Int J Adv Manuf Technol (2008) 36:263–269
DOI 10.1007/s00170-006-0849-z

ORIGINAL ARTICLE

Microstructure and hardness of Al-Mg-Si weldments produced by pulse GTA welding

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Received: 21 April 2006 / Accepted: 19 October 2006 / Published online: 12 December 2006

Abstract This paper describes the effects of pulsed TIG welding process parameters (pulse duration, peak current, and pulse frequency) on the microstructure and microhardness of Al-0.8%Mg-0.5%Si (6061) alloys. It was observed that pulse TIG welding produced finer grain structure of weld metal than conventional TIG welding (without arc pulsation). An increase in the pulse frequency has been found to refine the aluminium and eutectic grain structure of weld metal especially when welding is done using short pulse duration. Long pulse duration lowers the pulse frequency up to which refinement of constituents in weld metal takes place. Effect of the pulse frequency on the grain structure was found to be determined by pulse duration. For a given pulse frequency, long pulse duration produced a coarser structure than short pulse duration. An increase in the peak current coarsened the grain structure.

Keywords Al-Mg-Si alloy · Microstructure · Microhardness · Pulse parameters · TIG welding · Liquation

1 Introduction

Al-Mg-Si alloys (6xxx series) are the most frequently used heat-treatable aluminium alloys. These alloys are commonly used in aerospace applications, auto-body parts, parts machined from plate or bar, and piping, among many others. The fabrication of 6000 series alloys frequently needs welding to join the structural elements. Mechanical properties and solidification cracking tendency of the Al-Mg-Si weld joint are largely governed by its microstructural characteristics apart from the mechanical constraints. The microstructure includes types of phases, their relative amounts and distribution besides grain structure. The grain structure of the weld metal shows the size, shape and the distribution of phases in the alloy. Coarse columnar grains with a large amount of low melting phases along the grain boundary increase solidification cracking tendency over fine equaixed grains with well distributed second phase particles [1]. Literature [2, 3] revealed that various techniques of grain refinement such as inoculation, mechanical and electromagnetic vibrations, surface nucleation, arc pulsation and manipulation can be used to refine the grain structure of weld metal. Recently Rao et al. [3] investigated the influence of arc manipulation techniques (pulse current welding, magnetic arc oscillation) on the grain structure and tensile properties of Al-Cu alloy (2219) weld joints produced by TIG welding and they found that 4–6 Hz pulse frequency is effective to control the grain structure. Fine and equaixed grains obtained by arc manipulation improve the tensile strength and ductility. Recently, many studies [4–13] have been conducted on various aspects of welding of heat treatable 6XXX series alloys. Huang et al. [8–12] studied the mechanism of PMZ liquation in 2219, 2024, 6061 and 7075 alloys and found that the weakening of the PMZ is due to grain boundary segregation. Literature did not reveal detailed studies on the influence of pulse parameters of TIG welding on microstructure and microhardness of Al-0.8%Mg-0.5%Si alloy (T_4) weldment. Therefore, an attempt has been made to investigate the influence of the pulse parameters such as pulse duration, pulse frequency and peak current on the microstructure and microhardness of Al-Mg-Si weld joints produced by pulse TIG welding.

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2 Experimental procedure

2.1 Materials and methods

Al-0.8%Mg-0.5%Si alloy plate of 100×50× 5 mm^3 size was used in this investigation. A-404 filler wire (Al-5%Si) of 1.6 mm diameter was used to produce weld joints. Welding was carried out using an automatic TIG welding machine (CEBORA 360). An automated device (BUG-O system) was used to get the required speed of the welding torch. The following welding conditions were maintained during the welding:

1. Electrode: 2% thoriated tungsten
2. Electrode size: 3.5 mm diameter
3. Shielding gas: Argon
4. Arc length: 2.5 mm
5. Arc travel speed: 6.1 cm/min
6. Arc voltage: 18 volts

Welding conditions used in the present investigation are shown in Table 1.

