Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 922-927

Effect of Mechanical arc Oscillation on Partially Melted Zone (PMZ) Microstructure and Properties of AA2014 T6 TIG Welds

Biradar Nagendrappa, Mishra Saurabh, Ramalingam Raman

Department of Metallurgical Engineering & Materials Science
IIT Bombay, Powai-400076, Mumbai, India

PMZ of aluminum alloy welds is the region immediately adjacent to the fusion zone, where liquation occurs during welding because of the possibility of formation of low temperature eutectics. Liquation can occur along the grain boundary as well as in the grain interior, which will lead to inferior mechanical properties and possible liquation cracking of the substrate metal in that region. Microstructure changes in PMZ are related not only to welding techniques and welding parameters, but also depend upon the actual heat input due to welding procedures (for example, arc oscillation by mechanical means). Interestingly, hardly any studies are reported in the open literature in this respect. In the present work, effect of heat input by mechanical arc oscillation (for a defined amplitude and frequency) on PMZ microstructure and mechanical properties was studied. Two AA2014 T6 TIG single pass full penetration welds were prepared with and without arc oscillation. From this investigation, it was found that welds prepared with mechanical arc oscillation showed superior mechanical properties as compared to welds prepared without arc oscillation. A noticeable reduction in extent of liquation and change in microstructure morphology of the PMZ of the two welds were observed.

Key words: *Partially melted zone, mechanical arc oscillation, resultant velocity.*

1. Introduction

High strength aluminum alloys are invariably used as the material of choice substituting steels in aerospace and automobile industries. However, these alloys are quite difficult to weld as they crack around the weld area, i.e. adjacent to the fusion boundary during welding, which is one of the difficult problems to predict and eliminate, is a function of material characteristics, high thermal conductivity and large thermal-expansion coefficient. Furthermore, the complication of welding is due to the formation of oxide layer rapidly on the surface of these alloys; these oxides have very high melting point of ~2066 ^{o}C. Though the welding of pure aluminum and non-heat treatable aluminum alloys is well established, heat treatable aluminum alloys cannot still be welded without a significant loss in mechanical properties compared to base metals. This becomes even more evident when the base metals are in their highest possible strength (T6) obtained through precipitation process. In high strength aluminum alloys like AA2014 T6, the deterioration in strength in the vicinity of the welds is profound, resulting in inferior mechanical properties. Hence, understanding the welding of high strength aluminum alloys is crucial and there has been an increasing effort in research on the welding of these alloys [1-10].

In fusion welding of aluminum alloys with high alloying element contents, a major problem recognized is extensive melting in the PMZ [1]. The extent of melting is primarily dependent upon the welding techniques and welding parameters. The formation of PMZ during welding can be explained from Fig. 1 [1]. In AA2014 T6 alloy, partial melting can initiate at the eutectic temperature (T_E) due to constitutional liquation ($Al_2Cu + \alpha \rightarrow L$) at T_E (if Al_2Cu is still present at T_E), and melting of the residual eutectics ($Al_2Cu + \alpha$ (S) $\rightarrow Al_2Cu + \alpha$ (L)) at T_E (if eutectic is still present at T_E). Partial melting can result in liquation cracking in later stage of welding. It can result in the formation of extensive grain boundary network of brittle phase, lowering the ductility and toughness of the welds [1, 10].

