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Pulse TIG Welding of Two Al-Mg-Si Alloys

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This article reports the influence of pulse tungsten inert gas (TIG) welding parameters on the microstructure, hardness and tensile strength of weld joints of two Al-(0.5-0.8%)Si-(0.5-0.6%)Mg alloy (T4) produced by using three pulse frequencies (25, 33, and 50 Hz) and two duty cycles (40 and 50%). It has been observed that the mechanical properties (hardness and tensile strength) are sensitive to microstructure of weld metal, which is appreciably affected by the pulse parameters. Low frequency produced higher strength and hardness than high pulse frequency under identical welding conditions. Weld metal and HAZ were found stronger than the base metal. SEM study showed that the fracture of weldment was mostly brittle type.

Keywords Al-Mg-Si, hardness, microstructure, pulse parameter, tensile strength and SEM study, TIG welding

1. Introduction

Aluminum alloys have been a material of choice for aircraft construction since 1930s. The aerospace industry relies heavily on 2xxx and 7xxx aluminum alloys, while a wide variety of aluminum alloys are used by automotive industry. Currently, the automotive industry is showing an increasing interest in aluminum alloys as structural materials. 6xxx Aluminum alloys are of particular interest to both the aerospace industry (for fuselage skins and other applications) and 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 (Ref 1). During manufacturing of automotive and aerospace parts, welding of aluminum alloys (6xxx) is frequently needed. Welding of aluminum is generally performed either by gas metal arc welding or tungsten inert gas (TIG) welding. Gas metal arc welding offers the advantage of high deposition rate and high welding speed besides deeper penetration because of high heat input. However, excessive heat input imposes the problems such as melt through, distortion etc. specially in welding of thin aluminum sheets. Therefore, to produce high quality weldments TIG welding is preferred over gas metal arc welding. Presently, TIG welding process is one of the most well established processes which can not only weld all metals of industrial use but also produces the best quality welds amongst the arc welding processes. In pulsed TIG process, the current is supplied in pulses rather than at a constant magnitude. A typical variation of welding current with time is schematically shown in Fig. 1. The aim of pulsing is mainly to achieve maximum penetration without excessive heat build-up, by using the high current pulses to penetrate deeply and then allowing the weld pool to dissipate some of the heat during relatively longer arc period at a low current (Ref 2). It has been investigated by authors (Ref 3, 4) that the influence of pulse parameters on microstructure is very complex. Literature review did not reveal much work on the influence of pulse parameters of TIG welding process on weldability (microstructure, hardness, tensile strength, and fracture behavior) of Al-Mg-Si alloys with varying Mg and Si (wt.%). Therefore, to increase an understanding in this area attempts were made to study the effect of pulse frequency and duty cycle on the microstructure, hardness, tensile strength and fracture behavior of two Al-Mg-Si alloys.

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2. Experimental Procedure

In present investigation, two Al-Mg-Si alloys were used as base metal. Chemical compositions of the base metals are in Table 1. Alloy plates (T4 condition) having dimensions $90 \times 60 \times 7$ mm were prepared by controlled melting and casting in sand moulds. Cast Al-Mg-Si alloy were selected to investigate the influence of welding procedure on microstructure and hardness (weldability) of coarse-grained base metal and observe the cracking tendency of Heat affected zone in coarse-grained metals. As coarse-grained aluminum alloys exhibit greater tendency for cracking. The 6xxx alloys should not be welded with base alloy filler or without a filler addition, because it can result in cracking. However, these can be welded using aluminum-silicon alloy filler metal. Therefore, 1.6 mm diameter Al-5%Si (A-404) filler wires were used. Welding was carried out by using a semi automatic TIG welding machine (CEBORA 360, India). The following parameters were maintained during the welding:

(1) Electrode material: 2% thoriated tungsten electrode.
(2) Electrode size: 3.5 mm diameter.
(3) Shielding gas: a mixture of 98% argon and 2% oxygen.
(4) Arc length: 2.5 mm.
(5) Arc travel speed: 6.1 cm/min.
(6) Shielding gas flow rate: 12 L/min.