2.2 Microstructure and microhardness study

A transverse section of the weld joint was polished using a standard metallographic procedure, which consisted of grinding followed by polishing and etching. Specimens were etched with dilute HF. The microstructure of the specimens was studied under optical microscope (MM6, Leitz). Image analysis of micrographs of the weld metal was carried out using an image analysing software (Material Plus Version 4, Dewinter Optical Inc, India). For microstructure and microhardness study two specimens corresponding to each welding condition were analysed to ensure repeatability. Area fraction of different phases in the weld metal and HAZ were determined by setting the threshold value of images as per needs and determining the fraction of each phase one by one with the help of image analysis software. The microhardness (VHN) of weld metal was tested at constant load of 100 g.

Table 1 Pulse GTA welding conditions used in the present investigation

Sl. no.	Pulse duration (ms)	Pulse frequency (Hz)	Base current (Amp)	Peak current (Amp)
1	–	0	120	
2	4	25	120	160
3	4	50	120	160
4	4	100	120	160
5	6	25	120	180
6	6	50	120	180
7	6	100	120	180

3 Results

3.1 Influence of weld thermal cycle on microstructure

In general, a significant variation in the microstructure from base metal to weld center line was observed (Fig. 1). Approaching from the base metal towards the fusion boundary showed coarsening of aluminium grains (Fig. 1a–d). The base metal (Fig. 1a) showed mainly two phases, i.e. aluminium solid solution grains (light etched) and low melting temperature eutectic along the grain boundary (dark etched). The coarsening of aluminium grains was primarily observed in the HAZ (Fig. 1b). It can be seen that probably intermetallic compounds and beta phase (Mg_2Si) are present both along the grain boundary and within the grains. These phases are largely present in discrete manner along the grain boundary and are not forming networks. Cao et al. [13] also reported that eutectic of Al-Si in HAZ of 357 alloy is mostly converted into α-Al and silicon particles. However, some amount of the eutectic is left along the grain boundaries. Spherical morphology of few particles in a matrix of aluminium grains indicates the occurrence of the liquation of small second phase particles. Cracks in the HAZ and backfill can also be seen in the HAZ. Grain structure at the fusion boundary is very coarse and columnar showing that epitaxial growth has taken place. Liquation can be seen along the grain boundary in a region very close to the fusion boundary. Probably liquation is followed by solidification in both the directions parallel and perpendicular to the heat flow and this is evident from Fig. 1c. Fusion zone showed very fine equiaxed grain structure consisting of grains of aluminium solid solution and eutectic (Al-Si) mixture and beta phase along the grain boundary. Aluminium grains in the weld metal are finer than those in the base metal, HAZ and fusion boundary.

3.2 Pulse frequency and microstructure

The grain structure of the HAZ and weldments produced by conventional TIG welding was found coarser than that of pulse TIG welding. However, results showed that the pulse parameters such as pulse frequency, pulse duration and peak current affect the grain structure of weld metal appreciably. Influence of the pulse frequency on the microstructure is shown in Fig. 2a–d. The microstructure of weld metal primarily revealed aluminium grain, beta phase and eutectic (Al-Si). The low melting phases can occur both along the grain boundary and within the aluminium grains (Fig. 2). It is observed that increasing the pulse frequency from 0 to 100 Hz lowers average size of both aluminium grains and eutectic. Conventional TIG