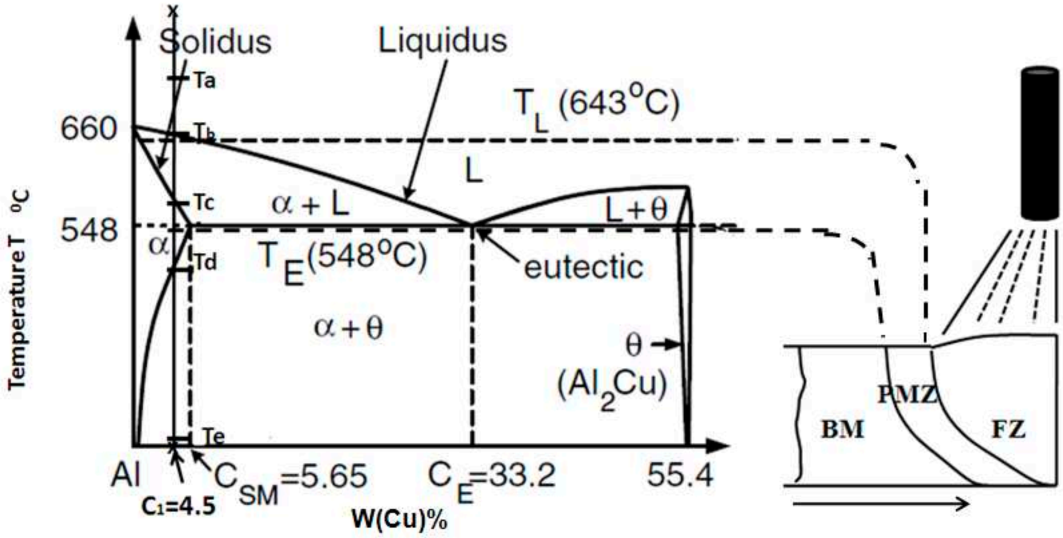

Fig.1 Illustration of PMZ formation during GTA welding of AA2014 T6

In recent past efforts have been made to minimize the extent of liquation and associated cracking in various high strength alloys using arc oscillation. Tseng and Savage [11] studied the effect of arc oscillation on microstructure and properties of autogenously GTA welds and reduced susceptibility to hot cracking in HY-80 steel welds. Garland [12] reduced the grain size and hot cracking susceptibility of Al/1.7-2.8%Mg welds by torch vibration. Kou and Le [3-5] observed significantly improved weld structure and properties, reduction in width of heat affected zone, reduction in the extent of melting of the grain boundary in the partially melted zone, and improvement in strength and ductility, due to low frequency magnetic arc oscillation during 2014 and 5052 aluminum alloy welding. Tseng and Savage [13] showed improvement in microstructure of HY-80 by both transverse and longitudinal arc oscillation electromagnetically and reported that such a beneficial effect on microstructure was also possible by arc oscillation by mechanical means for the same frequency and amplitude of oscillation. In spite of ample amount of research work on beneficial effects of arc oscillation (electro-magnetically) there is still inconsistency in reported results, which varies from material to material. In open literature hardly any claims have been made to understand the effect of heat input due to mechanical arc oscillation (MAO) on PMZ microstructure and mechanical behavior of AA2014 T6 TIG welds. As a step to understand how PMZ microstructure affects mechanical properties of aluminum alloy welds, the knowledge of microstructure evolution in PMZ is quite important. In this study examinations of PMZ microstructures of two AA2014 T6 TIG welds prepared with MAO and without MAO were conducted. The aim of this paper is to understand the effect heat input on PMZ microstructure and mechanical properties of the alloy weld using mechanical arc oscillator.

Mechanical oscillator consists of a slide assembly to which a machine torch is mounted, which slides on a linear guide rail on which a platen, riding on the linear guide rail bearing blocks, is driven back and forth. The platen is motorized via screw and ball nut assembly, which in turn is rotated by a high torque stepper motor. Suitable controls are provided to permit independent adjustment of amplitude and frequency of oscillation.

2. Experimental procedure

High-strength aluminum alloy AA2014 T6 was selected because it is severely prone to liquation cracking in the PMZ. Filler metal AA4043 (Al–6% Si) was used to weld AA2014 T6 base metal to prevent solidification cracking in the fusion zone. The chemical composition of the base metal and filler metal was determined to be: Mn-0.66%, Si-0.90%, Cu-4.49%, Fe-0.22%, Mg-0.68%, and Al remainder; and that of the filler metal was determined to be: Mn-0.01%, Si-6.0%, Cu-.094%, Fe-0.22%, Mg-0.01%, and Al remainder. Prior to welding, the base metal coupons and filler metal were mechanically brushed and thoroughly cleaned with acetone to remove the tenacious oxide layers from the surface. The welds were made in fully automatic TIG machine with an attachment of commercially available mechanical arc oscillator, Jetline make MO-150. Two AA2014 T6 TIG welds, one with mechanical arc oscillation (MAO-FPTIG) and second without arc oscillation (CC-FPTIG) were prepared. Square wave AC welding was carried out using a 2.4mm, 2% throated tungsten electrode and pure Ar shielding gas. Welding current of 190A, welding speed of 3.5mm/s, and arc gap of 3mm produced full penetration weld. Transverse arc oscillation was conducted by a mechanical arc oscillator (MO-150) with arc amplitude and frequency of 2.7mm and 1.8Hz, respectively.