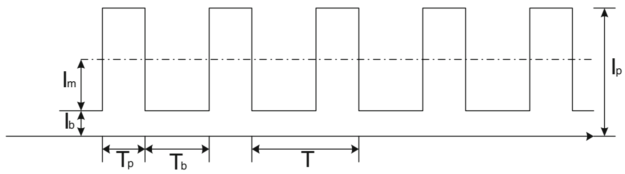

Fig. 1 Schematic representation of welding current vs. time relationship for pulse TIG welding

Table 1 Chemical compositions of base metals (wt.%)

Alloy	Aluminum	Magnesium	Silicon
A	98.6	0.8	0.6
B	99.0	0.5	0.5

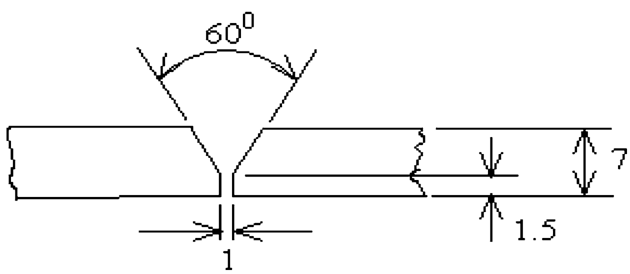

Fig. 2 Groove geometry used for producing weld joints (all dimensions are in mm)

Al-Mg-Si plates of size 90 mm × 60 mm × 7 mm were mechanically cleaned by grinding and wire brushing. One long edge of the plate was machined to have 30° angle and 1.5 mm root face as shown in Fig. 2. Hence, total groove angle was 60°. The grooved faces of two plates were firmly tack welded at both the sides maintaining a root gap of 1 mm. The plates were firmly held in position by using a fixture and an automatic feed system was used to move the welding torch at desired speed for welding in a single pass. The welding was done using peak current of 250 A, background current of 125 A at three pulse frequencies (25, 33, and 50 Hz) and two duty cycles (40 and 50%).

After welding the weldments were cut for the preparation of samples to study the microstructure, hardness and tensile strength. For Metallography, the specimens were collected from middle portion of the weldments to ensure a true representation of weld characteristics (Fig. 3). The specimens were cut into suitable size. Transverse section of the weld joints was polished by using standard metallographic procedure and then polished specimens were etched with mixture of dilute HF. The microstructure was studied under optical microscope (MM6, Leitz).

The mechanical properties of the weldments were studied by testing hardness (VHN) and tensile strength (MPa) of the weld metal. In order to measure the tensile strength of weld metals, 1 mm × 2 mm notch at the center of the weld was prepared to ensure the failure from weld region. The specimens were collected from the stable weld region by discarding the run-on and run-off portion of the weld (Fig. 3). The specimens for tensile strength were prepared after machining the top and root enforcement of the weld. The specimens were machined to size conforming to the relevant DIN standard. The tensile test

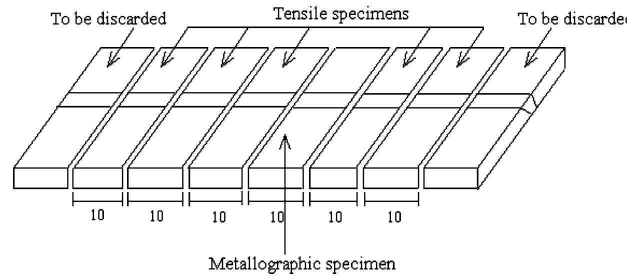

Fig. 3 Schematic diagram showing the regions wherefrom specimen were obtained for study after machining

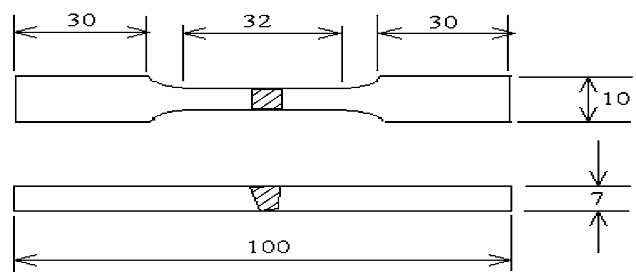

Fig. 4 Schematic diagram showing the dimensions of tensile specimen obtained by machining (all dimensions are in mm) with a notch of 1 mm × 2 mm at the weld center

specimens of both the weldment and base material conforming to DIN 50215 were obtained by machining (Fig. 4). The tensile testing was carried out on a hydraulically operated tensile testing machine, having a maximum capacity of 60 KN under static load condition. Load was uni-axially applied on the specimen at a crosshead speed of 1 mm/min. The ultimate tensile strength was determined from the ratio of maximum load and original cross-sectional area of the specimen.

