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Partially Melted Zone in A356 Al-Si Alloy Welds-Effect of Technique and Prior Condition

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Abstract:- Pressure die cast A356 Al-Si alloy with strontium modification was fusion welded by the continuous current gas tungsten arc welding (CCGTAW) and pulsed current gas tungsten arc welding(PCGTAW) techniques. Partially melted zone (PMZ) is an important region, as it is the weak link in the weldments. It is significantly affected by the welding techniques used and prior condition of the alloy. In the present work, effect of welding techniques on PMZ of A356 Al-Si alloy was studied. Microstructural changes in PMZ are related to the welding techniques. Susceptibility to liquation was found to be less in the weld made in as cast condition compared to that of artificially aged condition (T6). Resistance to liquation in PMZ was found to be better in as cast condition of the alloy with pulsed current gas tungsten arc welding, when compared to continuous current gas tungsten arc welding technique.

I. INTRODUCTION

Cast aluminium alloys are most widely used for automotive industries. The mechanical properties of cast aluminum alloys are largely dependent upon the solidification microstructure of the alloys [1, 2]. Many authors have studied the microstructure of A356 and the effects of additives on the mechanical behavior of the alloy. Liu and Kim observed α-Al plus several morphologically distinct intermetallic constituents as well as Si phase in the α-Al inter dendritic regions of the cast alloy [3, 4]. The β (AlB5BFeSi) phase generally appeared with platelet morphology [4]. The intermetallic compound π (AlB8BSiB6BMgB3BFe) appeared as typical lamellar or “Chinese-script” structure [4, 5]. MgB2BSi phase, with a Chinese script structure, was also observed in the inter- dendritic regions [4, 6]. These intermetallic phases were all the products of eutectic reactions [7]. Following reactions occur in the system as the alloy is cooled, although the formation of each intermetallic depends on cooling rate and amounts of each constituting elements
[4, 5].

Development of Dendritic network (T = 614^{O}PPC)………….(1)
Liq. → Al + AlB15B(Mn,Fe)B3BSiB2 B(T = 594^{O}PPC) ………………(2a)B
Liq. → Al + AlB5BFeSi + AlB15B(Mn,Fe)B3BSiB2B (T = 594P ^{O}PC) …..(2b)
Liq → Al +Si (T= 577C) ....(3)
Liq. → Al + Si + AlB5BFeSi (T = 575P ^{O}PC) …………………….(4)
Liq. → Al + Si + MgB2BSi (T = 555P ^{O}PC) …………………….…(5)
Liq. → Al + Si + MgB2BSi + AlB8BSiB6BMgB3BFe (T = 554P ^{O}PC) …….(6)

The partially melted zone (PMZ) is a region immediately outside the weld metal where liquation can occur during welding and lead to hot cracking and degradation of mechanical properties [8]. Intermetallic phases present in the alloys induce liquation in the PMZ by the eutectic reaction with surrounding matrix. Formation of type of inter metallics in Al-alloys is mainly controlled by the alloying elements and thermal temper. However, besides Mg and Si also other elements such as Fe (0.8%) and Mn (0.8%) can be present. Since Fe has a very low solubility in the Al-matrix, almost all Fe present in the alloy will bind with the excess of Si and the abundant Al to form typically one volume percent of Fe-containing inter metallics [9]. During solidification, these inter metallics form at the edges of the aluminum dendrites by an eutectic reaction, which explains their plate like shape.

