Light Metals 2012 *Edited by: Carlos E. Suarez*
TMS (The Minerals, Metals & Materials Society), 2012

Influence of Titanium-Boron Additions on Grain Refinement of AA2219 Gas Tungsten Arc Welds

N. Kishore Babu[1], Pan Dayou[1], Sun Zheng[1], Wei Jun[1], Mahesh Kumar Talari[2]

[1]Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075
[2]Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia
Keywords: Grain refinement, Tibor, Alternating current

Abstract

High strength AA2219 aluminum alloys have gathered wide acceptance in aeronautic and aerospace applications mainly due to their excellent mechanical properties, high corrosion resistance and good weldability. However, these alloys have poor as welded joint strength. The loss of strength is due to melting and quick resolidification, which renders all the strengthening precipitates to dissolve. One way of improving strength is through the modification of weld microstructures. The refinement of fusion zone microstructure helps in improving the mechanical properties of weld metal. The present study has investigated the influence of Tibor additions on the structure and mechanical properties of AA2219 gas tungsten arc (GTA) weldments. Full penetration GTA welds were prepared using alternating current (AC). It was observed that grain size was decreased with increasing amounts of Tibor. The observed grain refinement was shown to result in an appreciable increase in fusion zone hardness.

Keywords: Grain refinement, Tibor, AA2219 alloy

Introduction

AA2219 Aluminium alloys are attractive to automobile and aerospace industries because of high strength, high corrosion resistance and good weldability. However, these alloys have poor as welded joint strength. The loss of strength is due to melting and quick resolidification, which renders all the strengthening precipitates to dissolve.

Grain size is one of the most important factors determining the quality of weld metal because it significantly affects the mechanical properties. Weld fusion zones typically exhibit coarse columnar grains because of the prevailing thermal conditions during weld metal solidification. The grain size of weld metal can be manipulated by altering various welding parameters, such as cooling rate, or by adding alloying elements, nucleants (a grain refiner), surface nucleation induced by gas impingement and introduction of physical disturbance through techniques such as pulsed current welding and torch vibration [1]. The main advantage of fine grain size is enhanced mechanical properties such as tensile and yield strength.

Mousavi et al. [2] studied the effect of Tibor additions on the grain refinement and solidification behavior of castings and gas tungsten arc (GTA) welds of aluminum alloy 7108. They found that Tibor was a more efficient grain refiner for alloy 7108 than scandium, resulting in finer grain sizes with lower amount of grain refiner. Similarly Ramaniah et al. [3] studied the effect of grain refiners (Zr, Tibor and Sc) on partially melted zone (PMZ) of AA6061 GTA welds. They found that partially melted zone cracking tendency was improved because of grain refinement. Dvornak et al. [4] studied the effectiveness of Ti and Zr in refining the solidification structures of Al–Li–Cu alloy welds and reducing their hot cracking tendency. The improved weldability observed by them due to Ti and Zr additions was attributed to grain refinement as well as an alteration in the shape and distribution of the eutectic constituents in the weld metal microstructure. The main objective of the present paper is to study the influence of different Tibor content on microstructure and mechanical properties of AA2219 aluminum welds.

Experimental

Sheets of 3 mm thick, AA2219 Aluminium alloy in T31 condition were used in the present study. Conventional AA 2319 were used as filler metal. The chemical composition of base metal and filler metal are given in Table I. The modified filler metals (cast inserts) were prepared by adding master alloy (Al-5Ti-1B) to AA2319. The filler metal was modified with different Ti levels (0.15Ti, 0.25Ti and 0.35Ti) using casting route. In order to offset the possible dissolution of some of the grain refiner particles during welding, greater amounts of grain refiner were added in the filler. Just prior to welding, the base material coupons were wire-brushed and degreased with acetone and cast inserts were pre-placed along the weld joint and tacked. The schematic of weld preparation is shown in Figure 1.The welding parameters are given in Table II. These inserts were machined from modified 2319 filler, selected to provide a controlled variation in titanium content in the weld metal. Argon was used as the shielding gas and mixture of argon and helium (50%-50%) used for auxiliary trailing and backing gas shields. The flow rate of the shielding gas was 15 l/min and 20 l/min for the trailing and backing gas shields respectively.