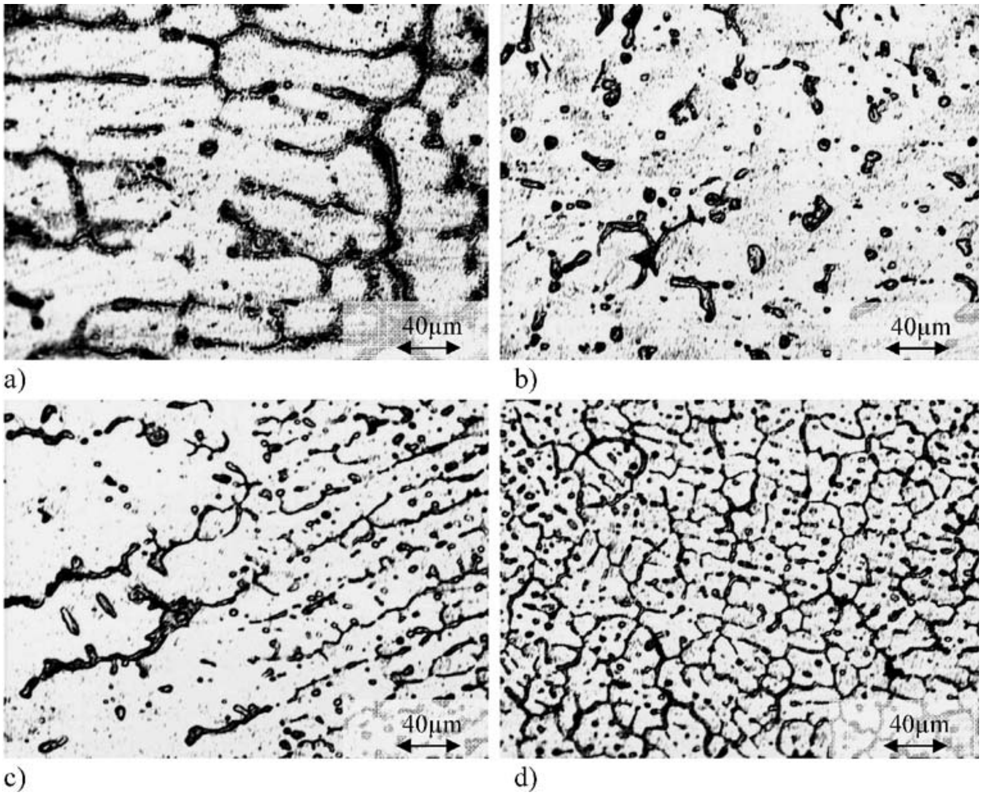


Fig. 1 Optical micrographs showing influence of the weld thermal cycle in weld joint produced without arc pulsing and 160 A welding current on the microstructure. **a** Base metal. **b** Heat affected zone. **c** Fusion boundary. **d** Weld metal

