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Effect of PWHT on Variability of fatigue Crack Propagation Resitance in TIG Welded Al 6013-T4 Aluminum Alloy
TIG 용접된 Al6013-T4 알루미늄 합금에서 피로균열전파저항의 변동성에서의 PWHT의 영향

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Key Words : Fatigue crack propagation (피로균열전파), Artificial aging time (인공시효시간), TIG (Tungsten inert gas welding) (용접), Reliability model (신뢰성 모델), Variability of fatigue crack propagation resistance (피로균열전파저항의 변동성)

Abstract : The experimental investigation focuses on an influence of artificial aging time in longitudinal butt welded Al 6013-T4 aluminum alloy on the fatigue crack growth resistance. The preferred welding processes for this alloy are frequently tungsten inert gas welding (TIG) process due to its comparatively easier applicability and better weldability than other gas metal arc welding. Fatigue crack growth tests were carried out on compact tension specimens (CT) in longitudinal butt TIG welded after T82 heat treatment was varied in three artificial aging times of 6 hours, 18 hours and 24 hours. Of the three artificial aging times, 24 hours of artificial aging time are offering better resistance against the growing fatigue cracks. The superior fatigue crack growth resistance preferred spatial variation of materials within each specimen in the Paris equation based on reliability theory and fatigue crack growth rate by crack length are found to be the reasons for superior fatigue resistance of 24 hours of artificial aging time was compared to other joints. The highest of crack propagation resistance occurs in artificial aging times of 24 hours due to the increase in grain size (fine grained microstructures).

1. Introduction

Aluminum alloys are widely uses as aerospace materials and automotive materials related to fatigue damage. Aluminum alloys with the addition of alloys elements consisting of Mg and Si, and Mn, Cr, Ti, Cu can improve the mechanical strength and tensile strength. Al-Mg-Si of aluminum 6000 series has the properties of light weight, high yield strength, workability, formability, and good corrosion resistance as aerospace and automotive body materials are widely recognized[1)].

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In all cases, welding is the primary joining method and fatigue is a major design criterion. However, as is well known, welded joints can exhibit low fatigue properties. Thus, clear design guidelines are needed to ensure that fatigue failures are avoided in welded aluminum alloy structures. Apart from basic design of new structures, there is also increasing interest in methods for assessing the remaining lives of existing structures[2)].

Prompted by difficulties experienced in reaching a consensus on fatigue design rule, extensive testing and analysis of the fatigue performance of welded aluminum alloy have been undertaken over the past few years. Analysis and extensive testing on fatigue properties of welded joints aluminum, many researchers have studied by the last decade[3].

TIG welding process is one of the most well established processes which can not only weld all metals of industrial use but produces the best quality welds amongst the arc welding processes, because of advantages such as lower prices, in particular, the easy and precise control of welding parameters. Unfortunately, a lot of hot cracking occurred in almost all of the heat treatment of aluminum alloys. The main problem in welding these alloys is welding cracking (solidification cracking) in the weld, and the heat treatment can be improved. At this time the aging time and temperature are important variables. Thus, by heat treatment after welding is very important to investigate the fatigue crack propagation behavior in terms of welded damage tolerance design [4].

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

Failure analysis of the weldedment indicated that fatigue alone is to be considered to account for most of the disruptive failures. Even though the failure properties of the weld metal is good, problems can occur when there is an abrupt change in section which is caused by excess weld reinforcement, undercut, slag inclusion, and lack of penetration, and nearly 70 % of fatigue cracking occurs in the welded joint. [6].

The fatigue behaviour of an Al-Mg-Si alloy lap welded joints and the improvement in fatigue strength due to post weld heat treatment were investigated by Pinho da Cruz et al [7].

In this study reports the influence of post weld heat treatment (PWHT) on fatigue crack growth resistance of TIG welded AL 6013-T4 aluminum alloy. Among them, artificial aging time is differently performed to heat treatment on 6 hours, 18 hours, and 24 hours. Based on reliability theory, according to the crack length and the spatial variability of the material fatigue crack propagation rate comparisons were investigated.