The samples for light microscopy were suitably sectioned, mounted, mechanically polished and etched. For etching, a solution containing 5 ml HNO_3, 3 ml HCl, 2 ml HF in 190 ml water was used. Scanning electron micrographs were taken using a secondary electron image mode at 15 and 20 kV. A microhardness measurements were done on the base metal, heat affected zone (HAZ) and weld metal by a diamond pyramid indenter under a load of 200 g for 15 s. A microhardness traverse was made across the weldments at 0.5 mm intervals.

Table I. Composition of base metal and filler (wt %)

	Si	Cu	Fe	Mn	Mg	Zn	Ti	Zr	Al
AA2219	0.05	6.5	0.10	0.32	0.02	0.04	0.04	0.11	balance
AA2319	0.20	6.8	0.30	0.20	0.02	0.10	0.10	0.10	balance

Table II. Welding parameters

Alternating current GTA Welds			
Arc voltage	15 V	Ar Shielding gas	20 l/min
Arc current	160 A	Travel speed	20 cm/min

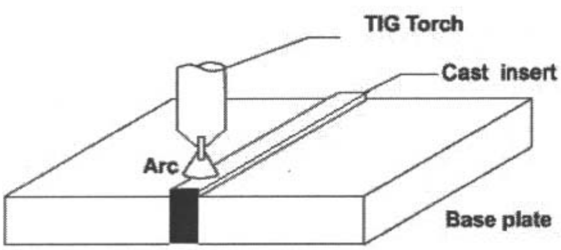

Figure 1. Schematic representation of weld preparation.

Results and Discussion

Microstructural investigation

The optical microstructure of base metal is shown in Figure 2a. The microstructure revealed round eutectic particles, distributed in the interior and along the grain boundaries of the matrix. It can be clearly seen from the SEM micrographs (Fig 2b) that the round shaped precipitates are distributed homogeneously throughout the matrix. Micro chemical analyses of these round shaped precipitates in the SEM micrograph showed that the precipitate regions are rich in Cu and Al and precipitates have been identified as $CuAl_2$. (Table III)

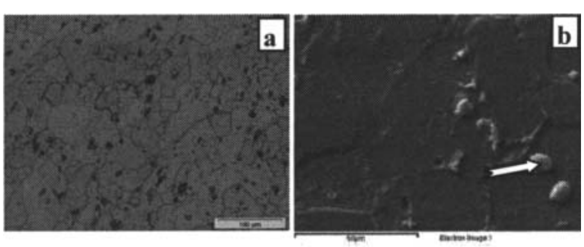

Figure 2 a) The optical and b) SEM micrographs of base metal

Table III. EDX quantification of precipitate particles in base metal

Element	Weight%	Atomic%
Al	44.52	65.39
Cu	55.48	34.61

Optical macrographs of the welds made using AA2319 filler and modified filler with 0.35% Ti are compared in Figure 3. These macrographs were taken from both top and transverse cross-sections of the welds. The fusion zone of the welds with AA2319 filler (Fig 3a and 3b) is composed of coarse columnar grains extending from the fusion boundaries to the weld center. Because of the presence of steep thermal gradients and the epitaxial nature of growth process in fusion welds, weld metal solidification often takes place in a columnar mode [5]. It can be observed from micrographs (Fig 3c and 3d), that weld metal inoculated with 0.35%Ti has resulted in not only fully equiaxed structures but also in reduced the grain size.