Vicker's hardness measurement was carried out by using diamond indenter on the metallographically polished section of the weld joint along the central line, at a load of 5 N. The diagonal length of the indentation was measured and mean of two diagonals was used to obtain the hardness from the standard chart. Indentations were taken at three different locations on the weld, namely at center of weld, fusion zone and middle of above two. The indentations were set at an interval of 2 mm along the weld center, transverse to the direction of weld deposition.

3. Results and Discussion

3.1 Microstructure

Optical micrographs of base metal A and B are shown in Fig. 5(a) and (b). The microstructure of two 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). Larger amount of Mg_2Si along the grain boundary of alloy A was observed compared to that of alloys B (Fig. 5). Kang and Liu (Ref 2) observed that the magnesium content in the alloys greatly influences the as-cast microstructure. Higher the magnesium content greater relative

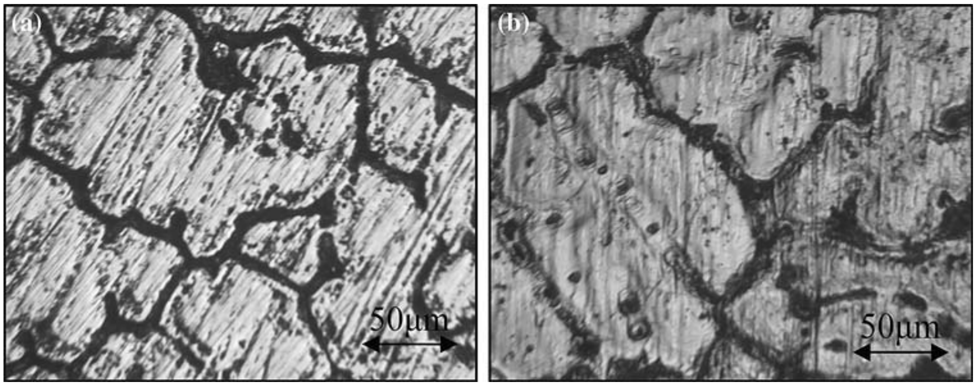

Fig. 5 Optical micrographs of base metal (a) A and (b) B alloy

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. A significant difference in microstructure of base metals A & B and weld metal was observed due to the weld thermal cycle experienced by the weld pool and the heat affect zone during welding in Fig. 6 and 7, respectively. 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. Depending upon the heat input for a given set of pulse parameters, dissolution took place to different levels. Less heat input resulted in partial dissolution of second phase particles and leaving behind some amount of these phases in form of network along the grain boundary besides a very few partially dissolved nearly spherical particle in the matrix of aluminum. Increase in heat input caused almost complete dissolution of the phases along the grain boundary and large number of round shaped particles. 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.

Microstructure study showed epitaxial growth at weld fusion boundary in almost all the weldments (Fig. 6 and 7a, d, g, j, m, p). In general, coarse columnar aluminum grains can be seen near the fusion boundary in weld metal while equiaxed grain structure was exhibited by weld metal. Pulse frequency of 50 Hz and 40% duly cycle resulted in finest grain structure in weld metal compared to other welding conditions.

The influence of pulse frequency on microstructure of weld metal is shown in Fig. 6 and 7. Increase in pulse frequency from 25 to 50 Hz refines the microstructure of weld deposit to a great extent. Aluminum solid solution (α-aluminum) was found more in HAZ, whereas fraction of low melting phases was found more in weld zone, because filler metal Al-5%Si produced larger amount of Al-Si eutectic. It was observed that the influence of duty cycle on the microstructure is determined by the pulse frequency. At low pulse frequency (25 Hz), effect of duty cycle on the microstructure of weld metal is not significant while at 33 and 50 Hz pulse frequency the effect of duty cycle is predominant. At 50 Hz pulse frequency, 40% duty produces finer aluminum grains than at 50% duty cycle while at 33 Hz pulse frequency long duty cycle (50%) produces finer grain than that for short duty cycle (40%).