Microstructure examination was carried out using a light optical microscope (OLYMPUS GX51) incorporated with an image analyzing software (OLYSIA m3). The specimens for metallographic examination were sectioned to the required size from the joint comprising weld metal, PMZ, and base metal regions and polished using different grades of emery papers. Final polishing was done using the diamond compound (1µm particle size) on the disc polishing machine. Specimens were etched with Keller's reagent to reveal the microstructure. Transverse sections of the welds were etched in Keller's reagent to reveal microstructure with scanning electron microscope (SEM). SEM micrographs were taken with secondary electron microscope (Hitachi S-3400N at 15 kV). Vickers's micro hardness tester (LM 300 AT micro-hardness tester) was used for measuring the hardness of the weld metal with a load of 100g. Several readings were taken with an interval of 25µm throughout the PMZ width; the range of PMZ hardness was reported. Width of the PMZ was measured using the micrometer inside the eyepiece of the microscope.

Subsize tensile specimens were prepared as per the ASTM E8M-04 standard to evaluate transverse tensile properties. The welded joints were sliced by wire cutting machine to obtain the required dimensions as shown in Fig. 2b. The reinforcement from the weld surface was left on all samples to know whether crack initiated in the PMZ or not. The 0.2% offset yield strength was derived from the load-displacement diagram. Optical, SEM, micro-hardness, and tensile testing were carried out on the welds prepared with and without mechanical arc oscillation, which are referred in all the figures and text by the acronyms MAO-FPTIG (with MAO) and CC-FPTIG (without MAO), respectively. Micrographs were recorded in the center of the measured PMZ with an intention to understand the effect of actual heat input on PMZ microstructure due to mechanical arc oscillation.

Table 1 Mechanical properties of base metal and welded joints

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness (VHN)	PMZ hardness (VHN)	PMZ width (mm)
BM AA2014 T6	452	478	8.86	156	--	--
CC-TIG	163	290	3.1	118	103-121	0.925
MAO-TIG	214	319	5.9	116	106-118	0.80

3. Results and discussion

3.1 Mechanical properties

In any welding, the heat input plays an important role on the tensile properties of the welds. The specific weld heat input for TIG welding is obtained by the ratio of the $Q_{nominal}$ (EI) to the linear welding speed (u). However, in MAO-FPTIG weld, the weld pool has two velocity components: one in the welding direction (u) and the other transverse to the welding direction (v). The resultant velocity (w) is greater than the velocity of the CC-FPTIG weld. In the present study the welding speed (u) of CC-FPTIG weld is 3.5mm/s. The frequency and amplitude of oscillation in MAO-FPTIG weld is 1.8Hz and 2.7mm, respectively. The amplitude of arc oscillation is defined in the present study as the maximum deflection from weld centerline. This means that arc traveled four times oscillation amplitude per second, v = (4x2.7)=10.8mm/s. Therefore, the resultant velocity w = $(u^2 + v^2) = (3.5^2 + 10.8^2)$=11.4mm/s. This significantly higher weld velocity apparently produced a higher cooling rate during solidification, resulting in a finer subgrain structure in fusion zone and less melting in the adjacent PMZ. Therefore, the mechanical properties of MAO-FPTIG weld are greatly influenced by actual heat input due to welding procedure using mechanical arc oscillation. Fig. 2a shows the result of transverse tensile testing for BM and both (CC-FPTIG and MAO-FPTIG) welds in as-welded condition. The dimensions of the test specimen are shown in Fig. 2b. Table 1 illustrates the mechanical properties of un-welded specimen (BM AA2014 T6) and welded samples prepared with (MAO-FPTIG) and without (CC-FPTIG) MAO. It is noticed that due to transverse MAO the ductility and strength of the weld increased significantly in comparison to weld prepared without arc oscillation. The improvement in mechanical properties can be attributed to the microstructure changes in PMZ and smaller PMZ width (Table 1). During tensile testing, the specimens fractured within the fusion zone (FZ) in CC-FPTIG, whereas in MAO-FPTIG, the fracture occurred more towards the FZ boundary. One of the MAO-FPTIG samples fractured along the FZ boundary ending in PMZ (Fig. 2c). Fine subgrain structure was observed in fusion zone (Fig. 4b) with fragmented boundaries with smaller dendritic arms. The interdendritic eutectic particles were more uniformly distributed as seen in Fig. 4b in comparison with Fig. 4a for CC-FPTIG weld. Similar results were reported by Kou and Le [5] when aluminum alloy 2014 was studied with magnetic arc oscillation.