2. Materials and Experiment Methods

2.1 Material and Specimens, Welding condition

Specimen materials used in this study, Al 6013-T4 aluminum alloy sheet as a test specimen length direction of the 500 × 250mm plate was carried out heat treatment-T82 after longitudinal TIG weld. Different treated artificial aging time, were carried out by 6 hours, 18 hours and 24 hours for CT specimens according to ASTM E647 standard fatigue tests. The shape and dimension of CT specimen used in this study are shown in Fig. 1. The chemical composition and mechanical properties of Al 6013-T4 are shown in Table 1 and Table 2, respectively [8].

Table 1 Chemical composition (wt.%)

Material	Mg	Si	Cu	Mn	Fe	Cr	Ti	Zn
6013-T4	1.0	0.8	0.9	0.4	0.3	0.1	0.1	0.1

Table 2 Mechanical properties of base metal and post welding heat treatment specimens

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
Al 6013-T4 (BM)	346	243	19.42
Al 6013-T82 / 6h	117	93	9.46
Al 6013-T82 / 18h	224	115	13.96
Al 6013-T82 / 24h	195	113	11.97

Fig. 2 shows for each the T82 solution treatment and artificial aging time, respectively. The welding conditions for TIG welding was carried out the rolling direction using the Al 5356 filler with 3.2mm diameter can be seen in Table 3.

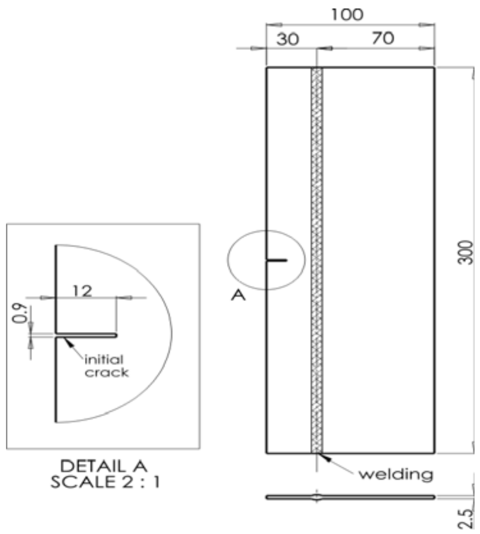

Fig. 1 Shape of CT specimen and dimension

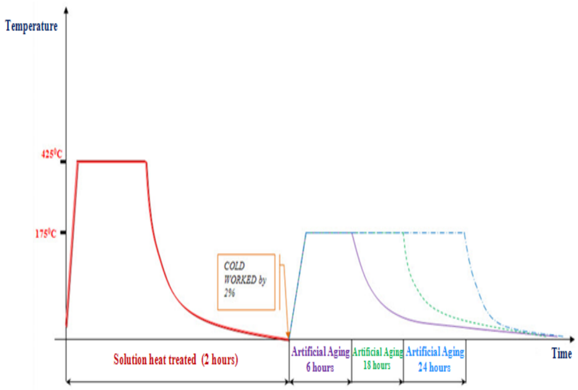

Fig. 2 Solution heat treated and artificial aging time

Table 3 TIG welding condition and parameters

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	2.5 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

2.2 Fatigue crack propagation experiments

The fatigue crack growth experiments were conducted using a close loop servo-hydraulic fatigue testing machine (Shimadzu) at room temperature. All test were carried out in a sinusoidal tension-tension under constant amplitude loading control mode for controlled loading range ($\triangle P$) 980 N, the stress ratio (R) 0.3, and the frequency 5-11 Hz. Conditions that was observed for each treatment and artificial aging 3 per prescription, for a total of 12 specimens. The measurement of crack length was measured using a travelling microscope, the equation of ASTM E647 were used by the crack tip stress intensity factor. The initial crack length a = 15 mm to 54.5mm including from pre-crack intervals in 0.5mm cracks were treated by normalization.