II. EXPERIMENT

Low pressure Die cast A356 Al-Si alloy plates of thickness 10mm in as cast and T-6 (Solution treatment at 530^{O}C-1 hour and aged at 140^{O}C-8 hours) condition are being used. Chemical composition of the base metal is given in the Table.1. Welding was done with on bead gas-tungsten arc welding. In GTA welding both continuous current and pulsed current techniques are used. In all cases bead-on plate welds were made. The common welding parameters used in continuous current mode (CC) are 150mm/min-welding speed, 28cft gas flow rate, 225A welding current and 10-12V arc voltage. The welding parameters used in Pulsed current mode (PC) are Ip/Ib- 300/150, tp/tb - 50%, frequency - 6Hz and speed-150 mm/min. The samples of base metal and welds with PMZ were polished on emery papers and disc cloth to remove the very fine scratches. Polished surfaces are etched with HF reagent. Optical microscopy (OM) and scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) has been done on the top surface of the weld. The locations PMZ where the microstructures are taken on top surface and is shown in fig.1.The microstructures were recorded with Image analyzer attached to the Metallurgical microscope and are given in the Figs 2,3,4,6(a),7(a),8(a) and 9(a). The SEM-EDS of the PMZ in different conditions are given in figs. 6(b), 7(b), 8(b) & 9(b) and also in tables 5-8. The thickness of the PMZ is measured by inserting micrometer in image analyzer and are given in Table-2. Vickers hardness testing has been carried out on weld and PMZ areas of the samples with 5 kgf load and 15 sec. dwelling time. Nearly 10 to 12 readings were taken and the range of hardness was reported and are given in the Tables. 3 & 4.

III. RESULTS AND DISCUSSIONS

LIQUATION IN PARTIALLY MELTED ZONE OF A356 GTA WELDS

Optical micrographs of the base metals are shown in the Fig.2. Micrographs reveal that more number of Si-rich particles are present in artificially aged (T6) alloy when compared to that of as cast alloy. Overview of the PMZ adjacent to weld metal and HAZ was shown in optical micrograph given Fig.3 Heat affected zone was observed near the fusion line as shown in the optical micrographs (Fig. 3). The temperatures within which partially melted zone occurs are shown in fig.5. It can be observed that coarsened dendrites occurred adjacent to the fusion line. Coarsening of denbrites indicated partial melting of A356 alloy GTA welds. Optical micrographs of A356-T6 GTA weld show clearly the dark etched dendritic boundaries indicating the liquation in the PMZ. Grain boundary filled with eutectic liquid can be seen in the optical micrographs.This suggests that in PMZ silicon rich particles react eutectically with surrounding α matrix to become liquid and formlarge eutectics upon solidification. The source of liquation could be due to liquid penetration. In general aluminium liquids that are richer in silicon are considered to be more fluid and penetration should be easier for the A356 alloy and lower solidus temperature of the alloy might have promoted liquid penetration to the HAZ for a longer distance [23].

Recently Huang C and Kou [11] proposed three different liquation mechanisms in the partial melted zone of wrought multi-component aluminum alloys during welding. For alloys behind the solid solubility limit, liquation-induced particles react with α matrix and liquation can occur at any heating rate (Mechanism I). For alloys within the limit but with liquation induced particles, liquation requires high heating rate (Mechanism II). For alloys within the limit and without such particles, liquation occurs when the aluminum starts to melt (Mechanism III). Liquation causing particles in the alloy 6061 are proposed in their study are not Mg_2Si but Silicon rich particles with varying Mg,Cu and Zn contents. Fe-rich particles do not appear to cause liquation. The eutectic particles identified in the PMZ are not Al-Mg_2Si eutectic particles, but eutectic particles consisting of Si-rich and Fe-rich phases. The formation of PMZ inA356 alloys can be explained from the portion of Al-SI phase diagram which is shown in Fig.5. The material at portion b is heated up to between the eutectic temperature (577^{0}c) and liquidus temperature (637^{0}c) during welding. The material becomes a solid plus liquid mixture (α + L), a partial melted zone. Liquation occurs by reaction α + θ →L and this liquid is of the eutectic composition $C_{E.}$ Upon cooling this liquid solidifies into the eutectic particles and rain boundary eutectic. Hence the possible eutectic reactions causing liquation in PMZ of the A356 GTA welds .of the present investigation are as follows.

α + AlB15B(Mn,Fe)B3BSiB2 → L B(T = 594^{O}PPC) ………………(7a)B
α + AlB5BFeSi + AlB15B(Mn,Fe)B3BSiB2 → L
(T = 594P ^{O}PC) …..(7b)
α +Si → L (T= 577C) ....(8)
α + Si + AlB5BfeSi → L (T = 575P ^{O}PC) …………………….(9)
α + Si + MgB2Bsi → L (T = 555P ^{O}PC) ………………….….(10)
α + Si + MgB2BSi + AlB8BSiB6BMgB3Bfe → L (T = 554P ^{O}PC) …….(11)

Evidence of liquation was clearly seen in optical micrographs of the PMZ ofA356-T6-CC-GTA welds (Fig.3). The presence of the substantial amounts of the eutectic metal at grain boundaries caused embrittlement in the partially melted zone after welding. SEM-EDS shown in Fig. 6(a) and Table 5 indicated the silicon enrichment of the particles at the areas prone to liquation.

