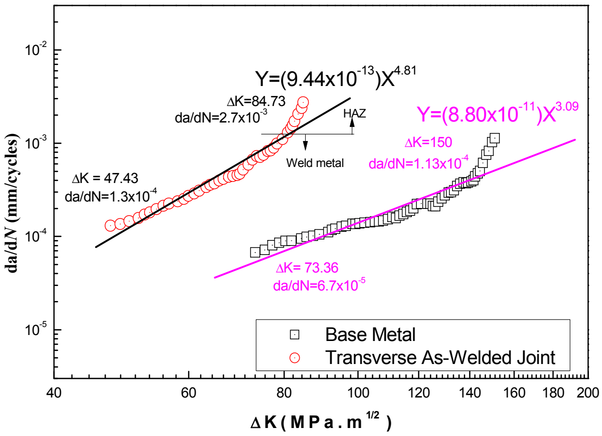

Fig. 7 Measured fatigue crack growth for BM and the transverse welded joint

From the results indicates that BM (*m* = 3.09) has the exponent lower than transverse welded joint (*m* = 4.81). The fatigue crack growth exponent of PWHT with 18 hours aging (m= 5.55) has the exponent lower than the PWHT-T82 for 6 (10.36) and 24 hours aging (6.74).

The crack propagation in the specimen of transverse welded joint, it starts from the area of the weld metal through HAZ. FCGRs increased significantly with increasing *ΔK* as the crack propagated within the weld metal and HAZ (Fig. 7). In addition, the weld metal had an obviously lower resistance to crack growth than the Al 6013 T4 plate, especially in the low *ΔK* range. As the growing crack growth through the HAZ (*ΔK*=80.93 MPa.m$^{1/2}$), the FCGRs stopped and the static fracture has occurred in the HAZ (*ΔK*=84.73 MPa.m$^{1/2}$), as shown in Fig.7.

For the PWHT-T82 specimens (Fig.8), the FCGRs were taken from the SIF region between *Δ*

K =29.86 MPa.m$^{1/2}$ and 69.76 MPa.m$^{1/2}$ in the weldmetal region and HAZ. The FCGRs on PWHT-T82 specimens in the weldmetal region increased significantly wit hincreasing ΔK as the crack propagation within the various aging specimens.

In the HAZ region, the FCGRs increased in all the PWHT-T82 specimens significantly. The marked reduction in resistance to crack growth for the T82 heat treated welds as compared with that for the as-welded would be attributed to the relief of residual welding stresses after PWHT[12]. Of the three PWHT-T82 joints, the weld metal region of PWHT-T82 for 24 hours aging consists of very coarse and uniform distribution of precipitates compared to other joints. Similarly, the uniformly distributed, very coarse particles might have impeded the growing fatigue cracks and hence the fatigue crack growth rate has been delayed[13] and subsequently the resistance to the fatigue crack growth has been enhanced compared to other joints.

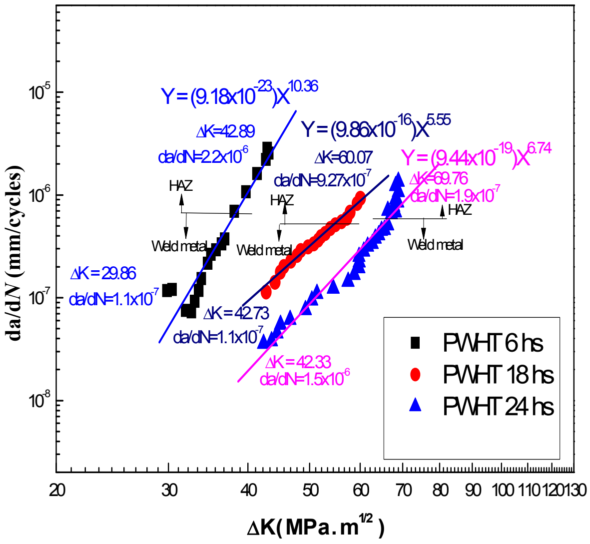

Fig. 8 Measured fatigue crack growth for the transverse welded joint after PWHT-T82

3.4 Microstructure

The optical micrographs of base metal, HAZ, and weld metal are shown in Fig. 9. The results suggest that the PWHT-T82 is effective in fusion zone grain refinement. Kang and Liu observed that the magnesium content in the alloys greatly influences the as-cast microstructure[14].

In the weld metal region, the measured average grain diameter of weld metal without heat treatment (150 μm) is bigger than the average grain diameter of PWHT with aging 6 hours (70 μm), 18 hours aging (10 μm), and 24 hours aging (60 μm).

As can be seen in Fig. 9, the average grain diameter in the weld metal region of PWHT-T82 for 24 hours aging is on the order of 60 μm and the grain size is much coarser in the weld metal region of PWHT-T82 for 6 and 18 hours aging. Coarse grained microstructures relatively contain lower amount of grain boundary areas than finer grained microstructure and in turn offer more resistance to fatigue crack growth rate[15]; this may be the reason for improved fatigue performance of PWHT-T82 for 24 hours aging compared to PWHT-T82 for 6 and 18 hours aging.

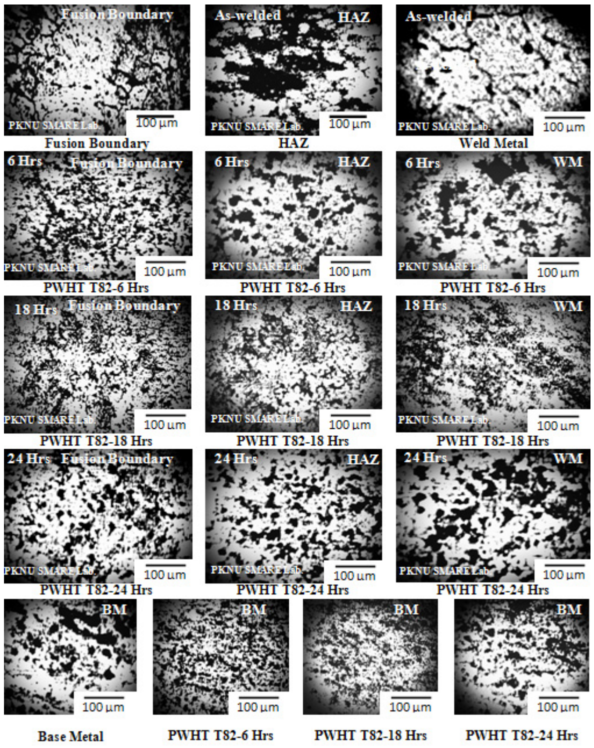

Fig. 9 Optical micrographs of As-welded and PWHT-T82 specimens for variety of aging

Ghosh et al.,[16] opined that more crack driving force is needed for crack extension and the fracture resistance of the higher strength weld metal is greater than the lower strength weld metal. This is one of the reasons for better fatigue crack growth resistance of the PWHT-T82 for 24 hours aging.

4. Conclusions

The following conclusions can be drawn from this research work:

TIG welding process such as transverse welded joint can decrease tensile strength and yield strength.

The PWHT-T82 for 24 hour of aging produces coarse grains in the base metal, HAZ and weld metal region compared to other PWHT-T82 for 6 and 18 hours aging.

The fatigue crack growth resistance of the Al 6013 T4 aluminum alloy was greatly reduced by welding processes; Of the three PWHT joints processes, the joints fabricated by PWHT on 24 hours aging process exhibited higher fatigue crack growth resistance compared to PWHT on 6 hours aging and PWHT on 18 hours aging.

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