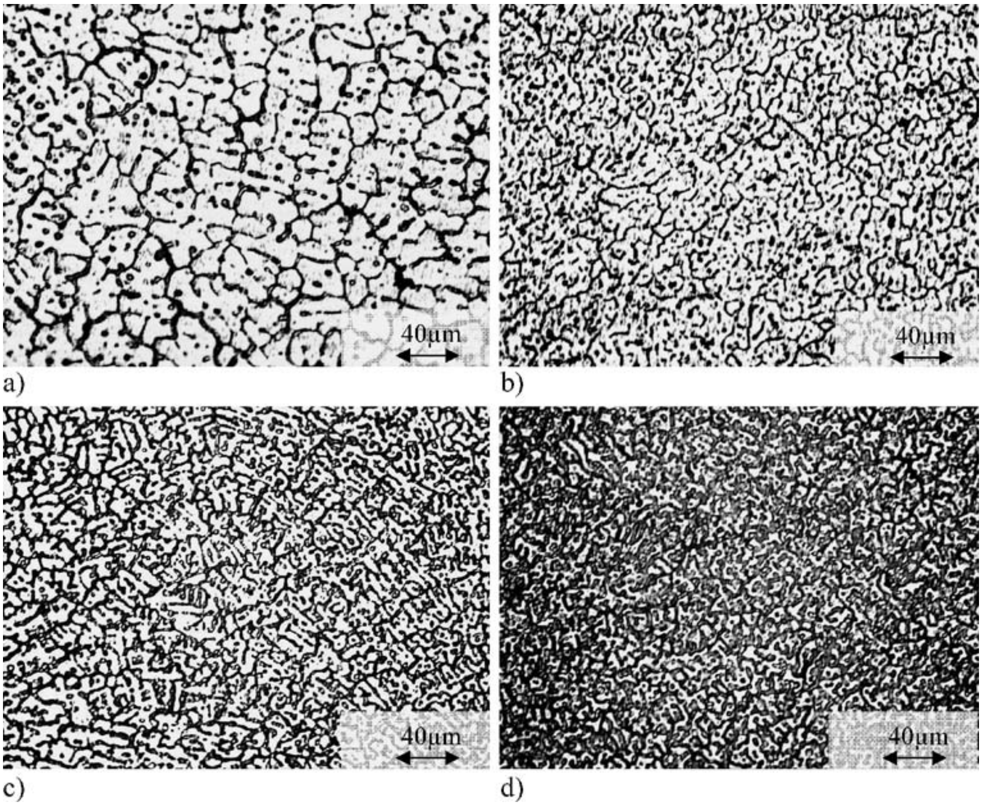
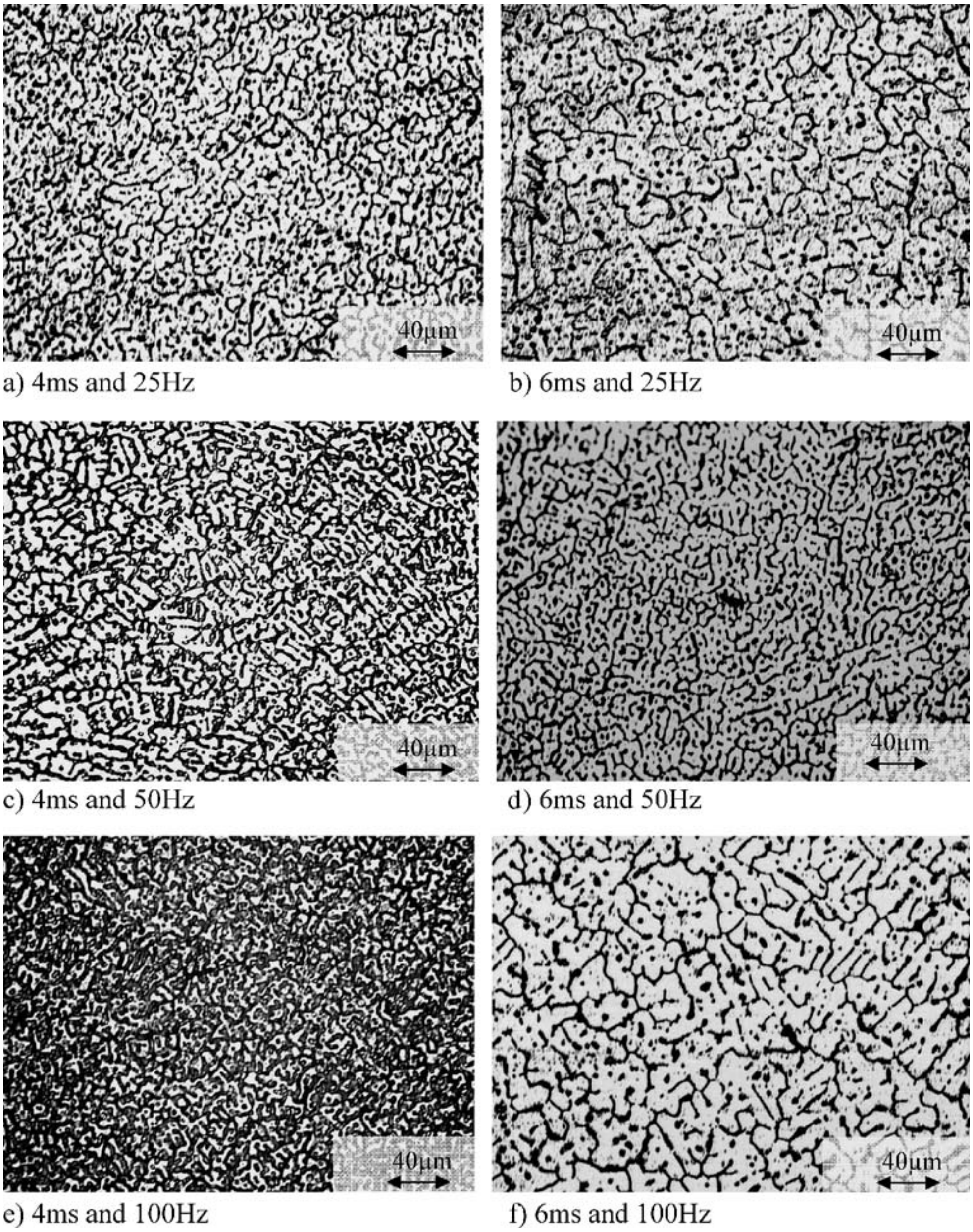