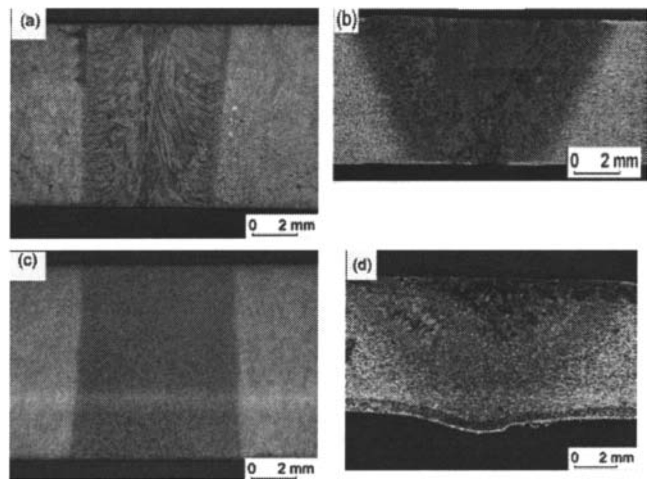

Figure 3. Optical macrostructure of GTA welded AA 2219 alloy a) AA2319 filler (top surface), b) AA2319 filler (cross-section), c) modified filler with 0.35% Ti (top surface), d) modified filler with 0.35% Ti (cross-section)

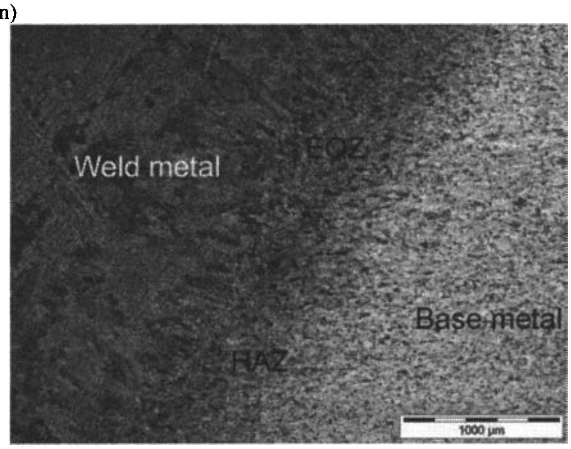

Figure 4. Optical micrograph of weld metal-base metal interface of a weld made of AA2319 filler.

Weld fusion line optical micrograph of the weld made of AA2319 filler is shown in figure 4, where weld metal exhibits the usual coarse columnar dendritic structure. A zone of fine equiaxed grains can be seen next to the fusion boundary from the micrograph. Existence of fine equiaxed zone adjacent to the fusion line was reported by earlier in Al–Li alloy welds containing Zr and the region has been called as nondendritic equiaxed zone (EQZ) [6] or the chill zone [7]. The fine grains in this region are believed to have formed by heterogeneous nucleation on particles such as Al_3Zr, which were originally present as dispersoids in the base material. These particles survive without dissolution in the region adjoining the fusion boundary because of the relatively moderate temperature and fluid flow conditions prevalent here. On the other hand, towards the centre of the weld, the higher temperatures result in particle dissolution and the usual columnar dendritic growth occurs [6].

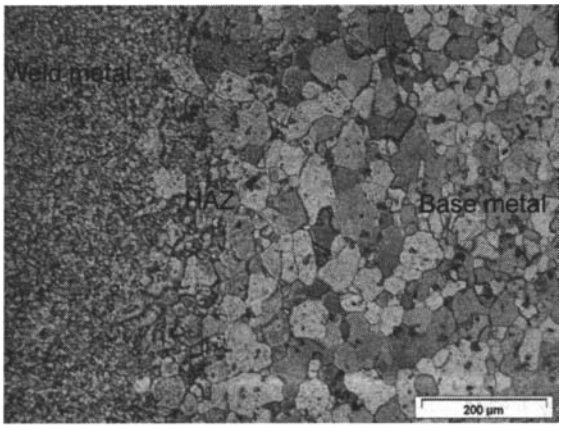

Figure 5. Optical micrograph of weld metal-base metal interface of a weld made of AA2319 + 0.35%Ti filler.

