Effects of using of Modified Al-Mg (AA 5356) Filler on Cracking Susceptibility of Al-Mg-Si (AA 6061) Alloy welds

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ABSTRACT

The paper deals with an intention of solving HAZ problems through manipulating fusion zone chemistry and microstructure. Grain refiners such as Sc, Ti+B and Zr have been added to fusion zone through the AA5356 filler metal. The results indicated that the maximum refinement in the weld microstructure and consequent reduction in cracking susceptibility in alloy AA6061 can be achieved using AA5356 filler metal with 0.5% Sc addition.

Keywords: grain refinement, welds, aluminium alloy, partially melted zone, HAZ cracks, liquation

INTRODUCTION

The Al- Mg -Si aluminum alloys exhibit a tendency to solidification cracking unless the weld metal composition includes appropriate filler metal additions. Intergranular cracking in partially melted base metal adjacent to the weld fusion boundary is also a known problem in Al-Si-Mg series arc welds. The susceptibility to solidification cracking in Al-Si-Mg alloys is high because of large freezing range. Further more, aluminum alloys contain small amounts of other elements (Fe, Mn and Cu), which further increase the freezing range of this alloy. The alloy has a ternary eutectic (Liquid ® $Al+Mg_2Si+Si$) at about 559°C or 100°C below the normal T_L (liquidus temperature). Besides the ternary eutectics at 559°C, other eutectic were observed at 536°C, 529°C, 508°C and 487°C, all of which involved phases high in Cu. Therefore, high solidification cracking susceptibility due to Cu addition could override the advantage of its strengthening effect.

Since the 1950s, liquation and liquation-induced hot cracking in aluminum alloys have been studied extensively, and alloys 2024, 6061, and 7075 are among the most frequently investigated materials. Filler metal compositions rich in Si or Mg were used to shift the weld metal composition towards less crack sensitive compositions. HAZ cracking susceptibility of Al-Mg-Si and Al-Zn-Mg alloys has been explained based on the relation between solidus of weld metal and base metal [1-4]. Tsujimoto, et al., [5] performed GMA groove welding in a butt joint and showed that liquation cracking occurs even when the solidus of the base metal is higher than that of the weld metal. The reason for liquation cracking was considered to be the invasion (or the diffusion) of Si and Mg, which are the major elements of filler metals, along the grain boundaries of the HAZ [5]. Gittons and Scott [6] showed that the HAZ cracking occurs parallel to the weld bead in GMA welds, using a patch test. They attributed cracking to the base metal solidus being below the weld metal solidus. The reason for liquation cracking was considered to be the invasion of Si and Mg, which are the major elements of the filler metals, along the grain boundaries of the HAZ [6]. Contrary to Gittos and Scott [6], however, Miyazaki et al. [7] found that the weld-metal solidus temperature was lower than the base-metal solidus temperature (597°C) regardless of whether the filler metal was 5356 or 4043. It was suggested that the Alloy 6061 probably liquated at 559°C by constitutional liquation induced by the $Al\text{-}Mg_2Si\text{-}Si$ ternary eutectic. It is apparent that there is some disagreement in previous papers over the mechanisms of liquation cracking. Moreover, the studies suggest that the appropriate modification of filler metal composition could completely eliminate the cracking problem in Al alloys.

Composition of base and filler metal						
Material	**Mg**	**Si**	**Fe**	**Mn**	**Cu**	**Al**
Base metal (AA6061)	0.689	0.531	0.23	0.331	0.305	Bal.
Filler metal (AA5356)	4.5	0.25	0.4	0.05	0.1	Bal.
Quantities of inoculants added to filler AA 5356						
Filler	Sc	TIBOR	Zr			
R1	0.25	-	-			
R2	0.5	-	-			
R3	-	0.02Ti	-			
R4	-	-	0.15			

Table : 1 Nominal composition (wt. %) of base metal (AA6061), filler metal (AA5356) and quantities of inoculants added to filler AA5356

Various grain refinement techniques have been investigated in welding, e.g. electromagnetic stirring, current pulsation, surface cooling and inoculation [8]. Of these, inoculation using grain refining additions offers the greatest promise for practical application. The use of nucleating agents to reduce grain size in castings has been widely practiced. However, only limited data are available regarding inoculant effects in weld pool solidification. Use of inoculants to refine weld solidification structure and improve weldability in Al alloys [9,10] is well investigated. Grain refinement was induced in the weld fusion zones through inoculation with Ti, Ti + B and Zr [9,10]. Microstructural characterization showed that all three reduced grain size considerably, with Zr being the most effective. The structural refinement was found to reduce hot cracking susceptibility (measured by Varestraint testing), enhance post-weld age-hardening response and also improve tensile properties, especially ductility.

Therefore, refinement of weld solidification structures will be useful not only because it is known to reduce the tendency to hot cracking, but also because the increased grain boundary area could reduce the grain boundary films which form during welding. The reduction in the grain boundary phases and the formation of intermediate aluminide particles ($TiAl_3$, $ZrAl_3$, etc.) are believed to serve as effective means to reduce the high concentration of Mg or Si along the HAZ cracks, which are thought to be responsible for HAZ cracking in Al-Si-Mg alloys. The use of Scandium to achieve grain refinement in aluminum alloys has received recent attention, particularly in literature from the former Soviet Union [11]. Several accounts of improved weldability have also been reported [12].

