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Influences of post weld heat treatment on fatigue crack growth behavior of TIG welding of 6013 T4 aluminum alloy joint (Part 1. Fatigue crack growth across the weld metal) †

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Abstract

The present study evaluates the influences of PWHT on FCG behavior and tensile properties of TIG butt welded Al 6013-T4 sheets. Crack propagation tests were carried out on compact tension (CT) specimens. The T82 heat treatment was varied in three artificial aging times (soaking) of 6, 18 and 24 hours. The results of T82 heat treatment with artificial aging variations were tested for their fatigue crack growth rates at the main metal zone, the heat-affected zone (HAZ), and the welded metal zone. It has been observed that the various agings in heat treatment T82 are sensitive to the mechanical properties (fatigue crack growth rate test, tensile test). The results show that PWHT-T82 for 18 hours aging is the highest fatigue resistance, while the aging 18 hours provided the highest tensile test result.

Keywords: A1 6013 T4; Post welding heat treatment; T-82; Fatigue crack growth rate; Longitudinal welded joint; TIG welding; Tensile strength

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1. Introduction

Aluminum alloys have been long used for aircraft construction since the 1930s. The aerospace industry relies heavily on 2xxx and 7xxx aluminum alloys, while a wide variety of aluminum alloys are now used by the automotive industry. Currently, the automotive industry shows an increasing interest in aluminum alloys as structural materials. 6xxx Aluminum alloys are of particular interest for both the aerospace industry (for fuselage skins and other applications) and the automotive industry (for body panels and bumpers) because of their attractive combinations of properties such as good strength, formability, weldability, corrosion resistance and low cost [1].

In manufacturing of automotive and aerospace parts, welding of aluminum alloys (6xxx) is frequently employed. 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 as well as deeper penetration because of high heat input. However, the excessive heat input may create the problems such as melt through, distortion etc., especially in welding of thin aluminum sheets. Therefore, to produce high quality weldments the use of TIG welding is preferred over gas metal arc welding. Presently, the TIG welding process is one of the most well established methods which not only can weld all metals for industrial use but also produces the best quality welds amongst the arc welding processes [2].

Even with good weld-ability and less demanding requirements with regard to pre-heating and interpass temperature, the weld metal (WM) and the heat affected zone (HAZ) have lower impact energy and fracture tenacity 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 microstructure changes, with the formation of both harder and more fragile structures [3].

Almost all the heat treatable aluminum alloys are unfortunately prone to hot cracking. The main problems in welding these alloys are: (i) hot cracking (solidification cracking) in the weld and (ii) excessive micro-fissuring due to hot tearing in the partially melted zone (PMZ) of the heat affected zone (HAZ). Substantial improvements in both yield strength and fatigue life have been observed for the postweld aged joints over the as welded joints. In most of the heat treatable alloys, part of the HAZ is degraded to such an extent that mechanical properties can be improved only by applying a full heat treatment after welding (solution treatment + aging). With Al alloys, however, joint properties can be improved by a simple precipitation (aging) treatment after welding the whole of the weld zone hardening. It became clear that explanation of the behavior of these alloys by a simple theory of averaging was incom-

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Table 1. Chemical composition of Al 6013 T4 , and filler wire Al 5356 [9].

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

patible not only with recovery but also with the known aging behavior of the alloys. In particular, the time and temperature because of welding were insufficient to produce overaging in these alloys owing to their very slow aging rates [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].

At the moment, fatigue and fracture tests are undertaken in accordance with standards and codes devised by different institutions such as the American Society for Testing and Materials (ASTM) and the British Standards Institution (BSI). These tests were originally devised for the use of uniform test samples and based on the concepts of $a - N$ and (da/dN)–ΔK for evaluating fatigue behavior. To carry out these tests on non-uniform materials, various techniques and recommendations were suggested for preparing and evaluating the results. 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 poor fatigue properties. Thus, clear design guidelines are needed to ensure that fatigue failures can be 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 [6].

The present paper examines the dependence of the constant-amplitude fatigue crack growth rates on the material for a variety of heat-treatable thin-sheet aluminum alloys in the laboratory. To this end the loading conditions and the specimen geometry, while known to be important parameters, were held as constant as possible. The aim of the paper was to achieve a better understanding of the relatively high variability of these rates and of the role of material parameters based on the analysis of experimental data. In the analysis a recently used ASTM method [7] aimed to suppress the correlation between the exponent, m, and the coefficient, C, in the Paris equation, Eq. (1) is applied, and the loading variables R, ΔK , and K max are related in accordance with the following relationship, Eq. (2) is applied [8]:

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

$$\Delta K = (1 - R)K_{max} \text{ for } R \geq 0. \quad (2)$$

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	2.5 mm/sec
Welding grade	99.95%
Melting point	543℃-640℃
Pulse frequency	6 Hz
Pulse on time	50 %
Shielding gas	argon
Gas flow rate	15 lit/min

The aim of this study was to evaluate the effects of post-weld heat treatment T82 – with various aging on the fatigue crack propagation of longitudinal welded butt joint, comparing them with the results obtained without post-weld heat treatment in Al 6013 T4 as base metal.