IV. EFFECT OF PRIOR CONDITION ON LIQUATION IN PMZ

In the present work optical observation (Figs.3 & 4 and Table-2) of the PMZ areas of the welds shown that grain boundary melting and coarsening of PMZ is severe in T-6 condition compared to that of as cast condition. Coarser grain size of PMZ in T6-condition, when compared to that of as cast condition (figs.-7 & 8) may be due to higher concentration of Silicon and magnesium at the grain boundaries. Silicon rich particles are more in T-6 condition of the alloy. Higher concentration of Mg and Si at grain boundaries could lower the solidus temperature locally and make the grain boundaries more susceptible to liquation during welding. It is also evident from Scanning Electron Microscopy- Energy dispersive spectroscopy (SEM-EDS) studies (Figs.7(b),9(a) and Table-6 & 8) that Silicon rich eutectic is more at the GBs of PMZ in the welds of T6 compared to that of as cast condition. From the previous studies, it was observed in casting that fine-grained materials are less susceptible to solidification cracking than coarse-grained materials [26]. This is due to the fact that in fine- grained materials low melting point segregates tend to be distributed over a larger grain boundary area, and therefore, becomes less harmful.

V. CONCLUSIONS

Eutectic reaction of excess silicon rich particles with surrounding α- matrix causes liquation in GTA welds of Alloy A356.Grain coarsening and melting in PMZ is more when the Alloy A356 is GTA welded in T-6 temper than in as cast condition. Pulsed current GTAW has reduced the liquation in partially melted zone of Alloy A356 welds compared to that of Continuous current GTAW. Prior thermal temper and the welding technique play an important role in the liquation of partially melted zone of the heat treatable Aluminium alloy GTA welds.

Table-1 Composition and constituents of the base metal A356

Element	Mg	Si	Fe	Mn	Ni	Sr	Ti	Available Si
Weight(%)	0.25-0.45	6.5-7.5	0.12	0.10	0.05	0.05	0.05	6.92

Table-2 Width of the PMZ formed during welding of A356 alloy (microns)

Process	as cast condition	T6 condition
CCGTAW	390	420
PCGTAW	280	310

Table-3 Vickers Hardness Values of A356 alloy CCGTA welds

Prior Condition	PMZ	Base Metal
As Cast	86-90	67-70
T6	90-95	87-90

Table-4 Vickers Hardness Values of A356 alloy PCGTA welds

Prior Condition	PMZ	Base Metal
As Cast	75-82	67-70
T6	89-91	87-90

Table-5 EDS of Grain Boundary(P1) and Matrix (P2) CCGTA welded A356 alloy in as cast condition

Element	Mg K	Al K	Si K	Ti K	Fe K	Sr L
P1	0.05	18.51	79.56	0.04	0.33	1.45
P2	0.45	98.11	1.20	0.16	0.08	--

Table-6 EDS of Grain Boundary(P1) and Matrix (P2) PCGTA welded A356 alloy in as cast condition

Element	Mg K	Al K	Si K	Ti K	Fe K	Sr L
P1	0.36	81.34	16.66	--	0.91	0.73
P2	0.43	94.29	4.95	0.06	--	0.27