3. Result and Discussion

3.1 Fatigue crack propagation behavior in artificial aging time

Fig. 3, three specimens and base metal parts to artificial aging treated by three each differently, a total of 12 specimens shows a relationship between in the number of cycles N and crack length for the stress. As shown in this figure that fatigue crack growth are differently indicated by artificial aging time in such a post weld heat treatment of T82, fatigue crack propagation resistance is 24 hours of artificial aging time greater than 6, 18 hours artificial aging time in order. In case of base metal were indicated softly curve shape by stress-number of cycles in crack propagation, but other data of 3 types in such cases were indicated irregular results at nearby 30 mm of crack length.

However, there is a variation of the specimen within the curve of the form is showing. On the other hand, randomness of a-N curve for each 3 specimens by same condition was known less than other structure steel materials. It is thought that crack propagation is due to passed through heat affected zone, weld fusion zone, and weld metal on nearby 30 mm of crack length. It is mean that specimen to specimen variation is low and it is considered that the variation within each specimen is some existed for fatigue crack propagation rate.

Fig. 4 shows the relation between fatigue crack propagation rate and stress intensity factor range. A figure represents for each solid line of 12 specimens obtained using least squares regression.

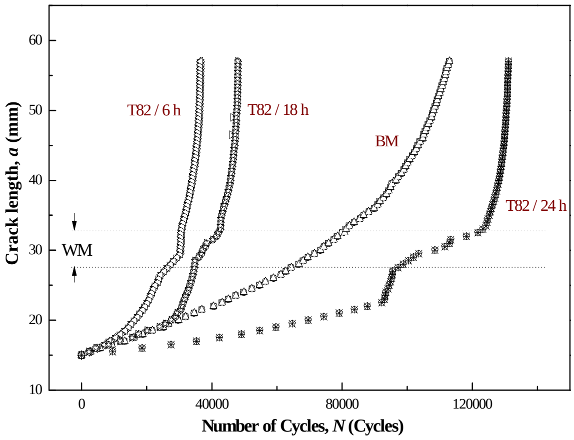

Fig. 3 Crack length a vs. number of cycle N

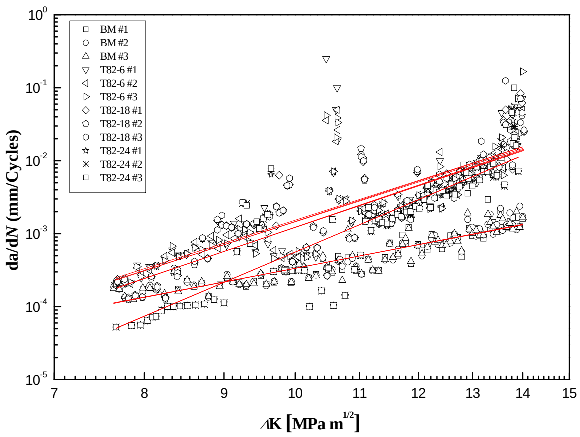

Fig. 4 Relationship between fatigue crack propagation rate and stress intensity factor range (all specimens)

In the actual practice, the regression line will be interpreted that all data. That data mean the fatigue crack propagation on weld metal delay and then acceleration phenomenon. The regression line is not in the actual welding, on the actual welds to be included by adding a non-linear. In the following, using the data based on reliability theory, the volatility of fatigue crack propagation is investigated.

3.2 Analysis of based on fatigue crack propagation model

Based on fracture mechanics to assess the fatigue crack propagation behavior has many different expressions, but the most widely used was based on the following Paris equation.

$$da/dN = C(\triangle K)^m \tag{1}$$

Where da/dN is the fatigue crack propagation rate and $\triangle K$ is stress intensity factor range (SIF), "C" and "m" are the material constants. To be random variable methods of fatigue crack propagation based on reliability theory can be largely split in three parts.