2. Material and experimental work

The material used in this study was Aluminum Alloy Al 6013 T4 in the form of sheets with thickness of 2.5 mm. The chemical composition of aluminum alloy 6013 T4 is given in Table 1 [9].

Specimens were made in several conditions the basic material conditions as Base Material Al 6013 T4, and other specimens were obtained from the process of welding without heat treatment, and post heat treatment T82 [10].

The welding process on specimens was performed by Al 5356 filler with 3.2 mm diameter, and the welding was done in elongated direction. The welding was done by using TIG method at Voltage of 10-15 Volts, and 60-70 Amperes, for the position of the positive electrode output (+). For argon shielding gas, welding grade is 99.95%, and the melting point is 543°C-640°C. Speed of the process of welding the elongated (100mm) is approximately 40 seconds. The welding conditions and process parameters of TIG welding can be seen in Table 2.

Tensile test specimens were made with dimensions of objects determined by a standard test ASTM B-557 (American Standard Testing Materials) and crack propagation tests specimens according to standard test ASTM E-647. The amount of longitudinal welded tensile test specimens can be seen in Table 3.

These specimens were grouped into three kinds of fracture conditions: cracks in the influence without of heat treatment, cracks in the welding simulation, and cracks in the welding simulation is continued with the T82 in various artificial aging. The surfaces of the specimens were machined off and the specimen dimensions have been given in Fig. 1.

T82 heat treatment on the specimen is hereafter referred as the specimen experiencing the process of solution treatment (The specimen is heated until it reaches 420℃), 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 [11]. The experimental procedure can be seen in Fig. 2.

Initial cracks on the specimen fatigue crack propagation test were made by using an electric discharge machine (EDM). The initial crack lengths measured are 12 mm and 0.9 mm width. Initial crack was made on compact tension (CT) specimens. The fatigue crack growth tests were carried out on CT type sample using side grooves to ensure crack propagation along a single plane. Fatigue crack growth experiments were conducted using a closed loop servo hydraulic controlled (Shimadzu, Japan; type of machine: servo purser, capacity 30 tons static load, 20 tons dynamic load). Fatigue crack growth experiments were carried out at 195 MPa for each PWHT condition, 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 (MITUTOYA; Model: 5010) was used to monitor the crack growth with an accuracy of 0.01 mm. In this investigation, the applied stress cycle was in the tensile mode as the compressive mode usually closes the fatigue crack. The data points measured with an accuracy of 0.01 mm were fitted with a smooth curve as in the form of crack length vs. number of cycles (a vs. N).

Table 3. The number of the tensile test specimens of longitudinal welded joint.

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

3. Results and discussion

3.1 Tensile properties result

Tensile tests were performed on specimens each of raw material (base material) of Al 6013 T4 and we obtained the results of welding without treatment and welding results with the T82 heat treatment aging variation. From the data testing, data was obtained of the ultimate stress (σu) and yields stress (σy). The data was obtained from drawing a line offset 0.2%. The 0.2% offset yield strength was derived from the load–elongation diagram. The percentage of elongation in cross sectional area was evaluated. Tensile test results and elongation of longitudinal welded joint specimens can be seen in Figs. 3 and 4.

The given results of tensile tests are the average of minimum three tests. As can be seen in Fig. 3, the tensile properties of longitudinal welded butt joint after aging 18 hours are higher compared to aging 6 hours and 24 hours. The reason

