JMEPEG (2008) 17:224–233
DOI: 10.1007/s11665-007-9129-9

1059-9495/$19.00

Effect of Postweld Aging Treatment on Fatigue Behavior of Pulsed Current Welded AA7075 Aluminum Alloy Joints

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(Submitted August 21, 2006; in revised form March 1, 2007)

This article reports the effect of postweld aging treatment on fatigue behavior of pulsed current welded AA 7075 aluminum alloy joints. AA7075 aluminum alloy (Al-Zn-Mg-Cu alloy) has gathered wide acceptance in the fabrication of light weight structures requiring high strength-to weight ratio, such as transportable bridge girders, military vehicles, road tankers, and railway transport systems. The preferred welding processes of AA7075 aluminum alloy are frequently gas tungsten arc welding (GTAW) process and gas metal arc welding (GMAW) process due to their comparatively easier applicability and better economy. Weld fusion zones typically exhibit coarse columnar grains because of the prevailing thermal conditions during weld metal solidification. This often results inferior weld mechanical properties and poor resistance to hot cracking. In this investigation, an attempt has been made to refine the fusion zone grains by applying pulsed current welding technique. Rolled plates of 10 mm thickness have been used as the base material for preparing multipass welded joints. Single V butt joint configuration has been prepared for joining the plates. The filler metal used for joining the plates is AA 5356 (Al-5Mg (wt.%)) grade aluminum alloy. Four different welding techniques have been used to fabricate the joints and they are: (i) continuous current GTAW (CCGTAW), (ii) pulsed current GTAW (PCGTAW), (iii) continuous current GMAW (CCGMAW), and (iv) pulsed current GMAW (PCGMAW) processes. Argon (99.99% pure) has been used as the shielding gas. Rotary bending fatigue testing machine has been used to evaluate fatigue behavior of the welded joints. Current pulsing leads to relatively finer and more equi-axed grain structure in GTA and GMA welds. Grain refinement is accompanied by an increase in fatigue life and endurance limit. Simple postweld aging treatment applied to the joints is found to be beneficial to enhance the fatigue performance of the welded joints.

Keywords AA7075 aluminum alloy, artificial aging, fatigue behavior, gas metal arc welding, gas tungsten arc welding, grain refinement, pulsed current welding

1. Introduction

Many of the structural components in machines, pressure vessels, transport vehicles, earthmoving equipments, spacecrafts, etc. are made of welded joints. The butt welds are the most common ones in the fabrication and construction of many structures. The wide application of butt welds in various structures including offshore and nuclear, gives large scope for the researchers to analyze the behavior under different types of loading conditions (Ref 1). Failure analysis of the weldments indicated that fatigue alone is to be considered to account for most of the disruptive failures. Even though the fatigue properties of the weld metal is good, problems can be caused when there is an abrupt change in section caused by excess weld reinforcement, undercut, slag inclusion, and lack of penetration, and nearly 70% of fatigue cracking occurs in the welded joints (Ref 2).

There is growing interest in the structural 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, as is well known, welded joints can exhibit poor 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. Prompted by difficulties experienced in reaching a consensus on fatigue design rules, extensive testing and analysis of the fatigue performance of welded aluminum alloys have been undertaken over the past 10 years (Ref 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). The heat treatable alloys, especially 2xxx and 7xxx series possess a substantial amount of copper and have a wide melting range with a low solidus temperature and is extremely sensitive to weld cracking when fusion welded. During solidification, there are two distinctive regions are formed and they are: (i) copper free zone and (ii) copper rich zone. The copper rich zone solidifies first, but copper free zone solidifies little later due to low melting temperature. Due to the difference in

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solidification rate, at the solid and liquid interface, there is a possibility of formation of cracks due to unfilling of weld metal, shrinkage stresses, etc. The susceptibility to solidification cracking is greatly influenced by the composition of the weld metal and hence the proper choice of filler material is an important aspect in controlling solidification cracking (Ref 4). The use of nonheat treatable fillers, which can resist hot cracking, is more meaningful in welding 7xxx series alloys. In these alloys, as long as the weld metal contains 3% Mg or more, hot cracking is not a serious problem. Postweld solution treatment is often not necessary for 7xxx series alloys and thus a direct aging treatment can be employed. Another way of controlling solidification cracking is to refine the fusion zone grain structure. Coarse columnar grains are often more susceptible to solidification cracking than fine equi-axed grains. This may be because fine equi-axed grains can deform to accommodate contraction strains more easily (Ref 5).

Current pulsing has been used by few investigators (Ref 6, 7) to obtain grain refinement in weld fusion zones and improvement in weld mechanical properties. Significant refinement of the solidification structure has been reported in aluminum alloys and titanium alloys. Most of the reported literatures are focused on effect of pulsed current welding on grain refinement in fusion zone microstructure and tensile properties. But the published information on the effect of pulsed current welding on fatigue behavior of aluminum alloys is not available. Hence, the present investigation has been carried out to understand the effect of postweld aging treatment on fatigue behavior of pulsed current welded AA7075 aluminum alloy joints.

2. Experimental Work

The rolled plates of AA 7075 aluminum alloy were cut into the required size (300 × 150 mm × 10 mm) by power hacksaw cutting and grinding. Single 'V' butt joint configuration, as shown in Fig. 1 was prepared to fabricate GTA and GMA welded joints. The initial joint configuration was obtained by securing the plates in position using tack welding. The direction of welding was parallel to the rolling direction. All necessary care was taken to avoid joint distortion and the joints were made after clamping the plates with suitable fixtures. Multipass welding procedure was applied to fabricate the joints. AA 5356 (Al-5%Mg) grade filler rod and wire were used for GTA and GMA welding processes, respectively. High-purity (99.99%) argon gas was used as shielding gas. The chemical composition and mechanical properties of base metal and weld metals are presented in Table 1. The welding conditions and process parameters presented in Table 2 were used to fabricate the joints. To study the influence of postweld aging treatment on tensile properties, the welded joints were divided into two groups viz., (i) as welded (AW) joints and (ii) postweld aged (PWA) joints. PWA treatment was carried out at 125 °C for a soaking period of 24 h. Joints were placed in the induction furnace and heated from room temperature to the soaking temperature at a rate of 125 °C per hour. After completion of the soaking period, the joints were cooled down in the furnace to room temperature.