First is the specimen-to-specimen variation, second is the variation within each specimen, and third is specimen-to-specimen variation and the variation within each specimen at the same time. In other words, the existing material constant C of the Paris-Erdogen equation is modeled as folllows.

$$C(a) = \frac{C_1}{C_2(a)} \tag{2}$$

Where a represents position (crack length) in the crack tip, C_1 is a positive random variable describing the deviation between the behavior of different specimens, C_2 is random process modeling the deviation of the crack propagation rate within each specimen [9].

$$\frac{da}{dN} = \frac{C_1}{C_2(a)}(\triangle K)^m \tag{3}$$

In this case, variation of crack propagation represents within each specimen if C_1 and m has fixed. Spatial variation of material is possible to treat the fatigue crack propagation model process. The variation of C_2 by crack length for each specimen of artificial aging times on base metal, 6 hours, 18 hours and 24 hours are shown in Fig. 5-8.

Appears on the picture, a results of investigation in variation of C_2 by crack length were represented that 24 hours specimens of artificial aging time is the most greatest in its variation.

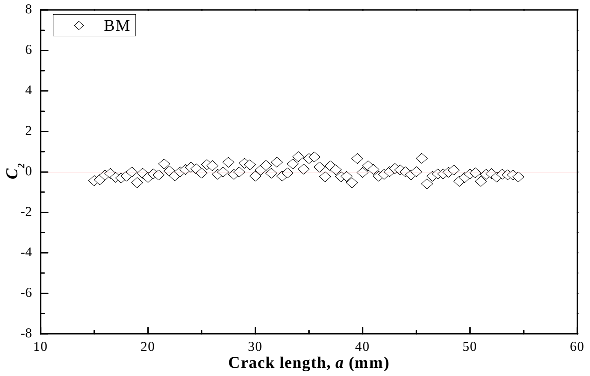

Fig. 5 Variation of C_2 base metal

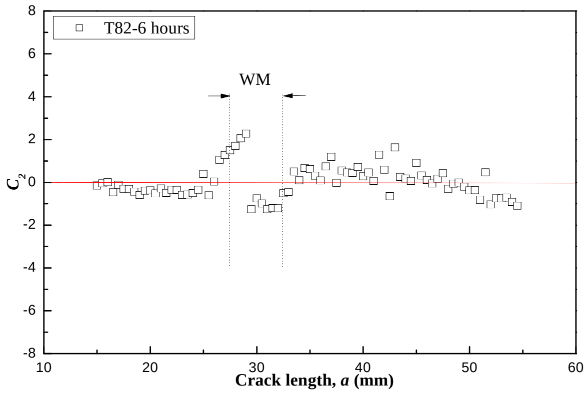

Fig. 6 Variation of C_2 PWHT T82-6 hours

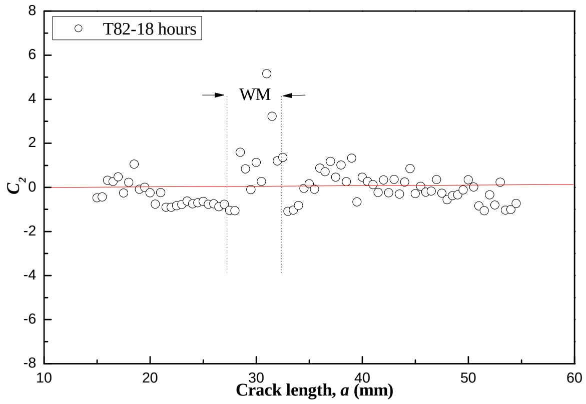

Fig. 7 Variation of C2 PWHT T82-18 hours

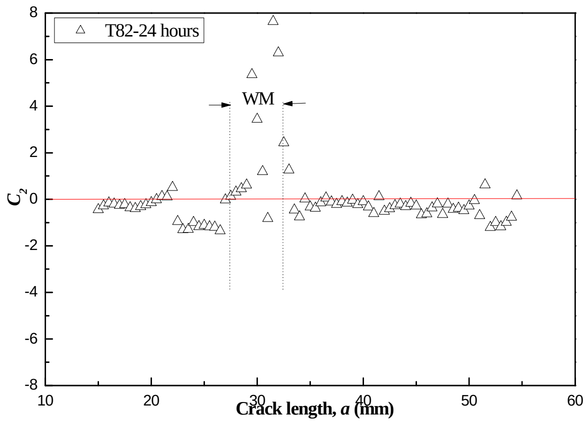

Fig. 8 Variation of C2 PWHT T82-24 hours

Meanwhile, the C_2 of the fluctuations around the weld metal of artificial aging tendency to increase with time, crack growth delay means to improve effectiveness.

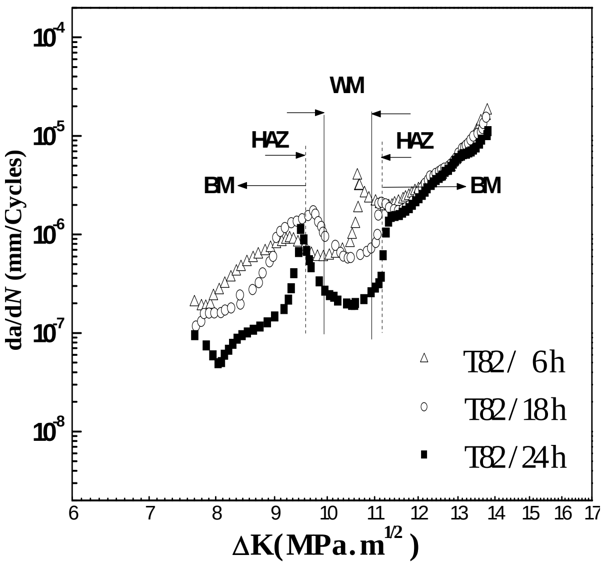

Fig. 9 Fatigue crack growth rate da/dN vs. SIF range ΔK

It indicated that the crack delay is appears due to the influence of PWHT. The relationship between the fatigue crack propagation rate and stress intensity factor range for the average of an artificial aging time test specimen is shown in Fig. 9.