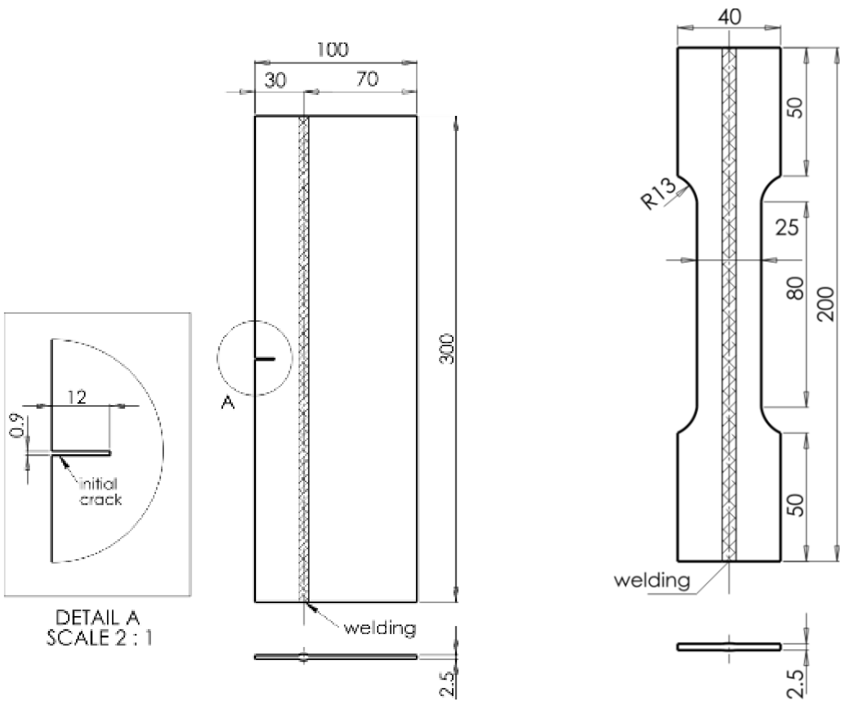

Fig. 1. The surfaces of the specimens were machined off and the specimen dimensions.

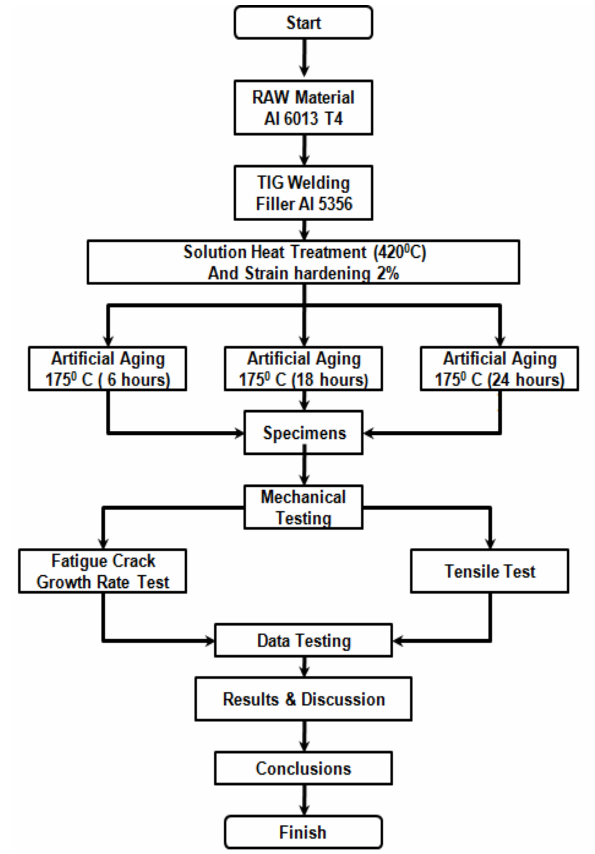

Fig. 2. Experiment procedure and analyze of PWHT of TIG welded on 6013 T4 aluminum alloy.

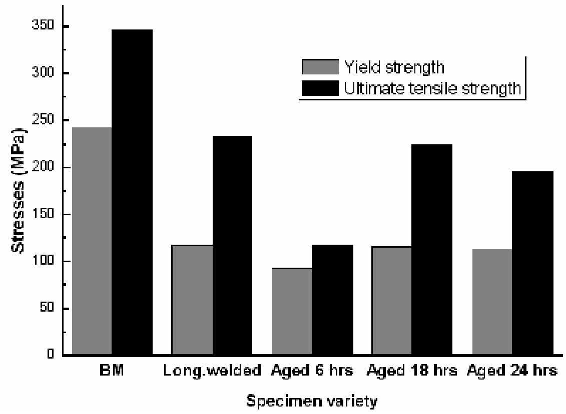

Fig. 3. Tensile properties of longitudinal welded joint Al 6013 T82.

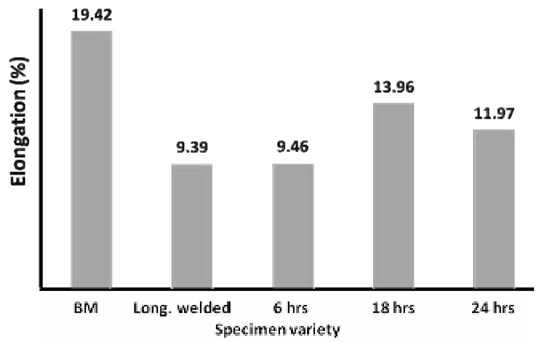

Fig. 4. Elongation of longitudinal welded joint Al 6013 T82.

for this is that the aging of 18 hours makes the joint more brittle compared to the aging of 6 hours and 24 hours, and also the aging of 18 hours makes the joint to have relatively lower ductility properties. In this case PWHT-T82 could reduce the value of tensile strength but the PWHT-T82 can increase the value of the elongation. In PWHT-T82 after 18 hours aging process, the value of tensile strength decreased, due to the over-aging process.