The hardness was measured along the transverse direction of the weld to appreciate the microstructure changes due to heat input in both the welds. The hardness of the unaffected base metal was about 135VHN in both the welds. However, the hardness of the PMZ for CC-FPTIG and MAO-FPTIG welds were in the range of (103-121) VHN and (106-118) VHN, respectively. This suggests that PMZ hardness of MAO-FPTIG welds had been reduced to some extent. In CC-FPTIG weld (Fig. 3a and 5a), liquation was relatively more severe in PMZ and GB eutectic formation appeared to be continuous and thicker, as compared to MAO-FPTIG weld (Fig. 3b), where the GB eutectic was discontinuous, broken and thin in PMZ. The eutectic concentration at the GB was relatively less in MAO-FPTIG weld (Fig. 5b) with less grain coarsening, which can be attributed to increased cooling rate and higher thermal gradient experienced in PMZ due to mechanical arc oscillation (MAO).

3.2 Microstructure

Microstructures of both CC-FPTIG and MAO-FPTIG welds were examined at different locations of the PMZ in the vicinity of the weld. The PMZ is located immediately outside the fusion boundary (Fig. 6a). It is the area where the peak temperature during welding is below the liquidus but above the eutectic temperature, T_E. This area is characterized by the melting of the eutectic material, especially along the grain boundary and grain interior as illustrated in (Fig. 6b). Width of the PMZ was marked approximately by two dashed lines (Fig. 6a). PMZ boundary was located by a transition in morphology where dark grain boundary etching vanished. The right side line to PMZ (Fig. 6a) corresponds to the FZ boundary of the weld, i.e. Liquidus Temperature (T_L) =643 ^oC. The left side line to PMZ corresponds to the Eutectic Temperature (T_E) =548 ^oC. Fig. 6b is a high magnification micrograph showing PMZ microstructure in a CC-FPTIG weld. The weld microstructures were examined throughout the FZ boundary and its vicinity to mark the entire PMZ region. Table 1 shows that the PMZ width was more in CC-FPTIG than that in MAO-FPTIG weld.

The reduction in PMZ width of MAO-FPTIG welds can be attributed to less melting of the eutectic and higher thermal gradient experienced in the PMZ, which is due to the reduction in heat input because of an increase in resultant welding velocity. The increase in welding velocity increases the cooling rate and results in smaller weld pool and narrower PMZ. Furthermore, lower heat input in MAO-FPTIG weld may result in a smaller heat-affected zone (HAZ), which in turn causes a narrower PMZ [6].

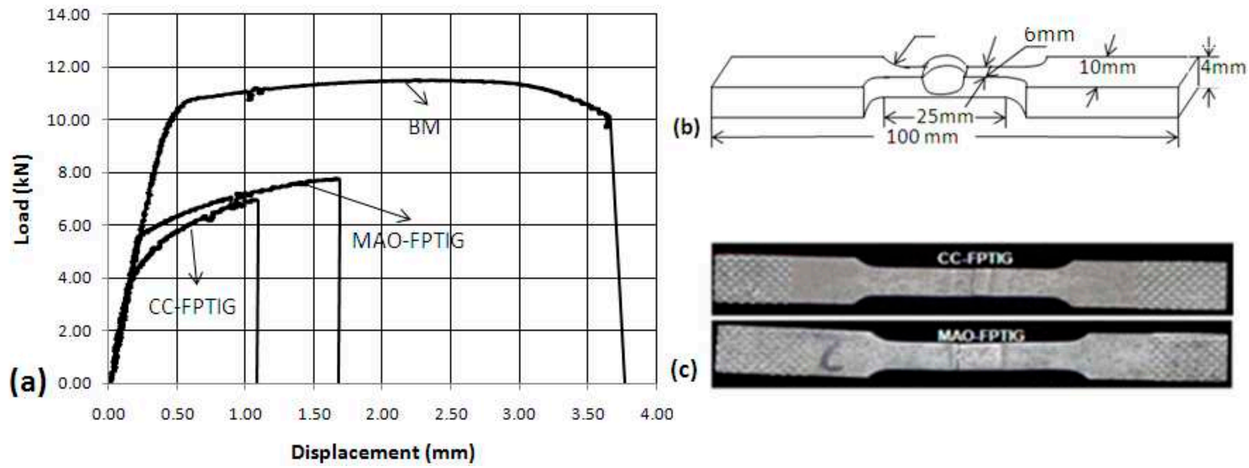

Fig.2 a) Tensile testing results for welds (CC-FPTIG & MAO-FPTIG) and base metal AA2104 T6, b) Sub-size tensile specimen, and c) Location of fracture in AA2014 T6 welds