The greater the value of C_2 will be the greater tendency of the value of the fatigue crack propagation rate. The value of C_2 describes the properties of material experiencing fatigue crack propagation. If there is change the value of C_2 of a material, the material tends to have a proficiency level properties of the non-homogeneous materials.

The value of C_2 is increased in the HAZ and welded metal region. It is explains that changes the different properties of the materials and occurs delayed fatigue crack propagation (shown in Fig. 9). After crack propagation occurs in the weld metal into the HAZ region, the value of C_2 decreases, and the fatigue crack propagation increased again until the base metal region. This phenomenon occurs in PWHT specimens 6, 18 and 24 hours of aging.

For the largest value of crack retardation of C_2 size is the most significant occurred to the specimen for 24 hours artificial aging time but stress intensity factor 9 MPa $(m)^{1/2}$ in 18 hours, the propagation rate was lowest, followed by 24 hours, and 6 hours. However, the cracking delayed recovery a high relatively after the area in 13 MPa $(m)^{1/2}$. Fatigue crack propagation rate was almost similar. This aging treatment time and the influence of welding residual stresses are considered.

3.3 Analysis of based on microstructure

Optical micrographs of base metal, HAZ, Fusion zone and weld metal are shown in Fig. 10.The microstructure of the as welded Al 6013 T4 and PWHT Al 6013 T82 alloys showed primarily two phases, i.e. aluminum solid solution (light etched). This suggests that the PWHT-T82 is effective in fusion zone grain refinement. From the micrographs, it is understood that there is an appreciable different in grain size (average grain diameter) of base metal, HAZ, fusion zone and weld metal. Kang and Liu [10] observed that the magnesium content in the alloys greatly influences the as-cast microstructure. Higher the magnesium content greater relative amount of Mg_2Si phase in Al-Mg-Si alloys. In the high magnesium alloys, not only binary eutectic structure, but also ternary eutectic structure formed.