Fig. 2 Optical micrographs showing influence of the pulse frequency on the microstructure of the weld metal produced using 4 ms pulse duration and 160 A welding current. **a** 0 Hz. **b** 25 Hz. **c** 50 Hz. **d** 100 Hz

welding (without pulsing) produced aluminium grains with an average size of 50.5 μm (Fig. 2a) while pulse TIG welding at 25, 50 and 100 Hz produced aluminium grains of average size 40.2 μm, 17.8 μm and 10.2 μm, respectively (Fig. 2b–d). An increase in pulse frequency lowered area fraction of aluminium grains from 71.2% (without

Fig. 3 Optical micrographs showing the influence of pulse duration on microstructure at different pulse frequencies. **a** 4 ms and 25 Hz. **b** 6 ms and 25 Hz. **c** 4 ms and 50 Hz. **d** 6 ms and 50 Hz. **e** 4 ms and 100 Hz. **f** 6 ms and 100 Hz



a) 4ms and 25Hz

b) 6ms and 25Hz

c) 4ms and 50Hz

d) 6ms and 50Hz

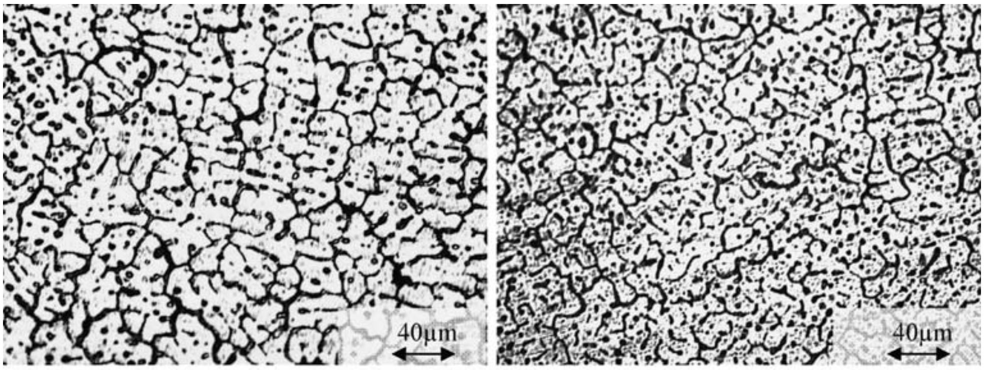
e) 4ms and 100Hz

f) 6ms and 100Hz

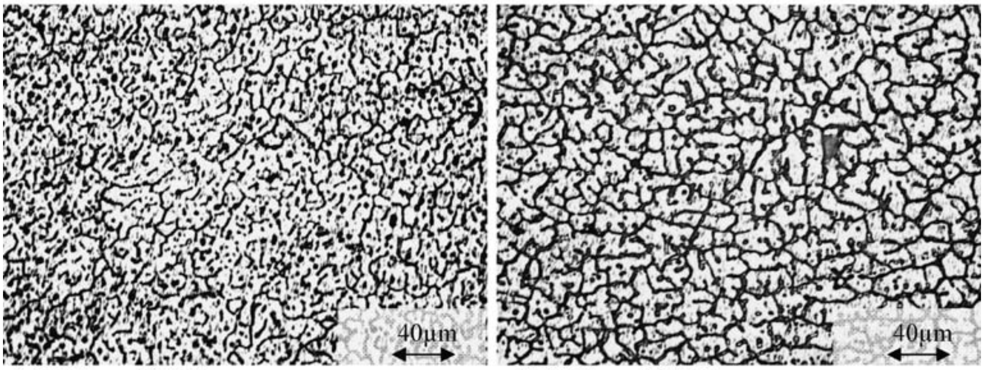
Table 2 Influence of the pulse parameter on microstructural characteristics