Mechanical properties of Al alloys are determined by the microstructural characteristics (grain and phase structure) of phases present in alloy such as α-aluminum crystals and second phase particles/intermetallic compounds depending upon the alloying elements. The refinement of α-aluminum, eutectic mixture and other intermetallic compounds improves the mechanical properties (Ref 1). Therefore, to refine the grain structure of weld metal many techniques such as arc manipulation, inoculation, arc pulsation etc., have been developed over the years. Arc pulsation is one of most effective methods to refine the grain structure (Ref 2). As reported by Authors (Ref 3, 4), in earlier work that the mechanism of grain refinement by arc pulsation has not yet been very well established. In general, there is agreement that the grain refinement is caused by (1) the high cooling due to reduced heat input, (2) increased turbulence would encourage the fragmentation of growing dendrites/cell, and (3) surface nucleation results in a large number of nucleants in weld pool which would eventually lead to finer grains.

An increase in the relative pulse width or duty cycle increases the heat input to the weld pool which in turn increases the reversion in HAZ and decreases the grain boundary precipitation. Increase in the pulsed frequency above a critical range a distinct deterioration in the structure characteristics takes place. A fine grained structure can be achieved by using both high and low pulse frequencies which in turn leads to a beneficial quantitative distribution of grain boundary impurities (Ref 5).

3.2 Hardness

Hardness of the weld metal of alloy A and B produced by using different pulse parameter are shown in Fig. 8(a) and (b). Results showed that the effect of pulse frequency on hardness depends duty cycle. In general, the weld metals of alloy A & B produced by using 125 A back ground current, 250 A peak current and 40 and 50% duty cycle showed a continuous decrease in the hardness with increasing pulse frequency from 25 to 50 Hz. However, weldment produced by using 50% duty cycle welding conditions showed lower hardness than that of 40% duty cycle.