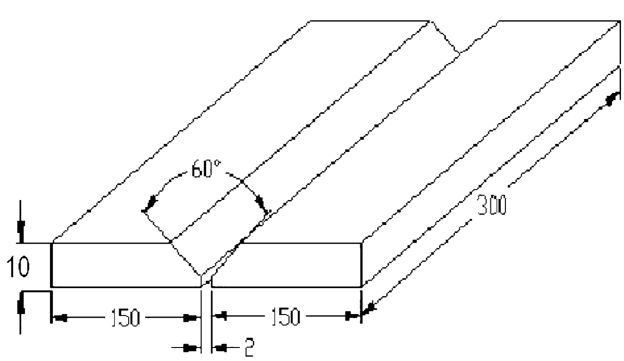

Fig. 1 Dimensions of single V butt joint configuration (all the dimensions are in mm)

The welded joints were sliced using power hacksaw and then machined to the required dimensions as shown in Fig. 2 for preparing fatigue specimens. American Society for Testing of Materials (ASTM) guidelines were followed for preparing the test specimens. Two different fatigue specimens were prepared to evaluate the fatigue properties. Hourglass type (smooth) specimens were prepared as shown in Fig. 2(a) to evaluate fatigue limit and notched specimens were prepared as shown in Fig. 2(b) to evaluate the fatigue notch factor and notch sensitivity factor. The rotary bending fatigue testing experiment was conducted at different stress levels and all the experiments were conducted under completely reversed bending load conditions, where mean stress is zero and stress ratio is −1.

Tensile specimens were prepared as shown in Fig. 2(c) to evaluate yield strength, tensile strength, and elongation. Tensile test was carried out in 100 kN, electro-mechanical controlled Universal Testing Machine. The specimen was loaded at the rate of 1.5 kN/min as per ASTM specifications, so that tensile specimen undergoes deformation. The specimen finally fails after necking and the load versus displacement was recorded. The 0.2% offset yield strength was derived from the diagram. Vicker's micro-hardness testing machine (Make: Zwick and Model: 3212) was employed for measuring the hardness of the weld metal with 0.05 kg load.

Microstructural examinations were carried out using a light optical microscope (VERSAMET-3) incorporated with an image analyzing software (Clemex-Vision). The specimens for metallographic examination were sectioned to the required sizes from the joint comprising weld metal, HAZ and base metal regions and polished using different grades of emery papers. Final polishing was done using the diamond compound (1 μm particle size) in the disk polishing machine. Specimens were etched with Kellers reagent to reveal the microstructure.

3. Results

3.1 Fatigue Properties

Three specimens were tested at each stress level and average of three test results is used to plot *S-N* curves as shown in Fig. 3 and 4. The *S-N* curve in the high-cycle fatigue region is sometimes described by the Basquin equation (Ref 8):

$$S^n N = A \qquad \text{(Eq 1)}$$

where '*S*' is the stress amplitude, '*N*' is the number of cycles to failure, and '*n*' and '*A*' are empirical constants. Each *S-N* curve shown in Fig. 3 and 4 can be represented by the above equation. From those equations, the empirical constants '*n*'

Table 1 Chemical composition (wt.%) of base metal and weld metal and mechanical properties of base metal and weld metal

Type of material	Zn	Mg	Mn	Fe	Si	Cu	Cr	Ti	Al
(a) Chemical composition (wt.%) of base metal and weld metal									
Base metal (AA 7075)	5.61	4.52	0.03	0.29	0.08	1.61	···	0.02	Bal
Weld metal (GTAW)	0.12	5.02	0.12	0.40	0.25	0.11	0.10	0.17	Bal
Weld metal (GMAW)	0.13	5.04	0.14	0.42	0.25	0.10	0.12	0.20	Bal
	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction in cross-sectional area (%)	Hardness (VHN)				
(b) Mechanical properties of base metal and weld metal									
Base metal (AA 7075)	417	520	14.2	9.1	140				
Weld metal (GTAW)	308	376	7.2	4.7	121				
Weld metal (GMAW)	303	380	6.8	4.5	114				

Table 2 Welding conditions and process parameters

Process	CCGMAW	PCGMAW	CCGTAW	PCGTAW
Welding machine	Lincoln	Lincoln	Lincoln	Lincoln
Tungsten electrode Diameter, mm	···	···	3	3
Filler rod/wire diameter, mm	1.6	1.6	3.0	3.0
Voltage, V	30	30	24	24
Current, A	200	···	150	···
Welding speed, mm/min	150	150	120	120
Heat input, kJ/mm	4	3	3	2
Peak current, A	···	200	···	150
Base current, A	···	100	···	75
Pulse frequency, Hz	···	6	···	6
Pulse on time, %	···	50	···	50
Shielding gas	Argon	Argon	Argon	Argon
Gas flow rate	16 L/min	16 L/min	16 L/min	16 L/min