The measured average grain diameter of base metal is 70 μm, but the average grain diameter of PWHT-T82 for aging of 6 hours is 30 μm and this indicates that reduction in grain diameter is 40 μm due to PWHT-T82 for 6 hours aging process. Similarly the measured average grain diameter of PWHT-T82 for 18 hours aging is 15 μm but the average grain diameter of PWHT-T82 for 24 hours aging is 50 μm, and this also pointing that the increasing in grain diameter is 35 μm due to PWHT-T82 for 24 hours of aging process.

In the heat affected zone, the measured average grain diameter of HAZ of as welded is 90 μm, but the average grain diameter of PWHT-T82 for 6 hours aging is 60 μm and this indicates that reduction in grain diameter is 30 μm due to PWHT-T82 for 6 hours of aging process. Similarly the measured average grain diameter of PWHT-T82 for 18 hours aging is 25 μm but the average grain diameter of PWHT-T82 for 24 hours aging is 40 μm, and this also pointing that the increasing in grain diameter is 15 μm due to PWHT-T82 for 24 hours of aging process.

In the weld metal region, the measured average grain diameter of weld metal without heat treatment is 150 μm, but the average grain diameter of PWHT-T82 aging of 6 hours is 70 μm and this indicates that reduction in grain diameter is 80 μm due to PWHT-T82 for 6 hours of aging process. Similarly the measured average grain diameter of PWHT-T82 for 18 hours aging is 10 μm but the average grain diameter of PWHT-T82 for 24 hours of aging is 60 μm, and this also pointing that the increasing in grain diameter is 50 μm due to PWHT-T82 for 24 hours of aging process.

As can be seen in Fig. 10, the average grain diameter in the fusion zone region of PWHT-T82 for 24 hours aging is in the order of 30 μm and the grain size is much coarser in the fusion zone region of PWHT-T82 for 6 and 24 hours aging. The fine grained microstructures relatively contain higher amount of grain boundary areas than coarse grained microstructure and in turn offer more resistance to fatigue crack propagation and 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 [11].

The changes in fatigue crack propagation occur because of differences in grain size. Fatigue crack propagation in metal base is almost similar to the material that has been carried out artificial aging. Fatigue crack propagation began changed after passing through the HAZ, and acceleration propagation has slowed. After passing through the WM region, rapid crack propagation began. This is due to the average grain diameter in the HAZ