Weld fusion line optical micrograph of the weld made of AA2319+0.35%Ti filler is shown in figure 5. Fine equiaxed grain structure can be seen in the weld metal with a marginal grain growth in the HAZ adjacent to the fusion line.

Grain refining Mechanism

Many theories were proposed to explain the role of the inoculants in grain refinement of Aluminum alloys. However, there is no single theory that can explain the experimental observations related to the role of inoculants. Theories that were proposed by many researchers are summarized in the following paragraphs.

The '*peritectic theory*' proposes that when Al-Ti Master alloy, when added to the melt with hypoperitectic composition, titanium aluminide ($TiAl_3$) crystals acts as heterogeneous nucleation sites for the nucleation of equiaxed grains [8] . These $TiAl_3$ crystals dissolve very slowly with time in the aluminum melt and gives fading effect at longer holding times. This grain refining is seen to be more prominent when Boron added Ti-Al master alloy was used for refinement of Aluminum alloys. Boron was proposed to stabilize the $TiAl_3$ crystals making them more efficient in refinement process by shifting the 'liquid + TiAl3 $\rightarrow$ α-Al' to lower Ti levels. However, the thermodynamic calculations of Sigworth *et. al,* have showed that peritectic point didn't shift to lower Ti levels with the boron addition to the Ti-Al master alloy. The '*carbide-boride particle*' theory proposes that TiC and TiB_2 particles act as heterogeneous nucleation sites for the equiaxed grains in the aluminum melt [9]. These TiC and TiB_2 particles doesn't show any solubility in molten aluminum and the fading effect with the long holding times was attributed to the particle agglomeration or settling to the bottom of the melt. However, the detailed explanation of the voluminous experimental data over past 30 decades couldn't be obtained from the above theories. The performance of grain refiners, such as Al-Ti-B and Al-Ti-C, is reported to be very sensitive to the alloying elements present in aluminum, thus making the explanation of '*carbide-boride particle*' heterogeneous nucleation theory incomplete [10]. Moreover, there is always a threshold limit to the amount of Ti that can be added for the refinement and no further grain refinement was observed at higher Ti levels [11]. According to the theoretical calculations by Maxwell *et al.*, [12] the ratio between nucleating particles added per unit volume, N_V^P and the resultant number of grains per unit volume, N_V^G is 1:1 at lower N_V^P levels. But at higher N_V^P levels, N_V^G is found to be constant value i.e, not all nucleating sites were being used for the nucleation of aluminum grains. This is because the latent heat released by the growth of aluminum grains raises the temperature of the bath above the heterogeneous nucleation temperature and suppresses the further nucleation. All the above theories are categorized as nucleant paradigm where heterogeneous nucleation is the central phenomenon.

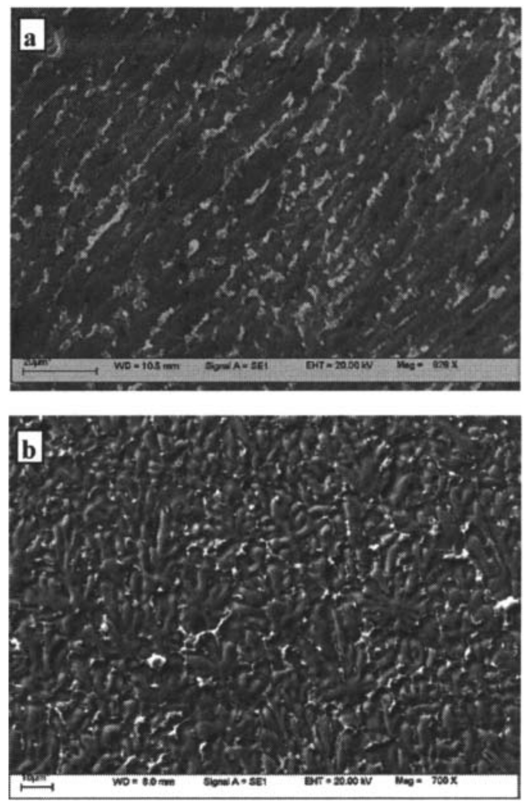

Figure 6. SEM micrographs of weld metal of the welds made using a) AA2319 filler b) AA2319 + 0.35%Ti filler