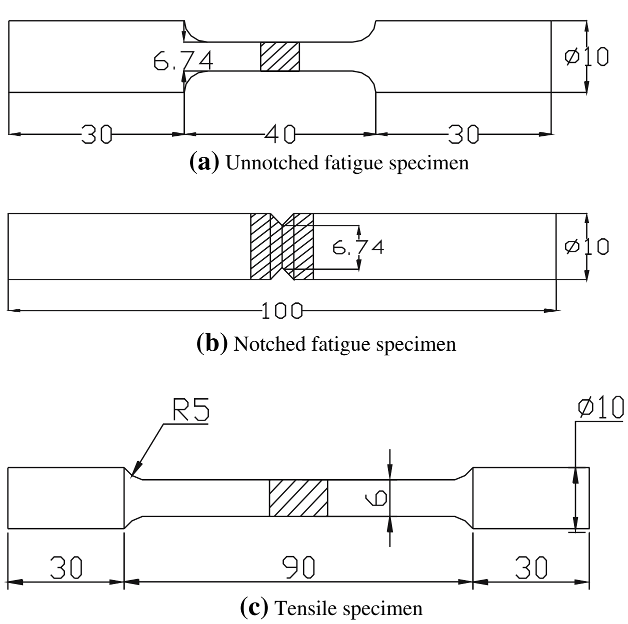

Fig. 2 Dimensions of fatigue and tensile specimens; (a) unnotched fatigue specimen, (b) notched fatigue specimen, and (c) tensile specimen (all the dimensions are in mm)

(slope of the curve) and '*A*' (intercept of the curve) have been evaluated and they are presented in Table 3. Slope of the curve gives an idea about the fatigue performance of the welded joints. If the slope of the curve is higher, then the joints will endure for large number of cycles under fatigue type of loading. From the Table 3, it can be understood that the PCGTAW joints exhibit larger slope compared to other joints and hence the fatigue performance of those joints are superior compared to other joints.

When comparing the fatigue strengths of different welded joints subjected to similar loading, it is convenient to express fatigue strength in terms of the stresses corresponding to particular lives, for example 10^5, 10^6, and 10^7 cycles on the mean *S-N* curve. The choice of reference life is quite arbitrary. Traditionally, 2×10^6 cycles has been used, and indeed some design codes refer to their *S-N* curves in terms of the corresponding stress range (Ref 9). For these reasons, in this investigation, fatigue strength of welded joints at 2×10^6 cycles are taken as a basis for comparison. The stress corresponding to 2×10^6 cycles is taken as an indication of the endurance limit and it has been evaluated for all the joints and is presented in Table 3. PCGTAW joints show higher fatigue limit (50 MPa) compared to other joints. A 20-25% increase in fatigue limit has been attained for the postweld aged joints irrespective of welding techniques.

The effect of notches on fatigue strength is determined by comparing the *S-N* curves of notched and unnotched specimens. The data for notched specimens are usually plotted in terms of nominal stress based on the net section of the specimen. The effectiveness of the notch in decreasing the fatigue limit is expressed by the fatigue strength reduction factor or fatigue notch factor, K_f. The fatigue notch factor for all