Sr. no.	Pulse parameters			α-Al Ave. grain size (μm)	Area fraction of α-Al (%)	Av. eutectic grain size (μm)	Area fraction of eutectic (%)
	Pulse frequency (Hz)	Pulse duration (ms)	Base current/ Peak current (A)				
1	Without pulsing		160 & 180	40.2	71.92	15.8	28.20
2	25	4	120/160	51.5	67.25	12.4	35.54
3	50	4	120/160	10	40.05	39.17	62.8
4	100	4	120/160	17.8	47.28	34.5	47.8
5	25	6	120/180	68.91	71	9	27
6	50	6	120/180	106.2	73	11.6	24
7	100	6	120/180	69.7	67	11.2	32

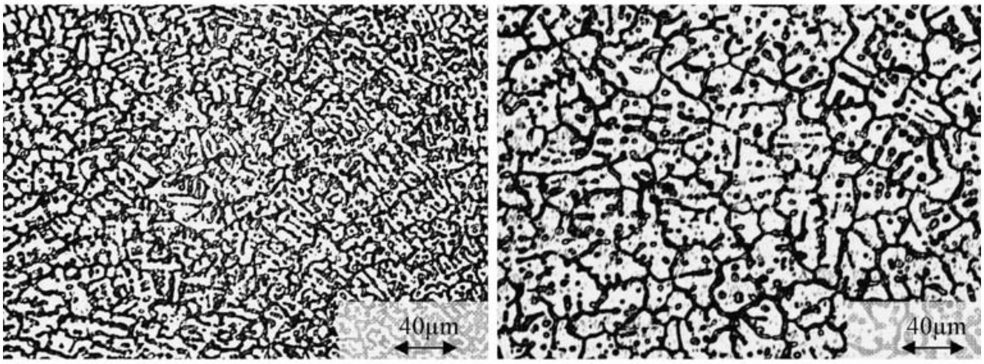
Fig. 4 Optical micrographs showing influence of peak current on the microstructure of weld metal produced using 4 ms pulse duration and different peak currents and pulse frequencies. **a** 160 A and 0 Hz. **b** 180 A and 0 Hz. **c** 160 A and 25 Hz. **d** 180 A and 25 Hz. **e** 160 A and 50 Hz. **f** 180 A and 50 Hz. **g** 160 A and 100 Hz. **h** 180 A and 100 Hz



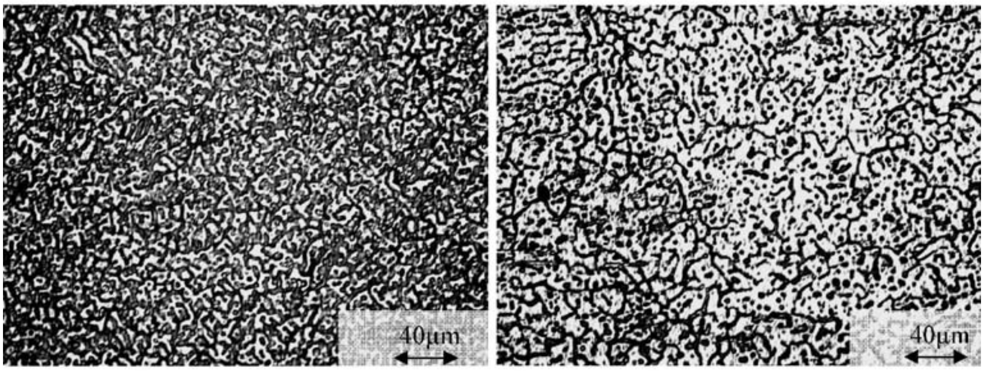
a) 160A and 0 Hz b) 180A and 0 Hz



c) 160A and 25 Hz d) 180A and 25 Hz



e) 160A and 50 Hz f) 180A and 50 Hz



g) 160A and 100 Hz h) 180A and 100 Hz

pulsing) to 40.05% (100 Hz pulse frequency). As far as eutectic is concerned, the conventional TIG welding (without pulsing) produced eutectic of average size 12.8 μm (Fig. 2a) while pulse TIG welding at 25, 50 and 100 Hz produced eutectic of average size 15.6 μm, 34.5 μm and 39.2 μm, respectively (Fig. 2b–d). An increase in the pulse frequency increased area fraction of the eutectic.