The solute paradigm incorporates the influence of solute elements on the grain refinement process [11]. According to the theory proposed by Mats Johnsson et al., [13] both additions of both the nucleant particles and the amount of segregating elements, quantified by the growth restriction factor (GRF) are important in grain refinement. The GRF may be defined as '$mC_0(k-1)$', where m is the liquidus gradient, C_0 the bulk composition, k the partition coefficient between solid and liquid. When there are more than one solute were present in the melt, GRF is calculated for each solute element separately and summed up to get the total GRF. According to the theory, the solute atoms segregate in to the liquid ahead of the growth front and results in the constitutional super cooling due to the local excess solute concentration. The segregation of the solute elements in to the liquid ahead of growth front is reported to slow down the further growth and at the same time constitutional super cooling ahead of growth front promotes nucleation of equiaxed grain on the existing nucleating particles such as TiB_2. The calculated GRF values of 3 wt% Si is 17.7 and for 0.1 % Ti is 24.5 thus addition of 0.1% Ti can restrict the growth fronts more effectively than 3% Si in the melt when added to the aluminum alloys during solidification. However, at higher concentrations, the dendrites develop lancet-like tips that grow into the liquid and reject solute orthogonally to the growth direction resulting in ineffective growth restriction [11].

Jones et al., introduces a new term hypernucleation to describe the proves of grain refinement at very low addition levels [14]. Jones proposed from his calculations that Ti atoms will segregate to the TiB2.melt interface providing excess Ti levels at the interface leading to the formation of stabilized layer of atoms on the TiB2 surface. This layer, which is Ti and Al is predicted to be stable above the melting temperature of pure Al and exists even before the beginning of the solidification. When solidification starts, such layers readily act as stable surfaces for heterogeneous nucleation. It was found that there is a low disregistry of 4.3% between α-Al and TiB2, indicating TiB2 as a good nucleant. ([11]

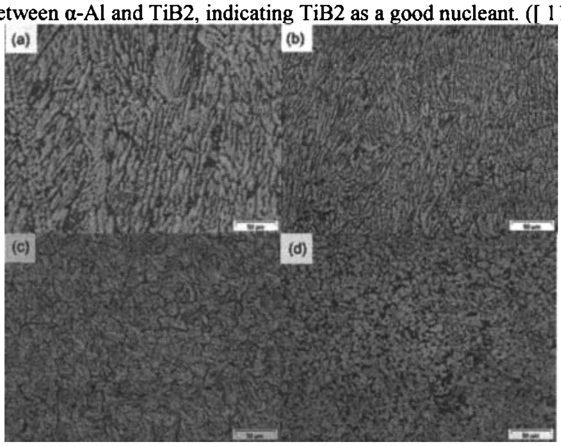

Figure 7. The fusion zone optical microstructures for AA2219 welds made using different fillers (a) AA2319, (b) AA2319+ 0.15Ti, (c) AA2319+ 0.25Ti, (d) AA2319+ 0.35Ti

Grain refinement of weld metal with Ti addition

SEM micrographs of weld metal of the welds made using AA2319 filler (6a) and AA2319 + 0.35%Ti (6b) filler are shown in Figure 6. Weld metal with AA2319 filler shows long columnar primary alpha phase grains with eutectic phase at the grain boundary, whereas, fine equiaxed grains grain structure can be seen in the weld metal micrographs with AA2319 + 0.35%Ti filler. Optical micrographs of weld metal are compared in the figure 7 for the welds made using AA2319 (7a), AA2319 + 0.15%Ti (7b), AA2319+ 0.25Ti (7c), and AA2319+ 0.35Ti (7d) fillers. The gradual transformation from columnar to equiaxed grain morphology and simultaneous reduction in grain size can be clearly seen from the micrographs with the increasing Ti addition. The effect of titanium additions on mean grain size of weld metal is shown in Figure 8. The addition of titanium in the form of modified filler caused significant grain refinement in welds. The effect of solute elements on the grain refinement is in controlling the growth of the nucleated grains and in subsequent nucleation, which has been investigated in various aluminum systems [13] and is explained in terms of the growth restriction factor (GRF). The constitutional undercooling generated by solute elements restricts grain growth by slowing diffusion of the alloying elements. The GRF values for various alloying elements in aluminum alloys are shown in Table IV. Some alloying elements, such as Ti, Ta, V and Zr have been reported to refine the pure aluminum obviously, because of the relatively larger GRF value [11].