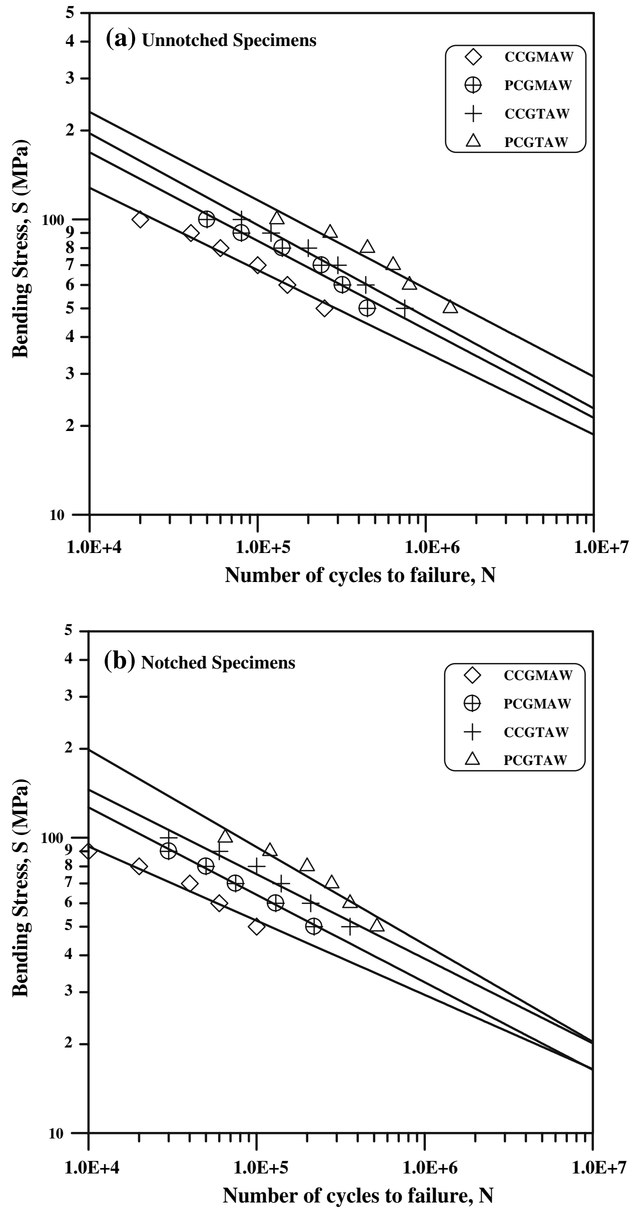

Fig. 3 *S-N* curves of as welded joints

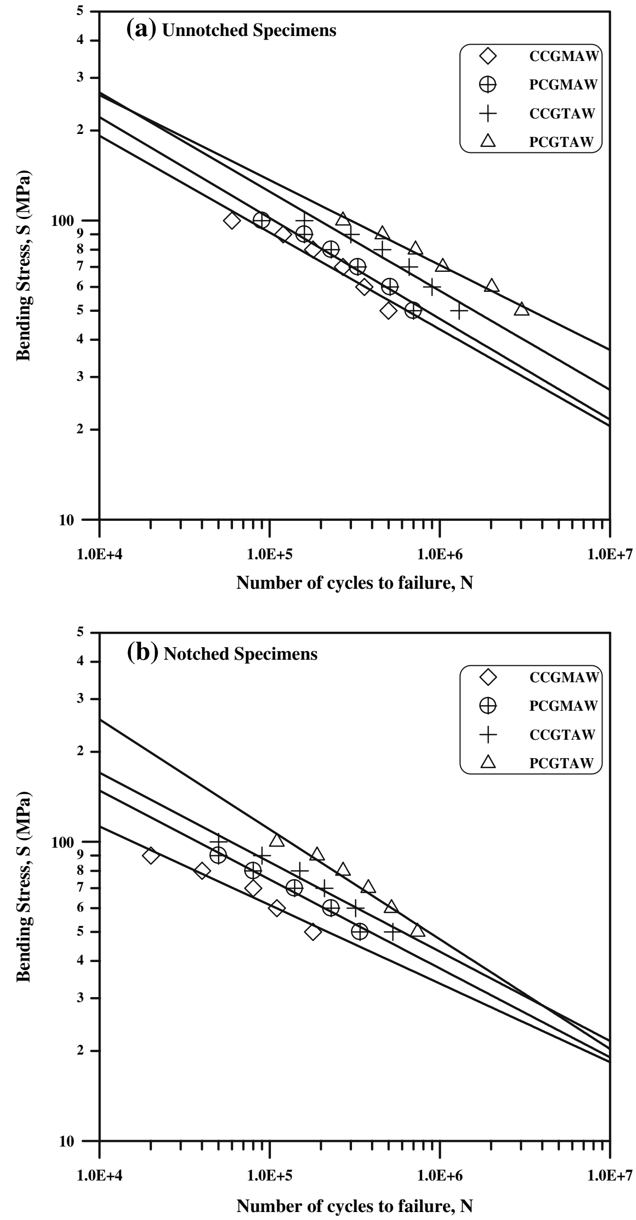

Fig. 4 *S-N* curves of postweld aged joints

the joints has been evaluated using the following expression (Ref 8) and they are given in Table 3.

$$K_{\mathrm{f}} = \text{Fatigue limit of unnotched specimen}/\text{Fatigue limit of notched specimen} \quad \text{(Eq 2)}$$

The notch sensitivity of a material in fatigue is expressed by a notch sensitivity factor '*q*' and '*q*' can be evaluated using the following expression (Ref 8):

$$q = (K_{\mathrm{f}} - 1)/(K_{\mathrm{t}} - 1) \quad \text{(Eq 3)}$$

where K_{t} is the theoretical stress concentration factor and is the ratio of maximum stress to nominal stress. Using the above expression fatigue notch sensitivity factor '*q*' has been evaluated for all the joints and they are presented in Table 3. If '*q*' is zero, then the material is notch insensitive. Low '*q*' values are generally preferred. Continuous current welded joints show better fatigue notch resistance compared to pulsed current welded joints. Sensitivity to notches is lower for continuous current welded joints compared to pulsed current welded joints. However, the postweld aging treatment increases the fatigue notch factor and notch sensitivity factor, irrespective of welding processes.

3.2 Tensile Properties

The transverse tensile properties such as yield strength, tensile strength and percentage of elongation of AA 7075 aluminum alloy joints have been evaluated. In each condition, three specimens have been tested and the average of three results is presented in Table 4. The yield strength and tensile strength of unwelded parent metal are 417 and 520 MPa, respectively. But the yield strength and tensile strength of CCGMAW joints are 180 and 235 MPa, respectively. This indicates that there is a 55% reduction in strength values due to

Table 3 Fatigue properties of as welded (AW) joints and postweld aged (PWA) joints

Joint type	Slope of the *S-N* curve, *n*	Intercept of the *S-N* curve, A	Fatigue limit at 2×10^6 cycles, MPa	Fatigue notch factor, K_f	Notch sensitivity factor, *q*
(a) AW joints					
CCGMAW	3.09	8.67×10^{10}	30	1.20	0.118
PCGMAW	3.14	1.77×10^{11}	34	1.25	0.148
CCGTAW	3.22	2.39×10^{11}	38	1.28	0.166
PCGTAW	3.34	7.72×10^{11}	50	1.44	0.260
(b) PWA joints					
CCGMAW	2.90	7.14×10^{10}	38	1.27	0.159
PCGMAW	2.97	9.37×10^{10}	40	1.29	0.172
CCGTAW	3.01	2.00×10^{11}	46	1.32	0.189
PCGTAW	3.52	3.28×10^{12}	60	1.66	0.390

Table 4 Transverse tensile properties of as welded (AW) joints and postweld aged (PWA) joints

Joint type	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %	Reduction in c.s.a., %
(a) AW joints				
CCGMAW	*180* (176, 182, 182)	*235* (233, 235, 238)	*6.5* (6.0, 6.5, 7.0)	*4.25* (4, 4.6, 4.2)
PCGMAW	*195* (192, 194, 198)	*254* (255, 260, 248)	*8.5* (8.0, 8.5, 9.0)	*6.75* (6.5, 6.8, 7)
CCGTAW	*205* (202, 206, 208)	*272* (272, 270, 275)	*10.4* (10.6, 11, 9.6)	*7.30* (7, 7.5, 7.3)
PCGTAW	*220* (216, 216, 228)	*295* (290, 295, 300)	*12.3* (12, 12.6, 12.4)	*8.55* (8.2, 8.6, 9.2)
(b) PWA joints				
CCGMAW	*192* (190, 196, 190)	*251* (248, 252, 254)	*7.2* (7.0, 7.3, 7.3)	*5.68* (5.0, 5.7, 6.3)
PCGMAW	*210* (214, 206, 210)	*270* (265, 270, 275)	*9.3* (9.0, 9.2, 9.6)	*6.85* (6.2, 6.8, 7.5)
CCGTAW	*220* (218, 222, 220)	*292* (290, 295, 290)	*11.5* (11, 11.5, 12)	*7.50* (7.0, 7.5, 8.0)
PCGTAW	*240* (236, 244, 240)	*314* (310, 315, 318)	*13.6* (13, 13.6, 14)	*8.75* (8.2, 8.8, 9.3)