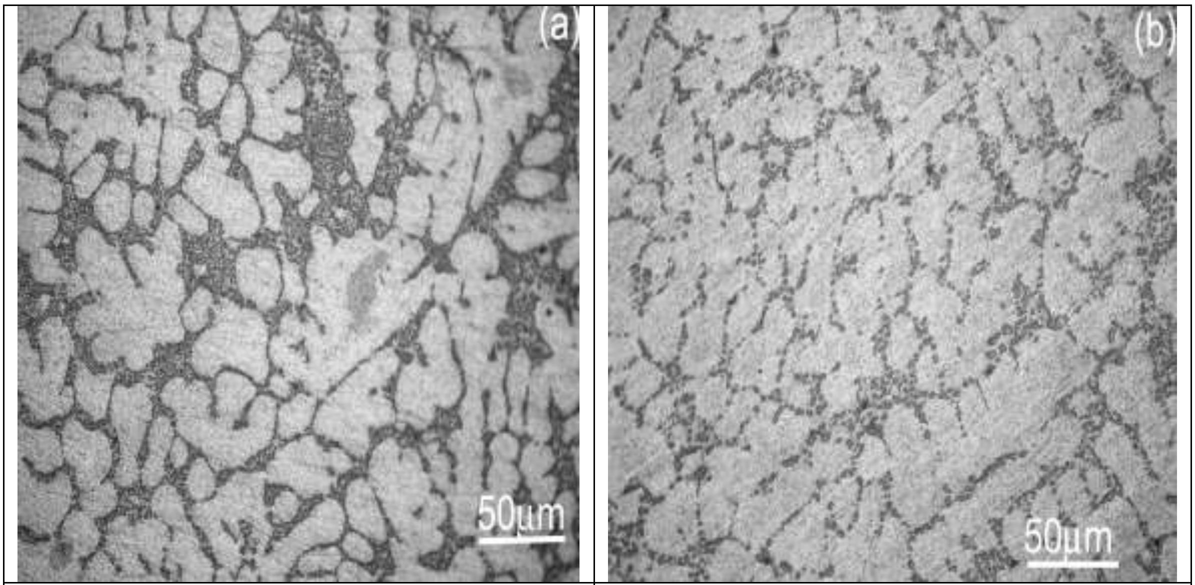
Table-7 EDS of Grain Boundary(P1) and Matrix (P2) CCGTA welded A356 alloy in T6 condition

Element	Mg K	Al K	Si K	Ti K	Fe K	Sr L	Mn K
P1	--	17.47	81.64	0.28	0.02	0.00	0.59
P2	0.60	93.93	2.31	0.66	0.05	2.33	0.12

Table-8 EDS of Grain Boundary(P1) and Matrix (P2) PCGTA welded A356 alloy in T6 condition

Element	Mg K	Al K	Si K	Ti K	Fe K	Sr L
P1	0.11	21.13	78.39	--	0.37	--
P2	0.11	97.29	1.34	0.30	0.48	0.48

Fig.1 Locations of the PMZ in welds where microscopy is done.



(a) As cast condition	(b) T-6 condition

Fig.2 Microphotographs of base metal A356 alloy.