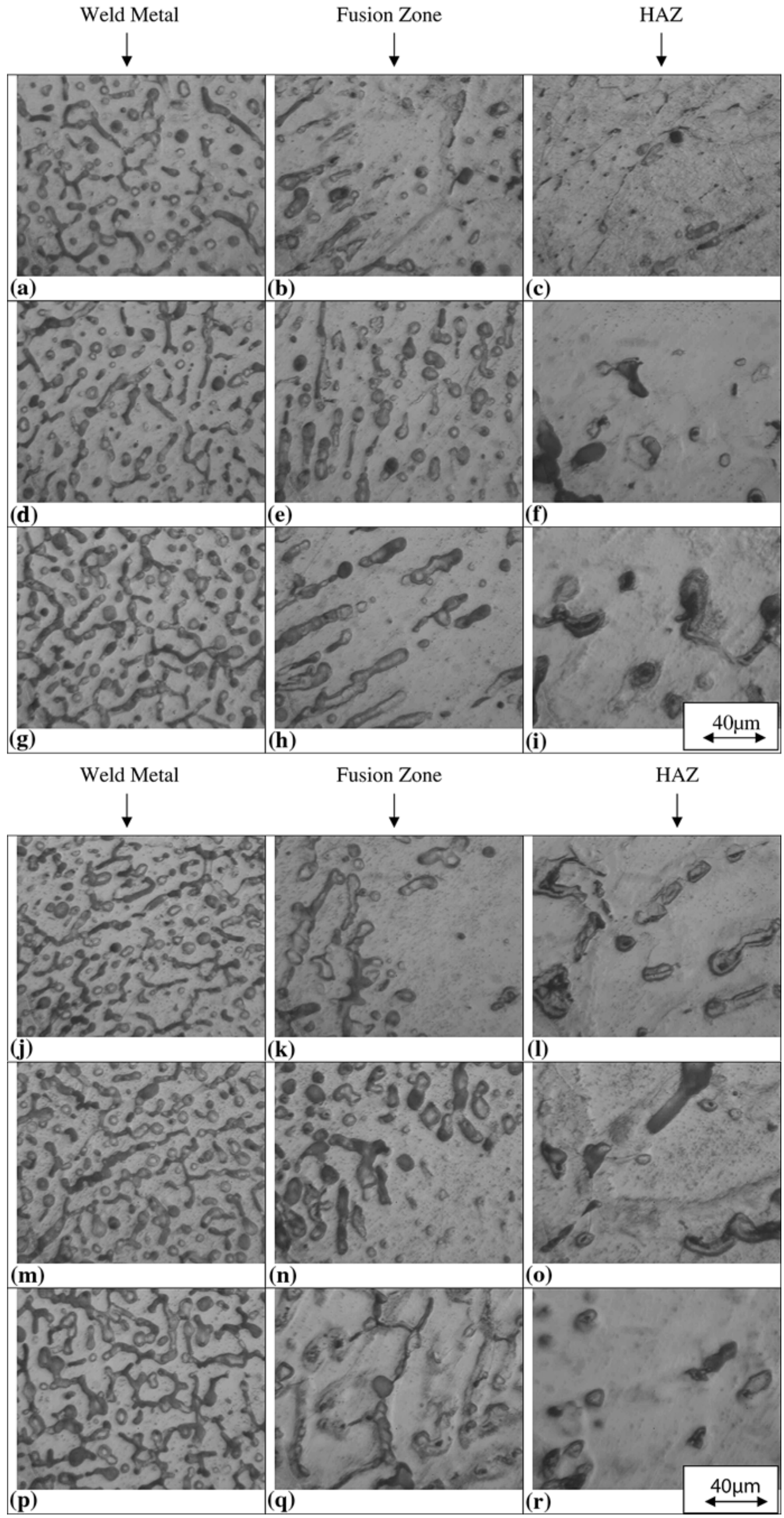

Fig. 6 Optical micrographs of alloy A at weld center, fusion boundary and HAZ of the weld joint produced by using (a-c) 25 Hz pulse frequency and 40% duty cycle, (d-f) 25 Hz pulse frequency and 50% duty cycle, (g-i) 33 Hz pulse frequency and 40% duty cycle, (j-l) 33 Hz pulse frequency and 50% duty cycle, (m-o) 50 Hz pulse frequency and 40% duty cycle, and (p-r) 50 Hz pulse frequency and 50% duty cycle