The values given in the parenthesis are the results of three test specimens. The values given in italics are average of three results

CCGMA welding. However, PCGMAW process is found to be beneficial to enhance the strength of welded joints and the yield strength and tensile strength of PCGMAW joints are 195 and 254 MPa, respectively. This shows that there is an 8% increase in strength values due to pulsed current welding. Similarly, the yield strength and tensile strength of CCGTAW joints are 205 and 272 MPa, respectively, which are 48% lower compared to parent metal. However, PCGTAW process is found to be beneficial to improve the strength of welded joints and the yield strength and tensile strength of PCGTAW joints are 220 and 295 MPa, respectively. This shows that there is a 7% increase in strength values due to pulsed current welding. Of the four types of welded joints, the joints fabricated by PCGTAW exhibited very high strength values and the enhancement in strength value is approximately 25% compared to CCGMAW joints and 15% compared to PCGMAW joints. Similar trend has been observed in postweld aged (PWA) joints and a simple postweld aging treatment applied to the joints has enabled to improve the yield strength and tensile strength of the welded joints and the improvement is 8-10%.

3.3 Hardness

The hardness across the weld cross section has been measured using Vicker's Micro-hardness testing machine and the values are presented in Table 5. The hardness of base metal (unwelded parent metal) in its initial T_6 condition is approximately 140 VHN. But the hardness of the CCGMAW joints in the weld metal region is 70 VHN. This suggests that the hardness is reduced by 70 VHN in the weld center due to welding heat and the usage of lower hardness filler metal (Al-5%Mg). However, the pulsed current welding technique has enabled to regain the hardness level to some extent in the weld metal region. Of the four joints, PCGTAW joints showing hardness of 100 VHN which is 30 VHN higher than the CCGMAW joints. Similarly, the CCGTAW joints recorded hardness of 85 VHN, which is 15 VHN higher than the CCGMAW joints. PCGMAW joints exhibited hardness of 80 VHN, which is 10 VHN greater than the CCGMAW joints. Similar trend has been observed in partially melted zone (PMZ), heat affected zone (HAZ), and base metal (BM) regions. The hardness is relatively higher in the PMZ and HAZ regions compared to WM region and this may be due to the formation of very fine recrystallized grains in that region.

In the case of postweld aged (PWA) joints, the weld metal hardness has been found to increase compared to as welded joints. This suggests that the simple aging treatment applied to the joints increased the weld metal hardness irrespective of welding processes and the increase in hardness is 15-20%. Of the four postweld aged (PWA) joints, PCGTAW joints showing hardness of 115 VHN which is 15 VHN higher than the as welded PCGTAW joints. Similarly, the postweld aged CCGTAW joints recorded hardness of 105 VHN, which is 20 VHN higher than the as welded CCGTAW joints. Postweld aged PCGMAW joints exhibited hardness of 96 VHN, which is 16 VHN greater than the as welded PCGMAW joints and postweld aged CCGMAW joints showed hardness of 85 which is 15 VHN higher than the as welded CCGMAW joints. As in the case of as welded joints, the hardness of PMZ and HAZ regions of postweld aged joints are higher compared to WM region but the increase in hardness in these

Table 5 Micro-hardness values (VHN) of as welded (AW) joints and postweld aged (PWA) joints

	Location			
Joint Type	**WM**	**PMZ**	**HAZ**	**BM**
(a) AW joints				
CCGMAW	*70* (68, 68, 74)	*80* (76, 80, 84)	*95* (90, 95, 100)	*136* (132, 136, 140)
PCGMAW	*80* (76, 80, 84)	*90* (88, 90, 92)	*104* (100, 104, 108)	*138* (134, 138, 142)
CCGTAW	*85* (85, 85, 85)	*100* (96, 100, 104)	*116* (112, 116, 120)	*140* (138, 140, 142)
PCGTAW	*100* (96, 100, 104)	*110* (108, 110, 112)	*122* (120, 122, 124)	*142* (140, 140, 144)
(b) PWA joints				
CCGMAW	*85* (84, 86, 85)	*90* (88, 90, 92)	*96* (92, 96, 100)	*138* (136, 136, 140)
PCGMAW	*96* (94, 98, 96)	*100* (100, 100, 100)	*105* (104, 105, 106)	*140* (138, 140, 142)
CCGTAW	*105* (102, 105, 108)	*110* (108, 110, 112)	*116* (115, 116, 118)	*142* (142, 142, 142)
PCGTAW	*115* (112, 116, 118)	*120* (118, 120, 122)	*126* (125, 126, 126)	*145* (145, 145, 145)

The values given in the parenthesis are the results of three measurements. The values given in italics are average of three measurements