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. Therefore, 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 are largely determined by metallurgical parameters such as type, size and morphology of second phase particles and other precipitates [12]. Precipitates and second phase particles act as barrier to the movement of dislocation which in turn increases hardness and strength. Precipitation hardening of Al-Mg-Si alloys has also been reported to occur due to increased energy requirement to break Mg-Si bond rather than coherency strains [13].

The percentage of elongation in cross sectional area (c.s.a) of base metal and longitudinal welded joint is presented in Fig. 4. The elongation in cross sectional area (c.s.a) of base metal and the longitudinal welded joint without heat-treated is 19.42% and 9.39%, respectively. But the longitudinal welded joint after heat treatment of 6 hours, 18 hours, and 24 hours provides 9.46%, 13.96% and 11.97% of elongation in c.s.a, respectively. This suggests that the reductions in ductility are approximately 48% due to the longitudinal welded joint and 60 % due to PWHT T82, respectively. This indicates that the PWHT-T82 for 18 hours aging can increase the elongation and the improvement in ductility.

3.2 Fatigue crack growth result

The measured variation in crack length (a) and the corresponding number of cycles (N) endured under the action of particular applied stress range are plotted (Fig. 5) for all the joints.

The relationship between SIF (ΔK) range and the corresponding crack growth rate (da/dN) in terms of best fit lines is shown in Figs. 6 and 7 for all 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.

The crack growth exponent 'm', which is derived from the relationship existing between crack growth rate (da/dN) and

Table 4. Fatigue crack growth parameters of longitudinal welded joints.

Specimens	Crack growth Exponent "m"	C
BM	3.31	1.55×10^{-10}
Long. welded	3.53	1.01×10^{-10}
PWHT-T82/6h	3.80	1.45×10^{-10}
PWHT-T82/18h	3.63	1.95×10^{-10}
PWHT-T82/24h	3.70	8.04×10^{-11}

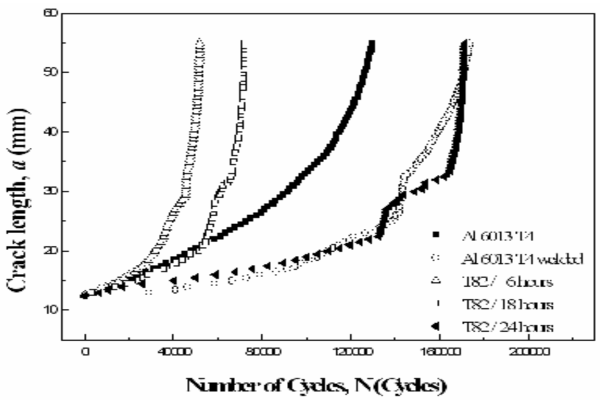

Fig. 5. Effect of PWHT-T82 on fatigue crack growth rate of longitudinal welded joint Al 6013 on various aging.

SIF range, is an important parameter to evaluate the fatigue crack growth behavior of materials since it decides the fatigue crack propagation life of the materials [14]. The fatigue crack growth exponent of BM is 3.31, and the longitudinal welded joint without PWHT-T82 is 3.53. This indicates that the longitudinal welded joint has the exponent lower than BM. The fatigue crack growth exponent of PWHT-T82 for 6 hours aging, 18 hours aging and 24 hours is 3.80, 3.63 and 3.70 respectively.

The fatigue crack growth exponent was obtained from the slope of the curve drawn between da/dN and SIF range. If this exponent is lower, then the slope of the curve is lower and that indicates the resistance offered by the material to the growing fatigue crack is higher and hence the fatigue life will be longer. If this exponent is larger, then the slope of the curve is higher and that explains the resistance offered by the material to the growing fatigue crack is lower and hence the fatigue life will be shorter [15].

The crack propagation in the specimen of longitudinal welded joint without heat treatment starts from the area of the base material, HAZ, and welding metal. Figs. 6 and 7 show the relation between fatigue crack growth rate and stress intensity factor range. And also, Paris constants for the five types of specimens are shown in Table 4. The variation in fatigue crack growth rates (FCGRs) with alternating stress intensity (ΔK) for the Al 6013 T4 plate and longitudinal welded joint conditions tested in air is shown in Fig. 6. For the longitudinal welded joint specimen with crack growth across the welding direction, FCGRs increased significantly with

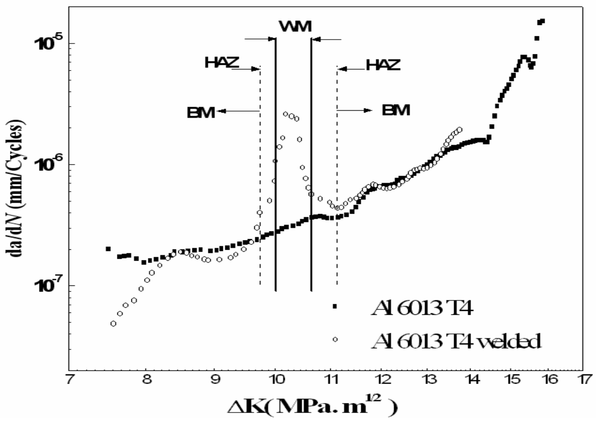

Fig. 6. Measured fatigue crack growth for the Al 6013 (Base metal) and the longitudinal welded joint.