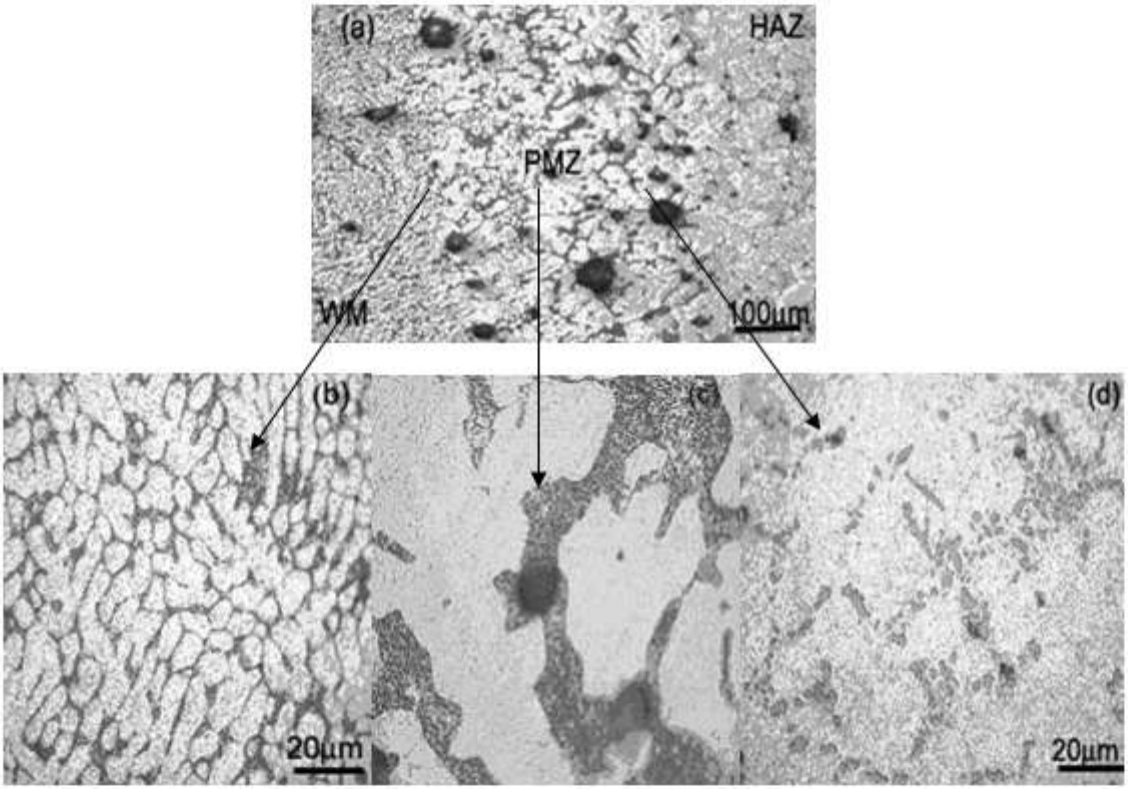


Fig.3 Microphotographs of WM, PMZ & HAZ in A356 alloy CCGTA weld in T6 condition.

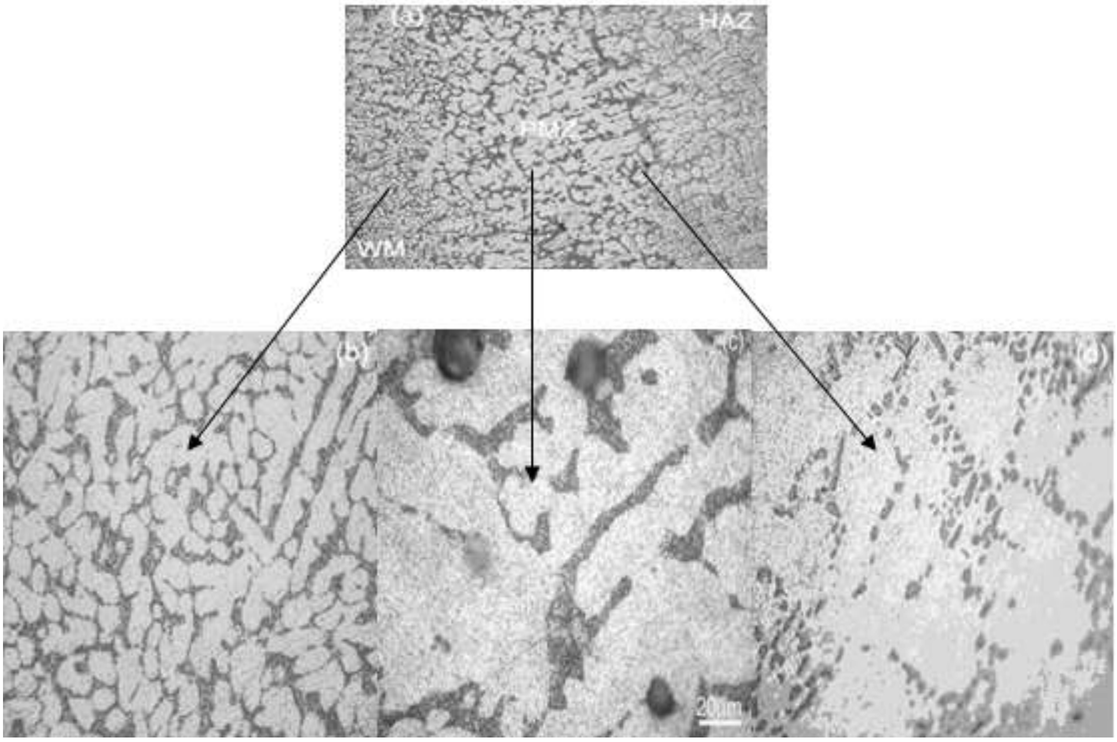
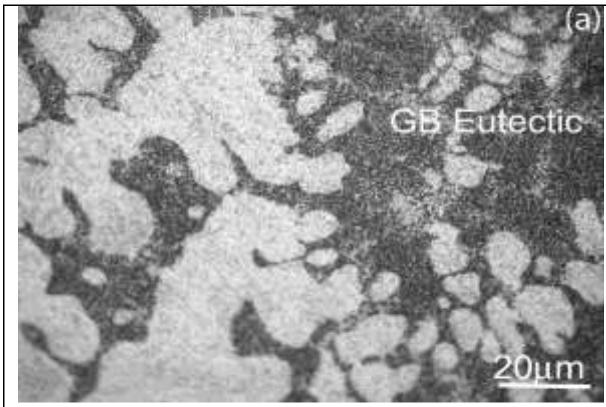
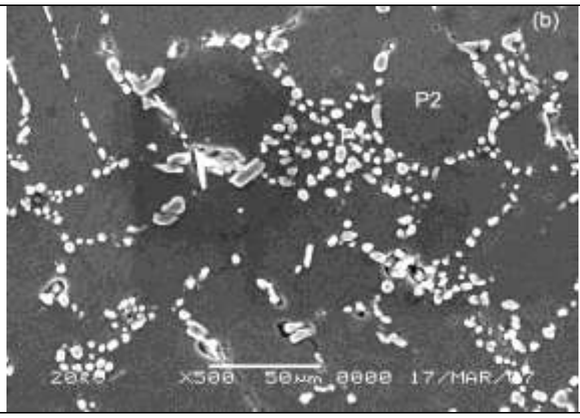