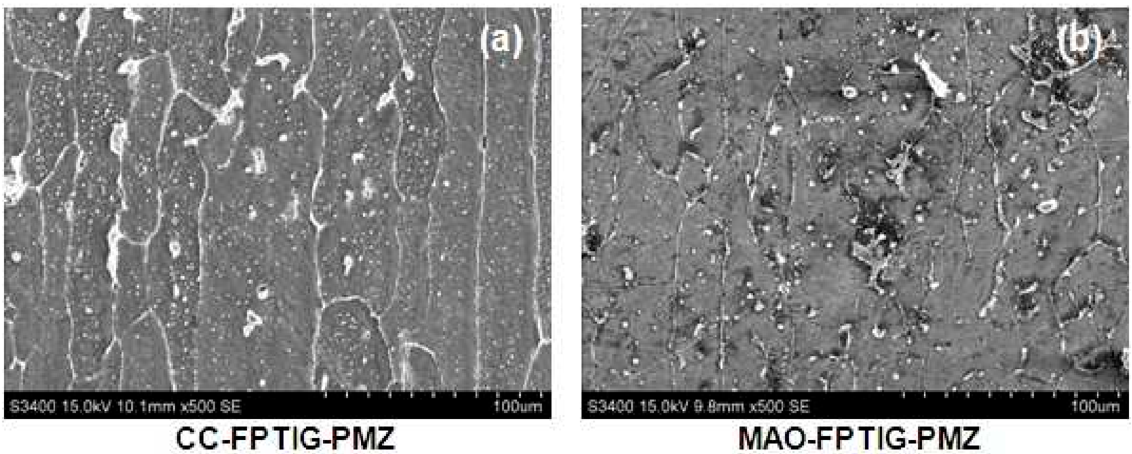

Fig. 3 SEM micrographs showing comparison in grain boundary melting in the PMZ between two welds made (a) without arc oscillation and(b) with transverse MAO (1.8 Hz, 2.7mm).

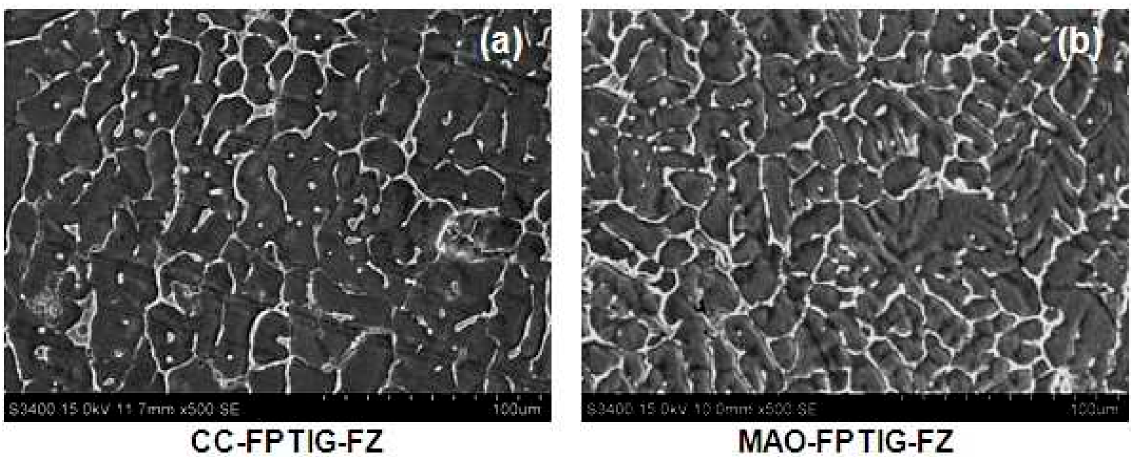

Fig. 4 SEM micrographs showing comparison of fusion zone (FZ) microstructure between two welds made (a) without arc oscillation and (b) with transverse MAO (1.8Hz, 2.7mm).