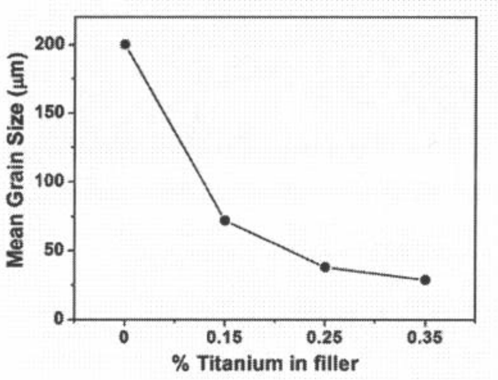

Figure 8. Variation of weld metal mean grain size with Ti content in the filler

Table IV. Segregating power of some elements in aluminum [15]

Element	K	m	(k-1)m	Max. Concentration (Wt.%)	Reaction Type
Ti	~9.0	30.7	245.6	0.15	Peritectic
Ta	2.5	70.0	105.0	0.10	Peritectic
V	4.0	10.0	30.0	~0.1	Peritectic
Hf	2.4	8.0	11.2	0.5	Peritectic
Mo	2.5	5.0	7.5	~0.1	Peritectic
Zr	2.5	4.5	6.8	0.11	Peritectic
Nb	1.5	13.3	6.6	~0.15	Peritectic
Si	0.11	-6.6	5.9	~12.6	Eutectic
Cr	2	-3.5	3.5	~0.4	Peritectic
Ni	0.007	-3.3	3.3	~6.0	Eutectic
Mg	0.51	-6.2	3.0	~3.4	Eutectic
Fe	0.02	-3.0	2.9	~1.8	Eutectic
Cu	0.17	-3.4	2.8	33.2	Eutectic
Mn	0.94	-1.6	0.1	1.9	Eutectic

Parameter m(k-1) of Ti in aluminum is 245.6 [15]. Therefore, the calculated GRF value of Ti in AA2319 weld metal is 9.82, AA2319 filler modified with 0.15Ti weld metal is 24.56, AA2319 filler modified with 0.25Ti weld metal is 46.66 and AA2319 filler modified with 0.35Ti weld metal is 71.22 in this work. Based on these results, the grain refinement of AA2219 alloy welded with different fillers are easily explained according to growth restriction mechanism. With increase in titanium content in the weld metal generates greater constitutional undercooling in a diffusion layer ahead of the advancing solid/liquid interface, which restricts grain growth since the diffusion of the solute occurs slowly, thus limiting the rate of crystal growth and hence refines the grain size[16]. In addition, further nucleation occurs in front of the interface (in the diffusion layer) because nucleants in the weld pool are more likely to survive and be activated in the constitutionally undercooled zone. In the current study, grain size was the least in the welds made using AA2319 modified with 0.35%Ti. However, at higher concentrations of titanium, the dendrites develop lancet-like tips that grow into the liquid and reject solute orthogonally to the growth direction resulting in ineffective growth restriction [11].

Microhardness

Transverse micro hardness measurements are shown in Fig. 9. The weld metal prepared using the 2319+0.35Ti cast insert exhibited higher hardness compared with other welds, and was attributed to finer grain structure associated with higher titanium content. On the other hand, a hardness reduction in the weld metal and HAZ compared with base metal is evident in all conditions. The welds prepared using the 2319 cast insert exhibited a lower hardness compared with other welds, attributed to a coarse grain structure.