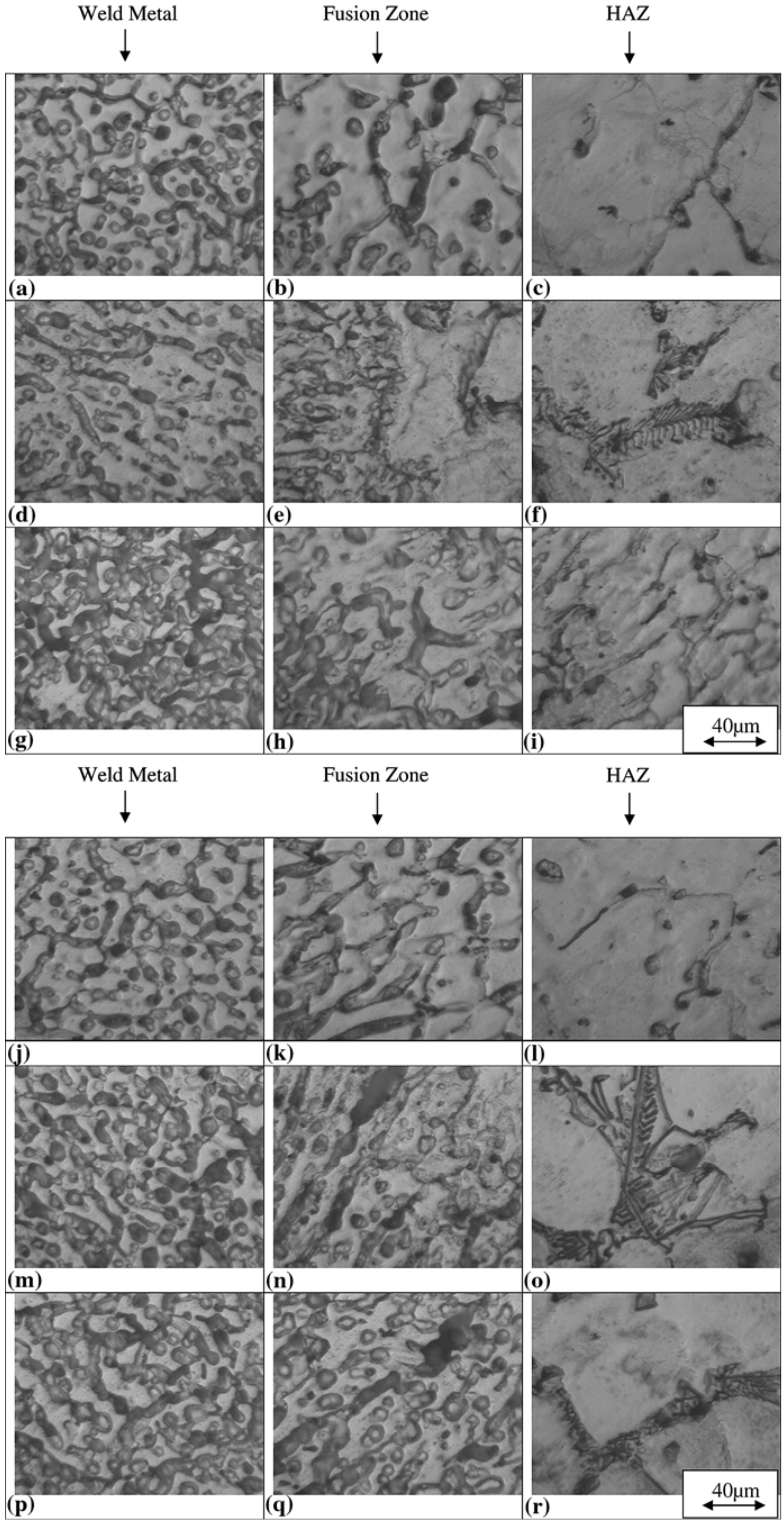

Fig. 7 Optical micrographs of alloy B at weld center, fusion boundary and HAZ of the weld joint produced by using (a-c) 25 Hz pulse frequency and 40% duty cycle, (d-f) 25 Hz pulse frequency and 50% duty cycle, (g-i) 33 Hz pulse frequency and 40% duty cycle, (j-l) 33 Hz pulse frequency and 50% duty cycle, (m-o) 50 Hz pulse frequency and 40% duty cycle, and (p-r) 50 Hz pulse frequency and 50% duty cycle

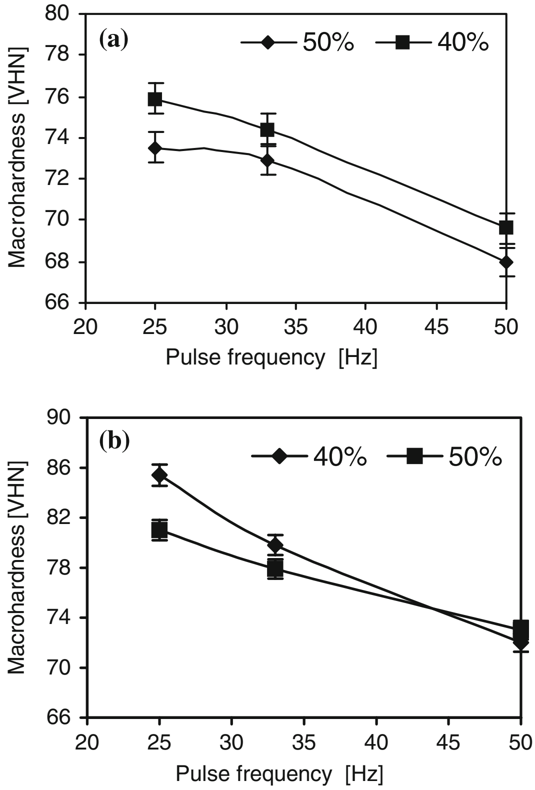

Fig. 8 Hardness of weld metal vs. pulse frequency relationship at different duty cycles of alloy (a) A and (b) B

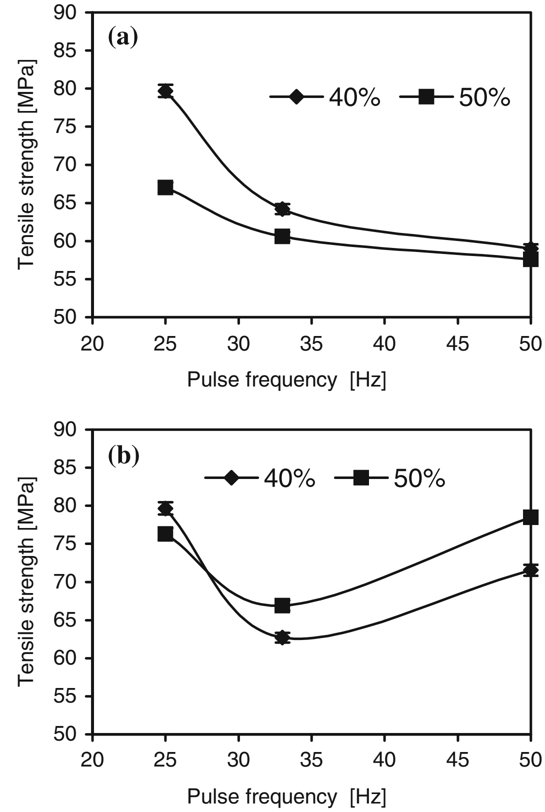

Fig. 9 Tensile strength of weld metal vs. pulse frequency relationship at different duty cycles of alloy (a) A and (b) B