3.3 Influence of pulse duration

Weldments were produced using two pulse durations, i.e. 4 ms and 6 ms, at four pulse frequencies (0, 25, 50 and 100 Hz). The influence of the pulse duration on microstructure is shown in Fig. 3a–c. It was observed that for a given pulse frequency short pulse duration (4 ms) produced finer grain than long pulse duration (6 ms). Aluminium grains produced using 6 ms pulse duration were found coarser than conventional TIG welding (without pulsing) irrespective of pulse frequency. Microstructure of weld metal primarily revealed aluminium grains and eutectic (Al-Si). Pulse TIG welding using 4 ms and 6 ms pulse duration produced aluminium grains of average size 40.2 μm and 68.9 μm, respectively, at 25 Hz pulse frequency. A similar trend was found at 50 and 100 Hz pulse frequencies (Fig. 3a–c).

An increase in pulse duration from 4 to 6 ms increased area fraction of aluminium grains at all pulse frequencies (Table 2). Fraction and size of eutectic was marginally affected by the pulse frequency at 6 ms pulse duration.

3.4 Influence of peak current

The weldments were also made using two levels of peak currents, 160 A and 180 A, and four pulse frequencies (0, 25, 50 and 100 Hz). Influence of peak current on the microstructure is shown in Fig. 4a–h. It can be observed that for a given pulse frequency low peak current produces finer aluminium grains than high peak current.

3.5 Microhardness

Influence of the pulse frequency, pulse duration and peak current on the microhardness of weldments of an alloy under study is shown in Fig. 5. Results showed that the effect of pulse frequency on the microhardness is determined by pulse duration and peak current. The microhardness (HV_{100}) of the weld metal produced using 160 A and 180 A peak current for 4 ms pulse duration showed that increase in pulse frequency from 0 to 25 Hz decreases the microhardness followed by continuous increase in the hardness up to 100 Hz pulse frequency. Pulse frequency corresponding to peak hardness of weld metal was found to be a function of both pulse duration and peak current. For 4 ms pulse duration and 160 A peak current maximum hardness was obtained at 100 Hz while for 6 ms pulse duration and the same peak current (160 A) maximum hardness was obtained at 50 Hz pulse frequency. In general, longer pulse duration (6 ms) produced lower microhardness of the weld metal than that produced by shorter pulse duration (4 ms) especially at higher pulse frequencies (50 and 100 Hz).

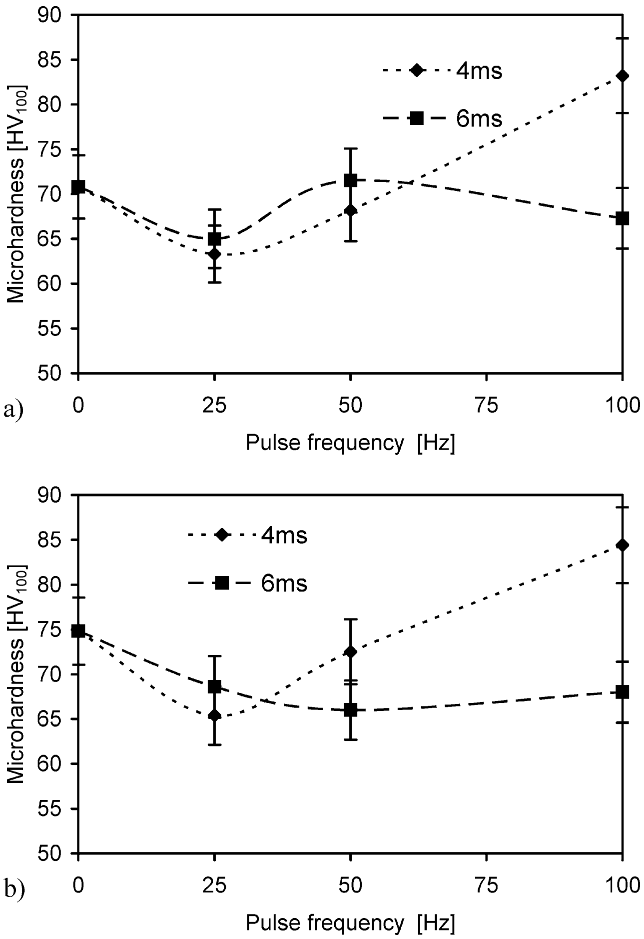


Fig. 5 Influence of pulse frequency on microhardness of weld metal produced using on microstructure. Peak current of 160 A (**a**) and 180 A (**b**)