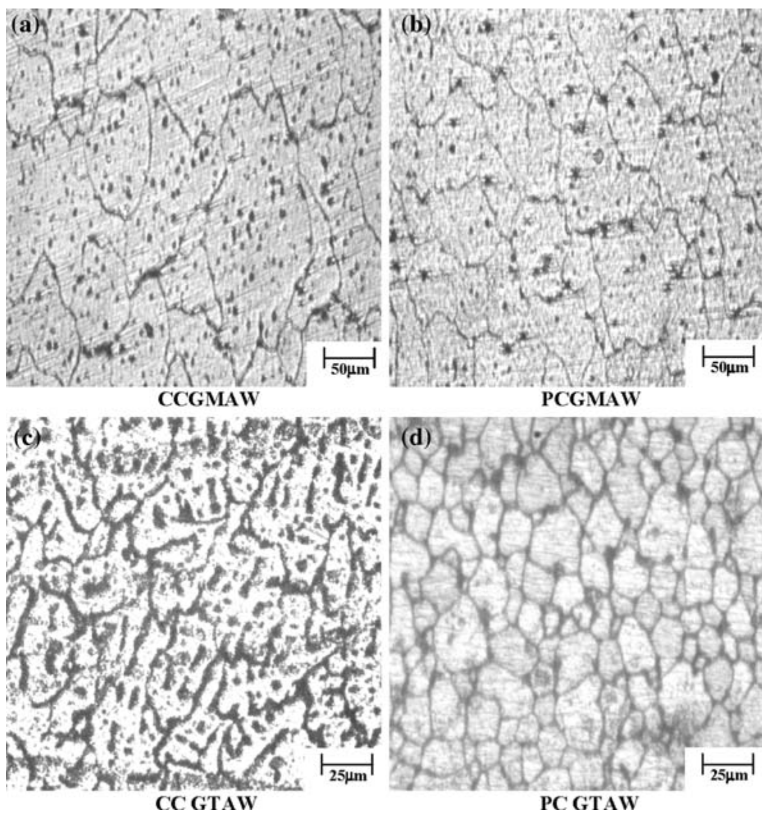

Fig. 5 Optical micrographs of weld metal region of as welded joints; (a) CCGMAW, (b) PCGMAW, (c) CCGTAW, and (d) PCGTAW

regions is not so high. This indicates that the simple aging treatment applied to the joints has reduced the differences in hardness across the joint cross section to greater extent.

3.4 Microstructure

Microstructure of all the joints has been examined at different locations but the optical micrographs taken at weld metal region alone have been displayed in Fig. 5 and 6. From the micrographs, it is understood that there is an appreciable difference in grain size (average grain diameter) of weld metal regions. This suggests that the current pulsing is very effective in fusion zone grain refinement. 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 CCGMAW joints is 75 μm but the average grain diameter of PCGMAW joints is 50 μm and this indicates that reduction in grain diameter is 25 μm due to pulsed current welding of GMAW process. Similarly the measured average grain diameter of CCGTAW joints is 40 μm but the average grain diameter of PCGTAW joints is 20 μm, and this also pointing that the reduction in grain diameter is 20 μm due to pulsed current welding of GTAW process. Of the four techniques, the PCGTAW technique produces very fine grains in the weld metal region compared to all other techniques. No appreciable

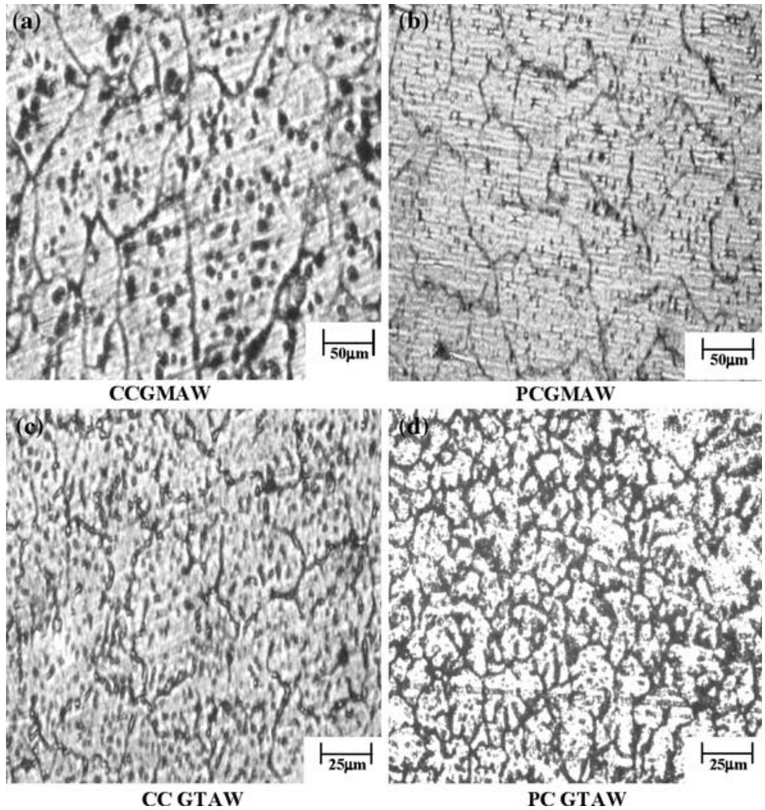

Fig. 6 Optical micrographs of weld metal region of postweld aged joints; (a) CCGMAW, (b) PCGMAW, (c) CCGTAW, and (d) PCGTAW

changes in grain diameter have been noticed in the postweld aged (PWA) joints, and this is clearly evident from the fusion zone microstructures. However, the simple aging treatment applied to the joints caused noticeable changes in the formation of precipitates and their distribution.