Fig.4 Microphotographs of WM, PMZ & HAZ in A356 alloy PCGTA weld in T6 condition.

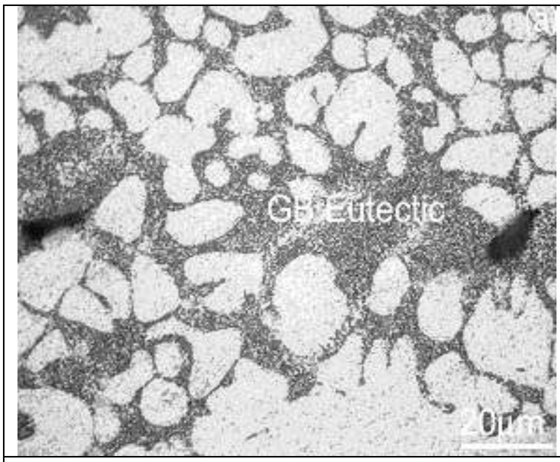


(a) Microphotograph

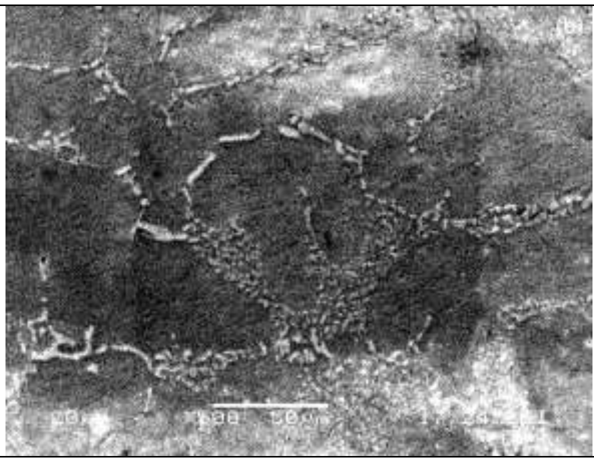


(b) SEM photograph

Fig.5 Microphotograph and SEM of PMZ of CCGTA welded A356 alloy in as cast condition