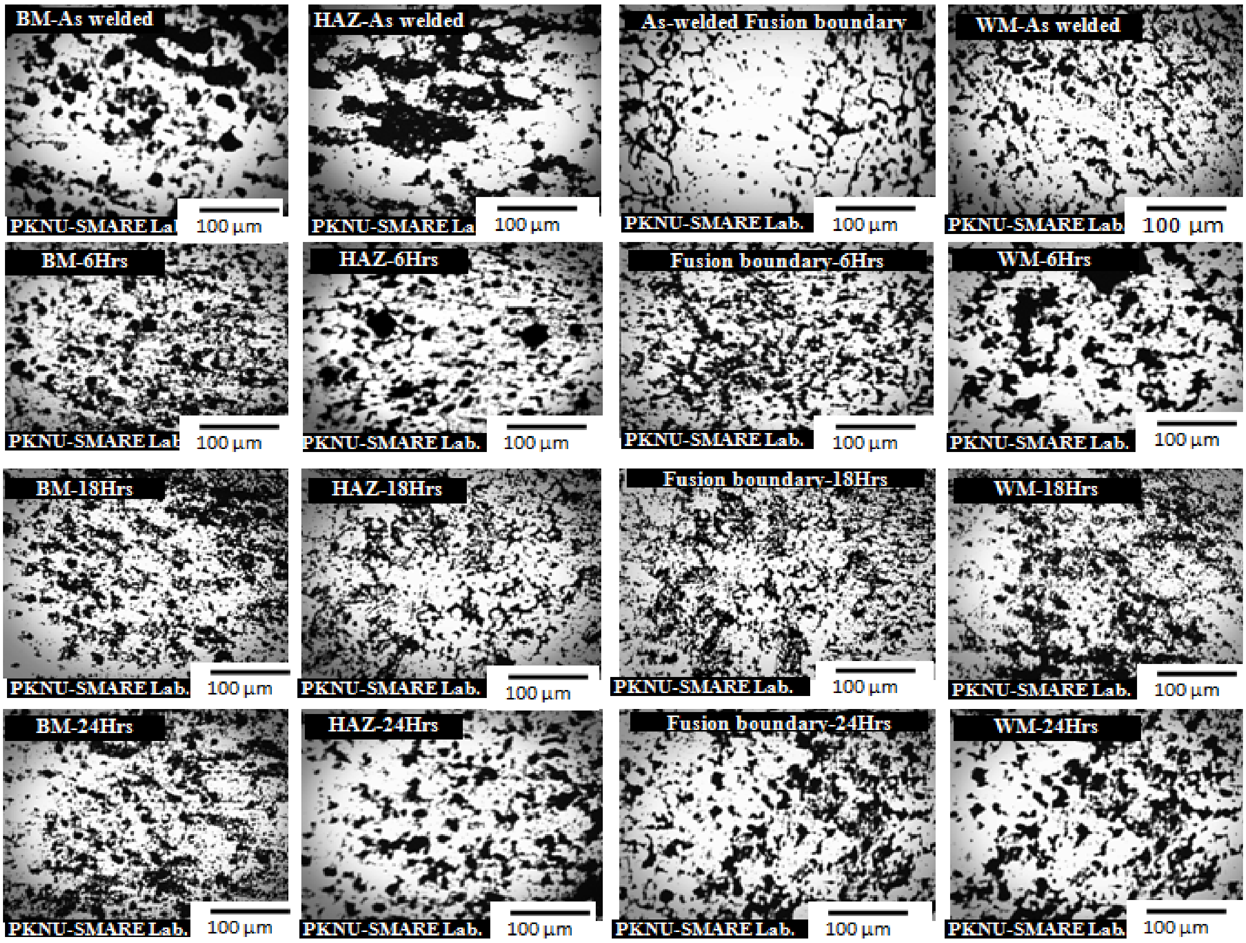

Fig. 10 Optical micrograph of As-welded Al 6013 T4 and PWHT-T82 specimens for variety of aging

is relatively higher and fine so that the fatigue crack propagation delayed. Fatigue crack propagation largest delayed occurred in the material with artificial aging 24 hours, because the grain size is relatively large and fine grained compared to artificial aging 6 hours and 18 hours [12].

The changes in graine T82 PWHT could potentially change the value of C_2. The value of C_2 increases due to the form of fine grains; this can be seen in changes in the welded metal grains in the PWHT T82. The changes the value of C_2 is significantly occurred in PWHT-T82 on 24-hour aging. This is due to the largest grain size on metal welded PWHT-T82 at 24 hours aging, compared with the size grains of 6 hours and 18 hours of aging.

On fatigue crack propagation testing with PWHT-T82 and variations aging decreased fatigue strength, as compared with Base Metal and as welded specimens. Decrease in fatigue strength is due to changes in micro structure (structure which increasingly coarse grains) as a result of the heat effect on the process of welding and tensile residual stress in the perpendicular direction [13].

4. Conclusion

In this study, the influence of post weld heat treatment on fatigue crack propagation behavior of TIG welded Al 6013-T4 aluminum alloy was investigated, from this study are derived that 24 hours of artificial aging time are offering better fatigue cracks propagation.

Fine grained microstructures relatively contain higher amount of grain boundary areas than coarse grained microstructure and in turn offer more increase to fatigue crack propagation and this may be the reason for improved fatigue performance of PWHT-T82 of artificial aging 24 hours.

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