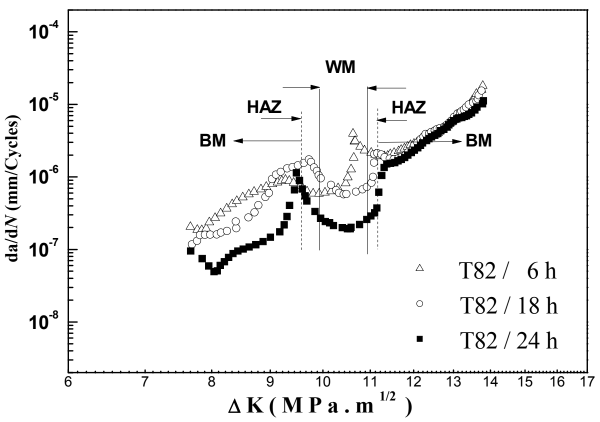

Fig. 7. Measured fatigue crack growth for the longitudinal welded joint Al 6013 after PWHT-T82.

increasing ΔK as the crack propagated within the weld metal and HAZ (Fig. 6). In addition, the weld metal had an obviously higher resistance to crack growth than the Al 6013 T4 plate, especially in the low ΔK range. As the growing crack propagated through the HAZ, the FCGRs dropped initially.

In PWHT-T82 specimens, the fatigue crack propagation is almost the same in all regions, due to the three regions through which the crack propagation in the HAZ and welding metal. The measured fatigue crack growth for the longitudinal welded joint Al 6013 after PWHT-T82 is shown in Fig. 7. For the PWHT-T82 specimens, the highest FCGRs are on specimens with aging of 18 hours, and lowest on specimens with aging of 6 hours at the BM region. The FCGRs were taken from the SIF region between ΔK =7.8 $MPa.m^{1/2}$ and 5.9 $MPa.m^{1/2}$ in the BM region. The FCGRs on PWHT-T82 specimens in the BM region increased significantly with increasing ΔK as the crack propagation within the various aging specimens.

In the HAZ region, the FCGRs decreased in all the PWHT-T82 specimens after ΔK = 9.5 $MPa.m^{1/2}$ and after ΔK = 10.5 $MPa.m^{1/2}$, the FCGRs of the PWHT-T82 specimens increased significantly.

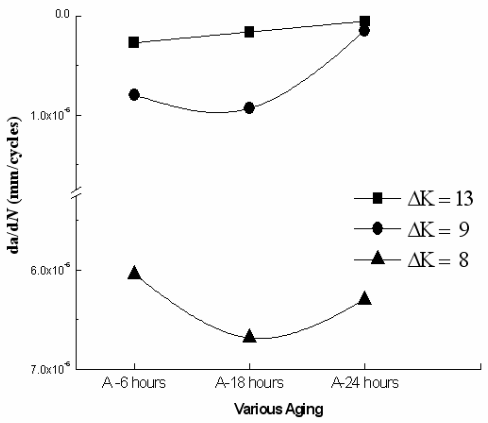

Fig. 8. The da/dN vs various aging specimen of welded as compared with those of ΔK.

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 [16].

The decrease in fatigue strength is due to the change in micro structure (structure with increasingly coarse grains) as a result of the influence of heat on the welding process and tensile residual stress in the vertical direction [17]. In the crack propagation test of the longitudinal welded joint specimens with the T82 heat treatment and aging variation decreased in fatigue strength compared to the base Material and the specimens of the longitudinal welded joint without heat treatment.

The FCGRs behavior for those of various aging comparing three regions in ΔK is shown in Fig. 8. On testing the fatigue crack propagation, in region of BM (ΔK = 8 MPa.m$^{1/2}$) is seen a significant difference. In the HAZ region (ΔK = 9 MPa.m$^{1/2}$) the difference in value da/dN is still visible difference, but in the BM region (ΔK = 13 MPa.m$^{1/2}$) after crack propagation through the WM da/dN is almost the same.

3.3 Microstructure

Optical micrographs of base metal, HAZ, and weld metal are shown in Fig. 9.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) and Mg_2Si phases and other low melting phases along the grain boundary (dark 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 difference in grain size (average grain diameter) of base metal, HAZ, and weld metal. Kang and Liu [18] observed that the magnesium content in the alloys greatly influences the as-cast microstructure. The higher the magnesium content the greater the relative amount of Mg2Si phase in Al-Mg-Si alloys. In the high magnesium alloys, not only binary eutectic structure but also ternary eutectic structure was formed.