4 Discussion

Mechanical properties of cast Al-Si-Mg alloys are predominantly governed by their microstructural characteristics such as morphology of silicon, α-aluminium and intermetallic compounds depending upon the presence of alloying elements. The refinement of α-aluminium, silicon and eutectic mixture is known to improve the mechanical properties of these alloys [1]. Various techniques such as inoculation, arc manipulation, arc pulsation, etc., are used to refine the micro-constituents of weld metal in order to enhance the mechanical properties [2]. Arc pulsation, obtained by pulsing the welding current between base current and peak current, has been found beneficial to refine the grain structure [2, 3]. However, mechanism of grain refinement by arc pulsation has not yet been very well established. Grain refinement by arc pulsing is likely attributable to three sources: (1) reduced heat input (for given penetration) increases the cooling rate which in turn results in fine structure, (2) increased turbulence created in the molten weld pool due to arc pulsation might increase the fragmentation of growing dendrites/cell and thereby provide a large number of nucleants to complete the solidification sequence, and (3) pulsing of the current between the base and peak current might cause undercooling of the liquid metal in the weld pool because net heat input to the weld pool is suddenly reduced during the base current part of pulse TIG welding. This undercooling may cause surface nucleation by producing many nucleants at the surface. These nucleants may later get distributed into the molten weld pool. A large number of nucleants produced by any means would result in grain refinement in the weld metal. Fine grain structure is known to offer better mechanical properties. In the present work, effect of three pulse parameters, namely, pulse frequency, pulse duration, and peak current on the grain structure of a Al-Mg-Si alloy weld joint has been evaluated. Results showed that these pulse parameters, i.e. pulse frequency, pulse duration, and peak current, have a tangible effect on the grain refinement.

The refinement of grain structure due to arc pulsation can be explained by the three above-mentioned reasons (reduced net heat input, turbulence in the weld pool and surface nucleation). However, effect of pulse frequency and pulse duration on the grain refinement requires separate explanations because of varying efficacy on grain refinement. The refinement of grain structure with an increase in the pulse frequency from 25 to 100 Hz (4 ms pulse duration) may be due to greater turbulence in the weld pool which would encourage the fracture of growing dendrites to provide a large number of nuclei. Increased net heat input at 6 ms pulse duration lowers the pulse frequency up to which grain refinement takes place. High net heat input above 50 Hz pulse frequency (6 ms pulse duration) can cause the grain growth due to reduced rate of solidification and increased solidification time. The influence of peak current on grain size can be simply explained using the net heat input and cooling rate concept. For a given pulse duration and pulse frequency, high peak current is known to increase heat input and lower the cooling rate encountered by the weld pool. Low cooling rate allows the grain to grow to large extent due to longer solidification time and thereby coarsen the structure. Microhardness appears to be closely related to the microstructure. In general, refinement of grain structure showed improvement in the hardness. Maximum hardness was found in the weld metal produced by using 4 ms pulse duration, 100 Hz pulse frequency and 160 A peak current and it may be attributed to the finest grain structure of the weld metal obtained for this set of welding conditions.

5 Conclusions

Arc pulsation in TIG welding produces a finer aluminium grain structure in the weld metal than welded joints produced without arc pulsation. An increase in the pulse frequency refines the grain structure of weld metal especially when welding is done using short pulse duration. Long pulse duration lowers the pulse frequency up to which refinement of constituents takes place. Influence of pulse frequency on the grain structure was found to be determined by the pulse duration. For a given pulse frequency, long pulse duration produced coarser grain structure than short pulse duration. An increase in the peak current coarsened the grain structure.

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