Generally, in Al-Zn-Mg-Cu alloys two different strengthening precipitates will form and they are: (i) Mg_2Zn and (ii) $CuAl_2$. The black particles seen in weld metal region are strengthening precipitates, but there is an appreciable difference in size and distribution of the precipitates with respect to welding techniques and postweld aging treatment. Fine precipitates generally belong to $CuAl_2$ and coarse precipitates belong to Mg_2Zn because the maximum available copper for the precipitation reaction is 1.6% (from the base metal and not from the filler metal) only in this alloy, but the available magnesium (5% from the filler metal alone) for the precipitation reaction is plenty. However, both the precipitates are uniformly distributed throughout the matrix of weld metal in pulsed current welds but in continuous current welds the precipitates are more densely available in the grain boundaries than in the grain interior. Relatively higher amount of precipitates are seen in postweld aged (PWA) joints compared to as welded (AW) joints.

4. Discussion

During fatigue tests all the specimens have been failed exactly in the weld region. Thus it may be understood that the weld metal regions have poor resistance compared to other regions against the action of fatigue loading. The use of pulsed current welding improves the fatigue resistance of the weld more than that observed for the case of continuous current welding. The enhancement in fatigue properties and tensile properties is mainly due to the refinement in fusion zone grain size. Hence, the basic reason for the improvement in fatigue properties is the refinement produced in fusion zone grain size by pulsed current welding technique.

4.1 Effect of Pulsed Current Welding on Fusion Zone Grain Refinement

Pulsed current welding is a variation of constant current welding which involves cycling of the welding current from a high level to a low level at a selected regular frequency. The high level of the peak current is generally selected to give adequate penetration and bead contour, while the low level of the background current is set at a level sufficient to maintain a stable arc. This permits arc energy to be used efficiently to fuse a spot of controlled dimensions in a short time producing the weld as a series of overlapping nuggets and limits the wastage of heat by conduction into the adjacent parent material as in normal constant current welding. In contrast to constant current welding, the fact that heat energy required to melt the base material is supplied only during peak current pulses for brief intervals of time allows the heat to dissipate into the base material leading to a narrower HAZ (Ref 10).

The amplitude of thermal oscillations has been found to increase with increasing ratio of the peak to base currents and to decrease with rising pulse frequency. The consequence of the thermal fluctuations leads to periodic interruption in the process of solidification. As the pulse current decays, the solid-liquid interface advances toward the arc and increasingly becomes vulnerable to any disturbances in the arc form. Heat transfer experienced by the weldment during welding can alter the microstructure and thus the property of the weldment. Therefore the heat transfer and fluid flow in the weld pool can significantly influence factors such as weld pool geometry, temperature gradient local cooling rates and solidification structure (Ref 11).

The evolution of microstructure in weld fusion zone is also influenced in many ways by current pulsing, principally, the cyclic variations of energy input into the weld pool cause thermal fluctuations, one consequence of which is the periodic interruption in the solidification process. As the pulse peak current decays, the solid-liquid interface advances toward the arc and increasingly becomes vulnerable to any disturbances in the arc form. As current increases again in the subsequent pulse, growth is arrested and remelting of the growing dendrites can also occur. Current pulsing also results in periodic variations in the arc forces and hence the additional fluid flows that lowers temperatures in front of the solidifying interface. Furthermore, the temperature fluctuations inherent in pulsed welding lead to a continual change in the weld pool size and shape favoring the growth of new grains. It is also to be noted that effective heat input for unit volume of the weld pool would be considerably less in pulse current welds for which reason the average weld pool temperatures are expected to be low (Ref 12).

The refinement of microstructure due to the pulsed current welding results in a uniform distribution of the fine precipitates more effectively governed by its zinc pick up enhancing the amount of precipitates in the matrix. Similar observation has been made by other investigators also (Ref 13, 14). Hardness in the fusion zone is the lowest due to the as-cast nature of the microstructure, which is characterized by coarse dendritic grains, interdendritic segregate phases, and the lack of strengthening phases. Hardness is slightly higher in pulsed current welds as compared to continuous current welds and this could be due to the refined microstructure and low segregation of strengthening phases. The moderately higher hardness of pulsed current welds close to the fusion boundary is possibly due to a large fraction of alloying elements in solid solution at the end of the weld thermal cycle, thereby giving conditions for extensive age hardening. This can be explained as follows: at the fusion boundary, precipitate dissolution occurs as the particles are exposed to temperatures higher than 400 °C during heating and cooling as a result of welding. Dissolution process enriches the solid solution of the aluminum matrix with Mg, Zn, and Cu. This resulted in increasing hardness.

4.2 Effect of Postweld Aging Treatment

Substantial improvements in both yield strength and fatigue life has 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. Berg and Hansen (Ref 15) have studied the GP (Guinier-Preston) zones and their role in artificial aging of Al-Zn-Mg alloys. Two types of GP zones, GP(1) and GP(11) are characterized by electron diffraction patterns. GP(1) zones are independent of quenching temperature and formed over a wide temperature range, i.e., 140-150 °C. GP(11) zones are formed after quenching from temperature above 150 °C, by aging above 70 °C. GP(1) zones are coherent with the aluminum matrix, with internal ordering of Zn and Al/Mg on the matrix lattice. The GP(11) zones are described as the zinc-rich layers with internal order in the form of elongated domains. The hardening precipitate η' is a metastable hexagonal phase. These precipitates are found also in the absence of GP(11) zones. The formation of zinc-rich phase [GP(11)] depend on magnesium atoms that relieve local strain. Several GP(11) zones associate to form a thicker zone, in the presence of Mg atoms corresponding to Zn/Al plane often with considerable disorder within the η' precipitate.

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-Zn-Mg-Cu 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 overaging was incompatible, 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. This led to the reversion instead of overaging in Al-Zn-Mg-Cu alloy. Reversion may be defined as the re-solution of a hardening precipitate, which can occur, on heating above the highest previous aging temperature but to a temperature below the solid solubility limit, if the hardening precipitate becomes thermodynamically unstable, because of its size or morphology, even though re-solution may increase solute supersaturation, and will lead to reprecipitation on holding at such temperatures (Ref 16).