In general, approaching from the base metal toward fusion boundary coarsening of aluminum grains was noticed while aluminum grains in the weld metal were finer than that of base metal, HAZ and fusion boundary. Second phase particles and other intermetallic compounds were found in comparatively lesser amount as probably they get dissolved in aluminum matrix in a region close to the fusion boundary. This dissolution is termed as reversion in welding metallurgy. These particles may be the result of re-precipitation of dissolved phases during the cooling after welding. Probably a region zone very close fusion boundary is subjected to full reversion and during the post-natural aging GP zones can be formed. Mechanical properties of Al alloys are determined by the microstructural characteristics (grain and phase structure) of phases present in alloy such as an aluminum crystals and second phase particles/intermetallic compounds depending upon the alloying elements.

Hence, an attempt has been made to measure the average grain diameter of the weld metal region (fusion zone) of all the joints applying Heyn's line intercept method. 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 this is also pointing out 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, also indicating 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, also pointing out that the increasing in grain diameter is 50 μm due to PWHT-T82 for 24 hours of aging process.

Of the PWHT techniques, PWHT-T82 with variation of aging time produces in a different form of grain structure. The PWHT-T82 for 18 hour of aging produces fine grains in the base metal, HAZ and weld metal region compared to other PWHT-T82 for 6 and 24 hours aging. No appreciable changes in grain diameter have been noticed in the postweld heat treatment, and this is clearly evident from the fusion zone

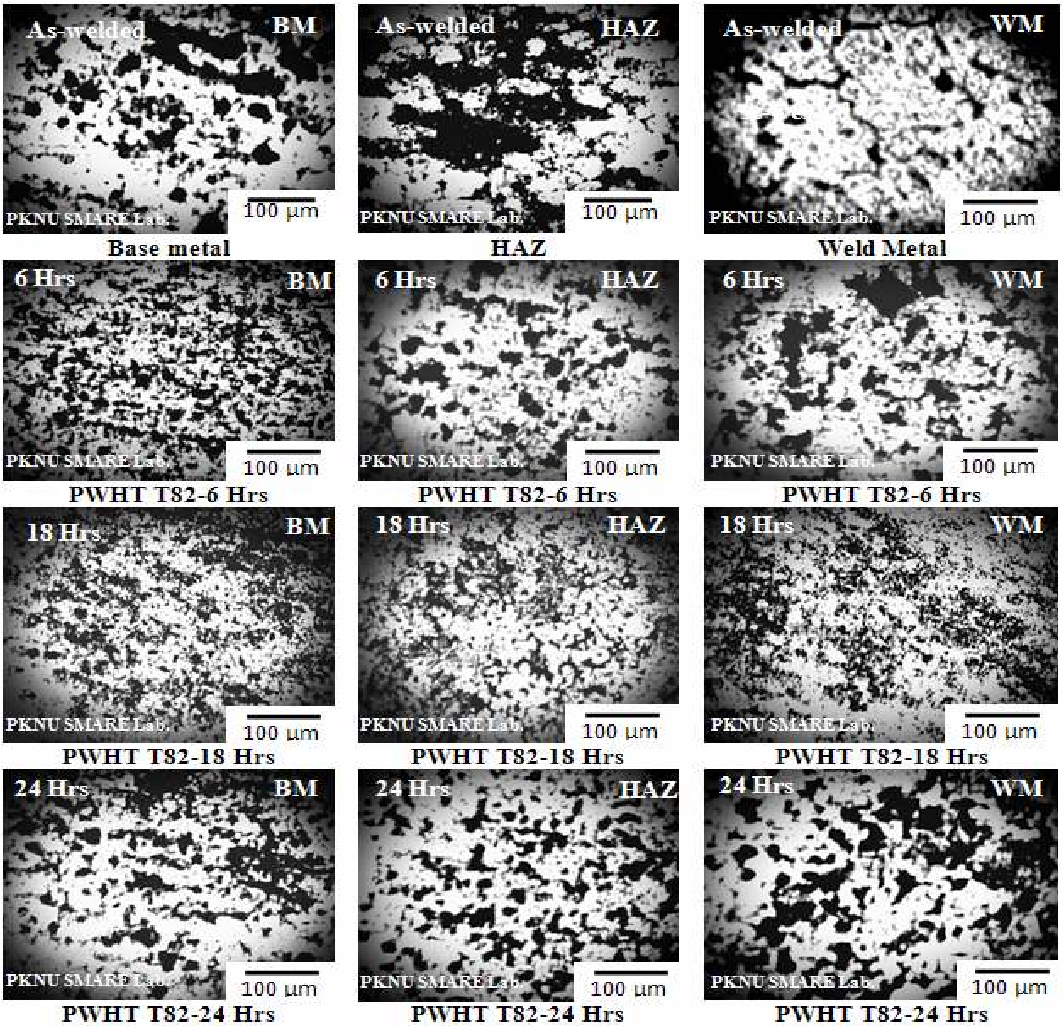

Fig. 9. Optical micrographs of As-welded Al 6013 T4 and PWHT-T82 specimens for variety of aging.

microstructures. However, the postweld heat treatment applied to the joints caused noticeable changes in the formation of precipitates and their distribution. After solution heat treatment and cold working, precipitation of second-phase particles occurs.