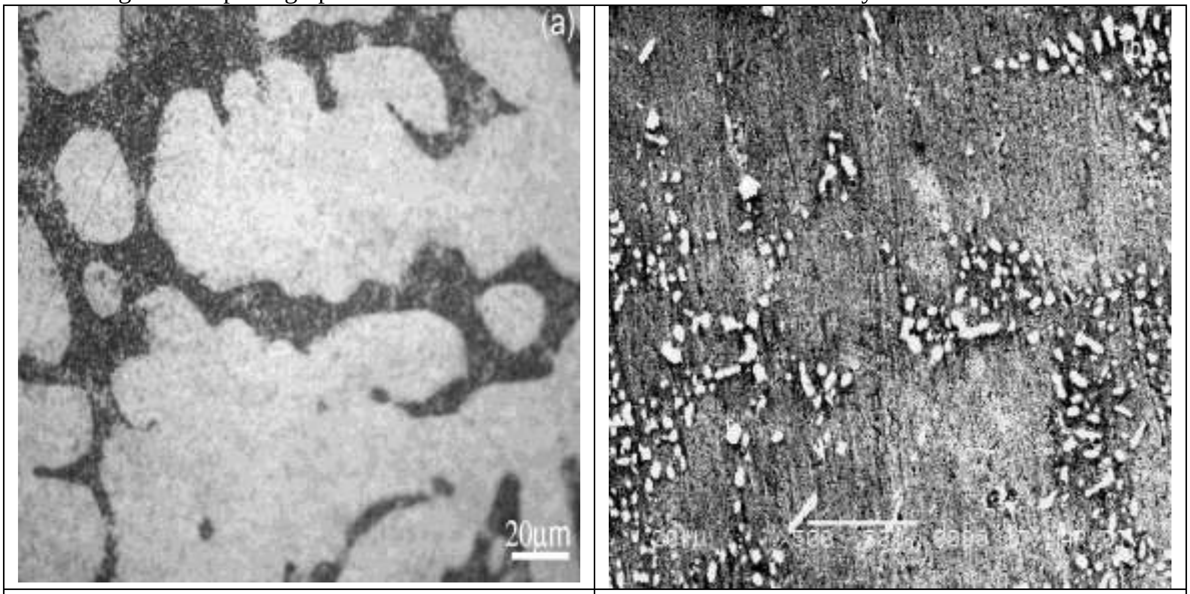


(a) Microphotograph



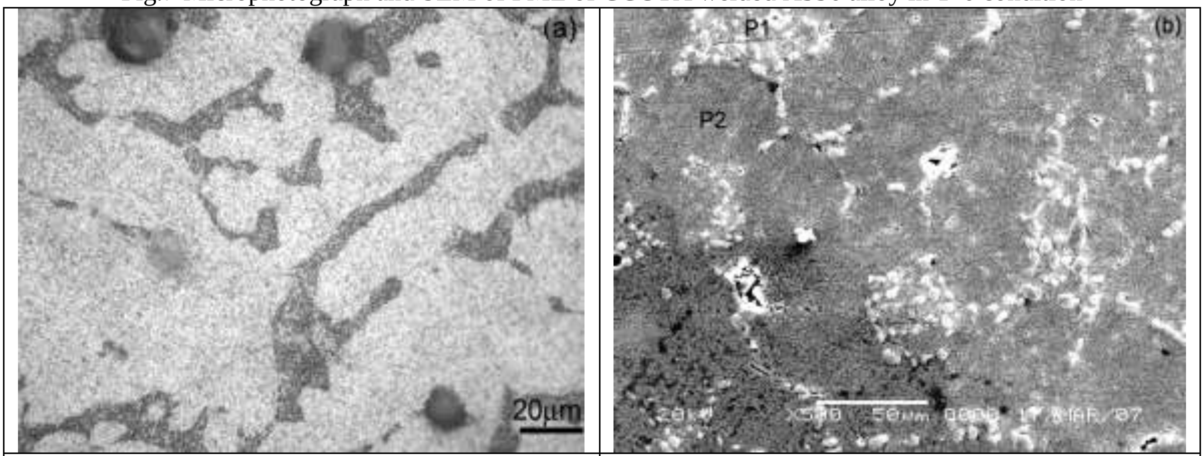
(b) SEM photograph

Fig.6 Microphotograph and SEM of PMZ of PCGTA welded A356 alloy in as cast condition



(a) Microphotograph	(b) SEM photograph

Fig.7 Microphotograph and SEM of PMZ of CCGTA welded A356 alloy in T-6 condition



(a) Microphotograph	(b) SEM photograph

Fig.9 Microphotograph and SEM of PMZ of PCGTA welded A356 alloy in T-6 condition

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