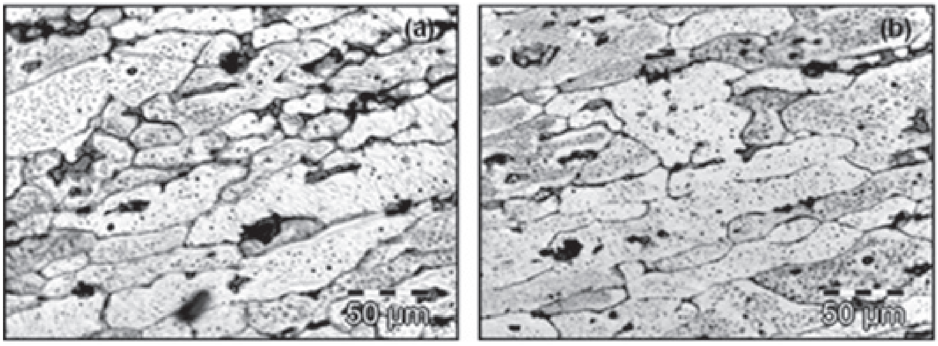

Fig. 5 Optical micrographs; a) CC-FPTIG and b) MAO-FPTIG welds

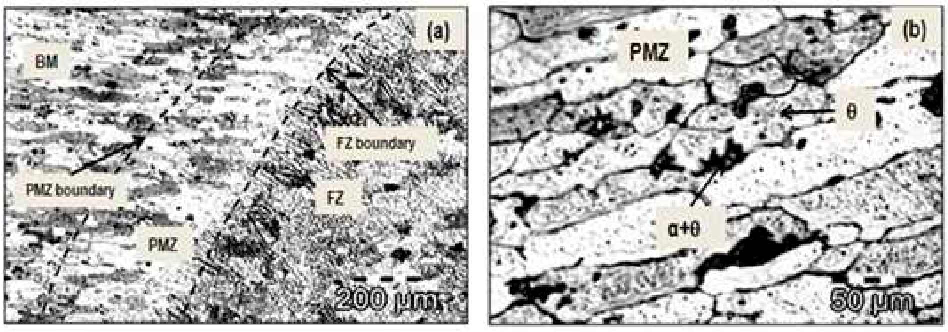

Fig. 6 Optical micrographs: a) CC-FPTIG showing distinct weld regions b) PMZ microstructure at high magnification

Conclusions

From the present study the following conclusions can be derived.

1. The weld made using mechanical arc oscillation (MAO-FPTIG) exhibited higher strength and ductility, and the enhancement in UTS and ductility was approximately 10% and 47%, respectively.
2. MAO-FPTIG weld showed lower range in hardness values (106-118) VHN as compared to the weld made without mechanical arc oscillation (CC-FPTIG) (103-121) VHN.
3. Extent of PMZ liquation along the grain boundary and within the grains was appreciably less in MAO-FPTIG weld with narrower PMZ width.

Acknowledgment

The authors would like to thank Indian Space Research Organization (ISRO), Trivandrum, India for providing AA2014 T6 alloy.

References

[1] C. Huang and S. Kou, Welding Journal 80 (2001), 9s-17s.
[2] C. Huang and S. Kou, Welding Journal 83 (2004), 50s-58s.
[3] S. Kou and Y. Le, Metallurgical Transactions A 16 (1985), 1888-1895.
[4] S. Kou and Y. Le, Metallurgical Transactions A 16 (1985), 1345-1352.
[5] S. Kou and Y. Le, Welding Journal 64 (1985), 51s-55s.
[6] C. Huang and S. Kou, Welding Journal 83 (2004), 50s-58s.
[7] C. Huang and S. Kou, Welding Journal 82 (2003), 184s -194s.
[8] G. Cao and S. Kou, Welding Journal 84 (2005), 63s-71s.
[9] K. S. Rao, G. M. Reddy & K. P. Rao, Materials Science & Engineering A 403 (2005), 69-76.
[10] C. Huang and S. Kou, Welding Journal 80 (2001), 46s-53s.
[11] C. Tseng and W. F. Savage, Welding Journal 50 (1971), 777s.
[12] J. G. Garland, Metal Construction and British Welding 21 (1974), 121-127.
[13] C. F. Tseng and W. F. Savage, Welding Journal 49 (1971), 777s-785s.