On PWHT-T82 for 6 hours aging, the formation of particles of the precipitating phase consists of rearrangement of atoms within the crystal lattice. In PWHT-T82 for 6 hours aging, the formation of particles precipitating phase consists of rearrangement of atoms in the crystal lattice. This is the formation of clusters and Guinier-Preston zones. During this process, mechanical properties need to be increased because of the development of micro-strain in the lattice resulting in low tensile strength values. Formation of the transition structure in the form of Guinier-Preston II zones and intermediate phases modified. This leads to the strengthening of the alloy. This form of structure is similar to the PWHT-T82 process for 18 hours of aging time. On PWHT-T82 for 24 hours aging, the growth of larger particles is at the expense of neighboring certain smaller particles. Since this eliminates the stress held in the lattice, which is usually at a higher aging temperature, which causes considerable decrease in strength.

Substantial improvements in both yield strength and fatigue life have been observed for the postweld aged joints over the as welded joints. The property improvement can be correlated to the precipitation of metastable phases during aging. In most of the heat treatable alloys, part of the HAZ is degraded to such an extent that mechanical properties can be improved only by applying a full heat treatment after welding (solution treatment + aging). With Al-Mg-Si alloys, however, joint properties are improved by a simple precipitation (aging) treatment after welding, the whole of the weld zone hardening. It became clear that explanation of the behavior of these alloys by a simple theory of averaging was incompatible not only with recovery, but also with the known aging behavior of the alloys.

Of the three PWHT-T82 joints, the weld metal region of PWHT-T82 for 18 hours aging consists of very fine and uniform distribution of precipitates compared to other joints. This is attributed to the superior tensile and elongation properties of

PWHT-T82 for 18 hours aging. Similarly, the uniformly distributed, very fine particles might have impeded the growing fatigue cracks and hence the fatigue crack growth rate has been delayed [19] and subsequently the resistance to the fatigue crack propagation has been enhanced compared to other joints. Higher yield strength and tensile strength of the PWHT-T82 for 18 hours aging is greatly used to enhance the endurance limit of the joints and hence the fatigue crack initiation is delayed. Larger elongation (higher ductility) of the PWHT-T82 for 18 hours aging also imparts greater resistance to fatigue crack propagation and hence fatigue failure is delayed. The combined effect of higher yield strength and higher ductility of the PWHT-T82 for 18 hours aging offers enhanced resistance to crack initiation and crack propagation and hence the fatigue performance of the joints is superior as compared to their counterparts.

In the lower strength weld metal, as in the case of PWHT-T82 for 6 hours aging, since the deformation and the yielding are mainly concentrated in the weld metal zone, the extension of the plastic zone is limited within the weld metal. As soon as the plastic zone reaches the fusion line, plasticity keeps on developing along the interface between the parent material and the weld metal [20]. The triaxial state of stress is high in the weld metal and the relaxation of this stress is poor. The crack driving force needed for crack extension is small.

So, the fracture toughness of the lower strength weld metal is not high. On the other hand, if the strength of the weld metal is higher, the plastic zone can easily extend into the parent material because the deformation and yielding occur in both weld metal and the base metal. The stress relaxation can easily take place in the crack tip region. So 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 [21]. This is also one of the reasons for better fatigue resistance of the PWHT-T82 for 18 hours of aging.

It has been proved earlier that the notch sensitivity increases with tensile strength and fatigue notch factor is higher for stronger materials [15]. It is also evident from fatigue test results that higher strength the PWHT-T82 for 18 hours of aging is more sensitive to fatigue notches and lower strength the PWHT-T82 for 6 hours aging is less sensitive to fatigue notches as compared to their counterparts. In low strength materials, the stress concentration must be lower at the root of the notch; the stress gradient set up between roots of the notch to the center of the specimen must be shallow; magnitude of triaxial state of stress must be smaller. In the as welded condition, the precipitates are completely dissolved in the aluminum matrix and it resembles like solution-treated condition.

Due to artificial aging, the precipitates have come out of the aluminum matrix and they are uniformly distributed all over the weld metal region. Even though the precipitates are found to be useful to enhance the strength and hardness of the weld metal, they are found to be detrimental to increase the fatigue notch factor and notch sensitivity factor. In high strength materials, the stress concentration must be higher at the root of the notch; the stress gradient set up between roots of the notch to the center of the specimen must be larger; magnitude of triaxial state of stress must be higher. This may be the reason for higher crack sensitivity of high strength for the PWHT-T82 for 18 hours aging compared to their counterparts.