3.3 Tensile Strength

Tensile strength (UTS) of weld metal of A and B alloy produced by using different set of welding conditions is shown in Fig. 9(a) and (b). Tensile tests were performed to evaluate the ultimate tensile strength (UTS). For alloy A, ultimate tensile strength was found to decrease with an increase in pulse frequency from 25 to 50 Hz at both 40 and 50% duty cycles while for alloy B, UTS was found to decrease with increase in pulse frequency from 25 to 33 Hz followed by an increase in UTS with further increase in pulse frequency from 33 to 50 Hz at both duty cycles. Ultimate tensile strength of alloys B was found higher than the alloy A in all cases except at 25 Hz and 40% duty cycle. The UTS of weld joint of alloy A produced by using 25 and 33 Hz pulse frequency and 40% duty cycle was found higher than that of 50% duty cycle. Alloy B at 50% duty cycle, showed higher UTS at 33 and 50 Hz pulse frequencies than that of 40% duty cycle. These results are also in agreement with earlier finding that the effect of the pulse frequency on mechanical properties is particularly marked and the best results with respect to mechanical properties and structures are obtained with low frequencies (Ref 6).

Failure of weld joints in most of the cases took place from the base metal. Poor strength of base metal compared to weld metal can be attributed to coarse grained as cast structure of base metal compared to that of weld metal. Therefore, reduced section & 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 (Ref 7). 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 (Ref 8). The tensile fracture of cast Al-Mg-Si alloys can be explained using the principles of fracture mechanics. The failure of these alloys is generally accepted to occur in three stages: (1) cracking of hard phases at low plastic strains; (2) as deformation proceeds, cracked particles generate localized shear bands which form micro-cracks by joining adjacent cracked particles; and (3) coalescence of micro-cracks followed by the propagation, leading to final fracture (Ref 9).

3.4 Scanning Electron Microscopic Study

Scanning electron microscopic (SEM) study of fractured surfaces tensile test specimens was carried out to investigate the mode of fracture. SEM images of fracture surface of tensile specimen of A and B alloy weld joint are shown in Fig. 10(a) and (b). Fracture surfaces of weld joints of both the alloys primarily revealed cleavage facets indicating the occurrence of brittle fracture and same is attributed to the present of large of hard second phase Mg_2Si and hard Al-Si eutectic mixture in the weldments.

4. Conclusions

The mechanical properties (hardness and tensile strength) are sensitive to microstructure of weld metal which is affected

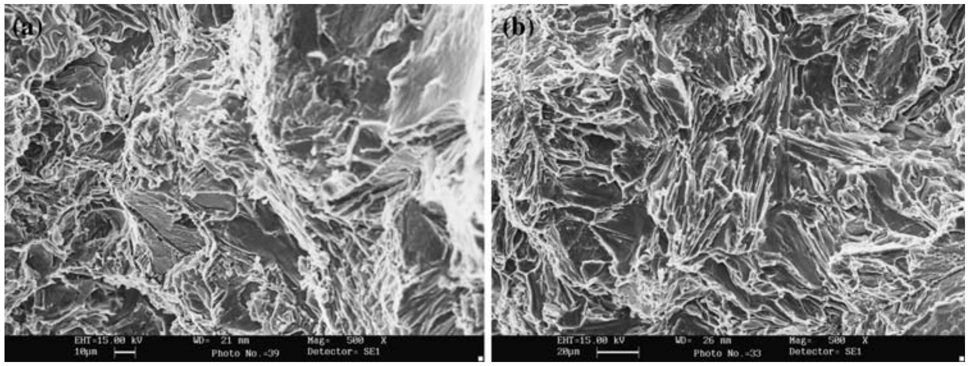

Fig. 10 SEM images of tensile fractured surfaces of weld joint specimen of alloy (a) A and (b) B produced by using 33 Hz pulse frequency and 50% duty cycle, primarily showing cleavage facets indicating the occurrence of brittle fracture

by the pulse parameters. Therefore, selection of pulse parameter for successful welding is very important. At low pulse frequency, both hardness and tensile strength were found better than those observed that higher pulse frequencies. Weld metal and HAZ were found stronger than the base metal. SEM study showed that the fracture of weldment is mostly brittle.

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