4.3 Effect of Weld Metal Strength on Fatigue Behavior of Joints

The tensile properties (yield strength, tensile strength and elongation) of PCGTAW joints are superior as compared to their counterparts (see Table 4). Higher yield strength and tensile strength of the PCGTAW joint 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 PCGTAW joints 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 PCGTAW joint 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 GMAW joints, 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 (Ref 17). 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 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 (Ref 18). This is also one of the reasons for better fatigue resistance of the PCGTAW joints.

In general, fatigue strength is seriously reduced by the introduction of stress raisers as a notch or hole. The presence of a notch in a specimen under uniaxial load introduces three effects: (i) there is an increase or concentration of stress at the root of the notch; (ii) a stress gradient is set up from the root of the notch toward the center of the specimen; (iii) a triaxial state of stress is produced (Ref 19). A material which experiences no reduction in fatigue strength due to a notch ($K_f = 1$) has a factor of $q = 0$, while a material in which the notch has its full theoretical effect ($K_f = K_t$) has a factor of $q = 1$. But, 'q' is not a true material constant since it varies with the severity and type of notch, the size of the specimen and type of loading. However, it has been proved earlier that the notch sensitivity increases with tensile strength and fatigue notch factor is higher for stronger materials (Ref 20). It is also evident from fatigue test results that higher strength PCGTAW joints are more sensitive to fatigue notches and lower strength CCGMAW joints are 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 root of the notch to the center of the specimen must be shallow; magnitude of triaxial state of stress must be smaller. This may be the reason for lower fatigue notch factor and lower crack sensitivity of low strength CCGMAW joints compared to their counterparts. 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 root 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 fatigue notch factor and higher crack sensitivity of high strength postweld aged PCGTAW joints compared to their counterparts.

4.4 Effect of Fusion Zone Grain Size on Fatigue Behavior

The fatigue properties of metals are quite structure sensitive. The dependence of fatigue life on grain size varies also depending on the deformation mode. Grain size has its greatest effect on fatigue life in the low stress, high cycle regime in which stage I cracking predominates. In high stacking fault energy materials, cell structures develop readily and these control the stage I crack propagation. Thus the dislocation cell structure masks the influence of grain size and fatigue life at constant stress is insensitive to grain size. However, in a low stacking fault energy material, the absence of cell structure because of planar slip causes the grain boundaries to control the rate of cracking. In this case, fatigue life is inversely proportional to grain diameter. While the concept has been useful in understanding fatigue mechanisms, the ability to control fatigue strength by altering stacking fault energy has practical limitations. A more promising approach to increase fatigue strength appears to be the control of microstructure through thermo-mechanical processing to promote homogeneous slip with many small regions of plastic deformation as opposed to a smaller number of regions of extensive slip. There is good evidence that high fatigue resistance can be achieved by homogenizing slip deformation so that local concentrations of plastic deformation are avoided (Ref 21).

Optimization of the microstructural dimensions for improved resistance to both crack initiation and crack growth would require a trade-off in the choice of grain size or even the development of a structure with a distribution of grain sizes. In the near-threshold regime of fatigue crack growth, where a significant portion of stable crack growth life is expended, an increase in grain size of the material generally results in a marked reduction in the near-threshold fatigue crack growth rates and an increase in threshold SIF range. On the other hand, the resistance of a material to fatigue crack initiation, expressed in terms of an endurance limit, often increases with decreasing grain size and increasing strength of the material. Although these results may appear contradictory, they can be rationalized by noting that the former inference is valid solely for fatigue crack growth, especially at low stress intensity range levels, whereas the latter conclusion pertains primarily to crack initiation (Ref 22).

The average grain diameter in the fusion zone region of PCGTAW joints is in the order of 20-30 μm and the grain size is much coarser in the fusion zone region of CCGMAW joints. 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 CCGTAW joints compared to other joints. In summary, the superior fatigue properties of postweld aged PCGTAW joints are mainly due to the following reasons: (i) Finer grains in the weld metal region in 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 weld region (enhances resistance to fatigue crack propagation).

5. Conclusions

In this article, the effect of postweld aging treatment on fatigue behavior of pulsed current welded AA7075 aluminum alloy has been reported. From this investigation following important conclusions have been derived:

(i) Pulsed current welding is found to be beneficial to enhance the fatigue resistance of the GMAW and GTAW joints and fatigue performance of pulsed current welded joints are superior compared to the continuous current welded joints.
(ii) A simple artificial aging treatment applied to joints is found to be useful to enhance the fatigue performance of welded joints. Nearly a 20-25% increment in fatigue life has been attained irrespective of welding techniques.
(iii) Of the eight types of welded joints, the postweld aged pulsed current gas tungsten arc welded (PCGTAW) joints endured large number of cycles compared to other joints.
(iv) The superior mechanical properties (higher yield strength and hardness) and preferred microstructures in the weld metal region (very fine equi-axed grains with higher amount of precipitates) are the reasons for better fatigue performance of the postweld aged PCGTAW joints.

Acknowledgements

The authors are grateful to the Department of Manufacturing Engineering, Annamalai University, Annamalainagar, Tamil Nadu, India for extending the facilities of Metal Joining Laboratory and Materials Testing Laboratory to carryout this investigation. The authors also wish to express their sincere thanks to Directorate of Extramural Research & Intellectual Property Rights, Defence Research & Development Organisation (DRDO), New Delhi for the financial support to carryout this investigation through sponsored project No. ERIP/ER/0203351/M/01/633. The first two authors are very grateful to the third author, Dr. G. Madhusudhana Reddy, Scientist-F, Defence Metallurgical Research Laboratory (DMRL), Hyderabad for his valuable suggestions, guidance and discussion.

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