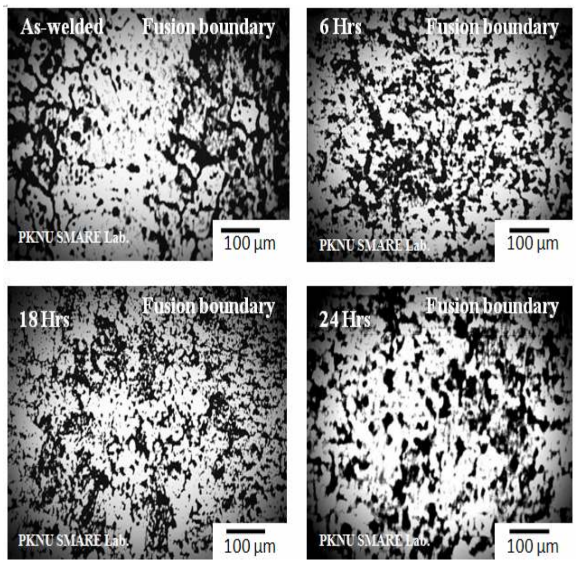

Fig. 10. Optical micrographs of fusion zone region for as-welded Al 6013 T4 and PWHT-T82 specimens for variety of aging.

As can be seen in Fig. 10, the average grain diameter in the fusion zone region of PWHT-T82 for 18 hours aging is on the order of 20 μm and the grain size is much coarser in the fusion zone region of PWHT-T82 for 6 and 24 hours aging. 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; this may be the reason for improved fatigue performance of PWHT-T82 for 18 hours aging compared to PWHT-T82 for 6 and 24 hours aging. In summary, the superior fatigue properties of postweld aged PWHT-T82 for 18 hours aging are mainly due to the following reasons: (i) Finer grains in the fusion zone region on the order of 20 μm; (ii) More grain boundary area due to fine grains (enhances resistance to deformation); (iii) Uniform distribution of precipitates all over the matrix (enhances resistance to indentation); (iv) Higher amount of precipitates in the fusion zone region (enhances resistance to fatigue crack propagation).

The mechanical properties (yield strength, tensile strength and elongation) of PWHT-T82 for 18 hours aging are superior as compared to other joints. Higher yield strength and tensile strength of the PWHT-T82 for 18 hours aging is greatly used to enhance the endurance limit of the PWHT-T82 for 18 hours aging and hence the fatigue crack initiation is delayed. Larger elongation (higher ductility) of the PWHT-T82 for 18 hours aging also imparts greater resistance to fatigue crack propagation and hence fatigue crack growth rate is comparatively slow. The combined effects of higher yield strength and higher ductility of the PWHT-T82 for 18 hours aging offered enhanced resistance to crack initiation and crack propagation and hence the fatigue performance of the PWHT-T82 for 18 hours aging is superior as compared to other joints. In the lower strength weld metal, as in the case of PWHT-T82 for 6 hours aging and PWHT-T82 for 24 hours aging, since the deformation and the yielding are mainly concentrated in the weld metal zone, the extension of the plastic zone is limited within the weld metal.

Eripret and Hornet [20] stated that as soon as the plastic zone reaches the fusion line, plasticity keeps on developing along the interface between the parent material and the weld metal. The triaxial state of stress is high in the weld metal and the relaxation of this stress is poor. The crack driving force needed for crack extension is small. Hence, the fracture toughness of the lower strength weld metal is not high. On the other hand, if strength of the weld metal is more or less equal to the base metal, as in the case of the PWHT-T82 for 18 hours aging, the plastic zone can easily extend into the parent material because the deformation and yielding occur in both weld metal and the base metal. The stress relaxation can easily take place in the crack tip region. Ghosh et al. [22], 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 also one of the reasons for better fatigue crack growth resistance of the PWHT-T82 for 18 hours 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 with increasingly coarse grains) as a result of the heat effect on the process of welding and tensile residual stress in the perpendicular direction. The specimen of PWHT-T82 for 18 hours aging has the highest fatigue strength compared with the aging of 6 hours and 24 hours. This is because the grain structure PWHT-T82 aging of 18 hours is finer than that of 6 hours and 24 hours.

4. Conclusions

The effects of PWHT-T82 for the longitudinal welded joint specimens of Al 6013 T4 aluminum plates on the tensile test and fatigue crack growth rate are presented in the present paper. The following results are obtained:

(1) TIG welding process on longitudinal welded joint of Al 6013 T4 can decrease tensile strength and yield strength.

(2) PWHT-T82 heat treatment process can decrease the value of elongation and elasticity on the longitudinal welded joint.

(3) The slope of PWHT-T82 varied between m = 3.63 and 3.80.

(4) For longitudinal welded joint of PWHT-T82 for variety aging, the highest fatigue resistance in PWHT-T82 for 18 hours of aging ($n = 3.63$ and $C = 1.95 \times 10^{-10}$), and lowest is PWHT-T82 for 6 hours of aging ($n = 3.80$ and $C = 1.45 \times 10^{-10}$).

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