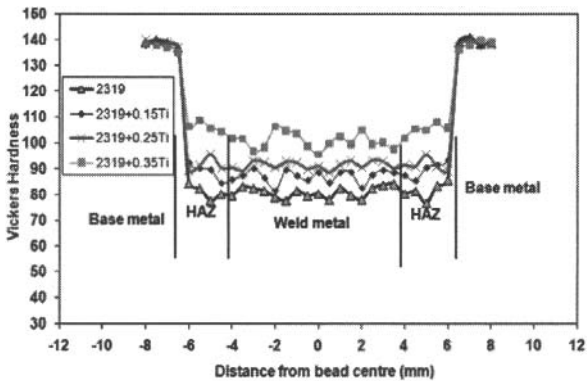

Figure 9. Transverse microhardness data for welds made from 'AA2319' and 'Ti added AA2319' fillers

Conclusions

The increase in titanium in the weld metal has resulted in grain refinement of weld metal because of the growth restriction effect caused by increased constitutional undercooling and simultaneous heterogeneous nucleation by TiB_2 particles during the solidification. Microstructural examination showed that the grain size was the least with equiaxed morphology in the welds made using the 2319+0.35Ti cast insert compared to the coarse columnar grains in the welds made from AA2319 cast insert. The welds prepared using the 2319+0.35Ti cast inserts also exhibited higher hardness compared with other welds, and was attributed to finer grain structure due to higher Ti content.

References

1. R. Wilsdorf, R. Pistor, J. J. Sixsmith, J. Huitang, Weld. J., 85 (2006) 42-43.
2. M.G. Mousavi, C.E. Cross, O. Grong, "Effect of scandium and titanium–boron on grain refinement and hot cracking of aluminium alloy 7108," Sci. Technol. Welding Joining 4 (6) (1999) 381–388.
3. N. Ramanaiah, K. S. Rao, B. Guha and K. P. Rao, "Effect of modified AA4043 filler on partially melted zone cracking of Al-alloy gas tungsten arc welds," Science and Technology of Welding and Joining 10 (5)(2005) 591-596.
4. M.J. Dvornak, R.H. Frost, D.L. Olson, "The weldability and grain refinement of Al–2.2Li–2.7Cu," Weld. J., 68 (1989) 327s–335s.
5. G.J. Davies, J.G Garland, Int. Met. Rev., 20 (1975) 83-105.
6. A. Gutierrez, J.C. Lippold, W. Lin, Mater. Sci. Forum 217–222 (1996) 1691–1696.
7. G.M. Reddy, A.A. Gokhale, K. Prasad Rao, Weld microstructure refinement in a 1441 grade Al–Li alloy, J. Mater. Sci. 32 (1997) 4117–4126
8. F. A. Crossley and L. F. Mondolfo: Trans. AIME, 191 (1951) 1143-1148.
9. A. Cibula: J. Inst. Met., 76 (50)(1949) , 321-360.
10. D. G. McCartney, "Grain refining of aluminum and its alloys using inoculants," International Materials Reviews,34 (5) (1989) 247-260.
11. T. Chandrashekar & M. K. Muralidhara & K. T. Kashyap & P. Raghothama Rao, Int J Adv Manuf Technol, 40 (2009)234–241.
12. Maxwell and A. Hellwell, Acta Metall., 23(1975) 229-237.
13. M. Johnsson , L. Z. Backerud, Metallkd 87(3) (1996) 216.
14. G. P. Jones and J.Peason: Me tall. Trans., 7B (1976) 223-234.
15. Easton M, St. John D (1999) Grain refinement of aluminium alloys: Part I. The nucleant and solute paradigms - a review of the literature. Metall Mater Trans 30A (1999)1613–1623.
16. Y.C. Lee, A.K. Dahle, DH. St John, Metall Mater Trans A, 31(2000) 2895-2906.