While the primary approach to the problem of solidification cracking is thus to modify weld metal chemistry by optimizing filler material composition, a secondary solution is to reduce the coarseness of the solidification structure [13]. Therefore, in the present investigation, the influence of Sc, Ti+B and Zr additions to the AA 5356 alloy filler metal and welding technique (pulsed current) on the HAZ cracking susceptibility was attempted for GTA welds by modifying the weld solidification structure using Varestraint test.

EXPERIMENTAL DETAILS

The investigations were carried out on AA6061 alloy in solution treated (at 530°c for one hour and artificially aged at 160°c for 18 hours) condition. The material was in the form of 4.0 mm thick sheet. The composition of this alloy is given in Table 1. Conventional AA5356 metal was used as reference filler (R). The inoculants used for grain refinement were scandium, titanium+boron, and zirconium. Filler materials containing inoculants (Sc, Ti+B and Zr) were also prepared using master alloys containing the elemental additions. The quantities of inoculants added are shown in Table 1. In order to offset the possible dissolution of some of the inoculant particles during welding, the amounts of inoculant additions were chosen to be larger than needed.

The HAZ liquation cracking susceptibility of AA6061 alloy welds was evaluated using moving torch Varestraint testing device. During test an autogenous gas tungsten-arc welding (Are shielding) with and without pulsing mode were performed using a square wave

Continuous current welds		Pulsed current welds	
Arc voltage	13-16 V	Arc voltage	13-16V
Welding current	66A	Peak current	88A
Welding speed	220mm/min	Base current	44A
		Pulse frequency	6Hz
		Pulse on time	50%
		Welding speed	220mm/min

Table : 2 Details of the welding parameters used in the present investigation

Filler	Maximum crack length (MCL)		Total Crack Length (TCL)	
	CC	PC	CC	PC
R	8.2	4.5	28.5	21.5
R1	4	2.7	22.0	18.5
R2	1.8	1.5	5.9	1.7
R3	1.7	1.6	7	4.0
R4	2.5	1.5	12.5	5.1

Table : 3 Observed crack lengths (mm) during Varestraint testing

power source. Details of the welding parameters are presented in Table 2. Initial studies were carried out at three strain levels (0.63, 1.26 and 2.54%) with reference filler and remaining experiments using modified filler metal was done at 2.54% strain level. This ensures the specific advantages of addition of inoculants to conventional AA5356 filler metal. Three specimens from each strain were tested. Quantitative cracking data in terms of total crack length and maximum crack length (in HAZ) were used for evaluating the weld metals. Before welding, a square grooves (4´3 mm) were made in overlay samples and machined to standard Varestraint specimen size (125´25´4 mm). The overlay samples, filler material and inoculants were cleaned thoroughly with wire-brush and acetone. Weighted filler material and inoculant strips preplaced in the square groove and tack welded. Schematic representation of the Varestraint test specimen is shown in Fig.1.

Specimens from the weld fusion zones were suitably sectioned prepared and examined using light microscope and Scanning Electron Microscope. The etchant used was Kellar's reagent. Energy dispersive X-ray analysis (EDAX) was also carried out in various regions of the welds and PMZ to collect the supportive evidences. The PMZ cracks were fractured at room temperature to expose the crack su-face and the fracture surfaces were observed under SEM to correlate with the microstructural observations.

RESULTS

Varestraint test results in terms of maximum and total crack length (MCL and TCL) are presented in Table 3. It can be seen from the results that both the filler metal composition and welding technique have strong influence on the PMZ cracking susceptibility of AA 6061 alloy. The total crack lengths of this alloy were found to be in the range of 1.7 mm to 28.5 mm depending on the process parameters. In all cases the reference filler metal (AA5356 without inoculants) showed high cracking susceptibility. Similarly CC welds showed greater cracking susceptibility than PC welds irrespective of filler metal used. The cracking susceptibility was found to decrease with inoculant additions to

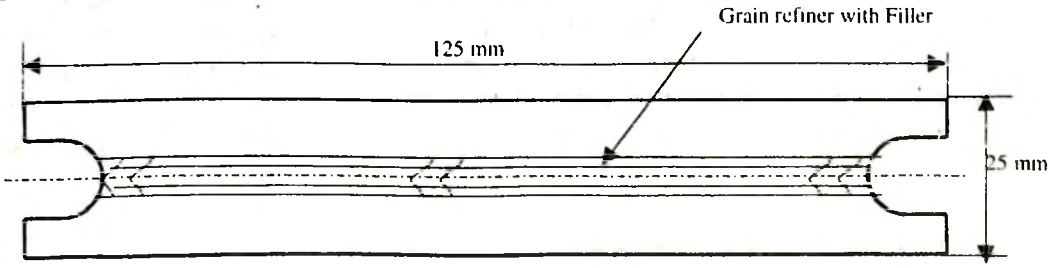


Figure 1 Schematic diagram of Varestraint test specimen

Element	Reference filler (AA5356)	AA5356+ 0.5% Sc	AA5356+ 0.02% Ti	AA5356 + 0.15% Zr
Mg	5.36	1.45	2.20	2.42
Si	1.24	0.44	0.55	0.90
Cu	0.20	0.05	-	0.06
Fe	0.56	0.25	0.03	0.32
Sc	-	0.95	-	-
Ti	-	-	0.33	-
Zr	-	-	-	0.50
Al	92.64	96.86	96.62	95.80

Table : 4 Energy dispersive X-ray (EDX) microanalysis (in wt.%) carried out near the HAZ cracks.

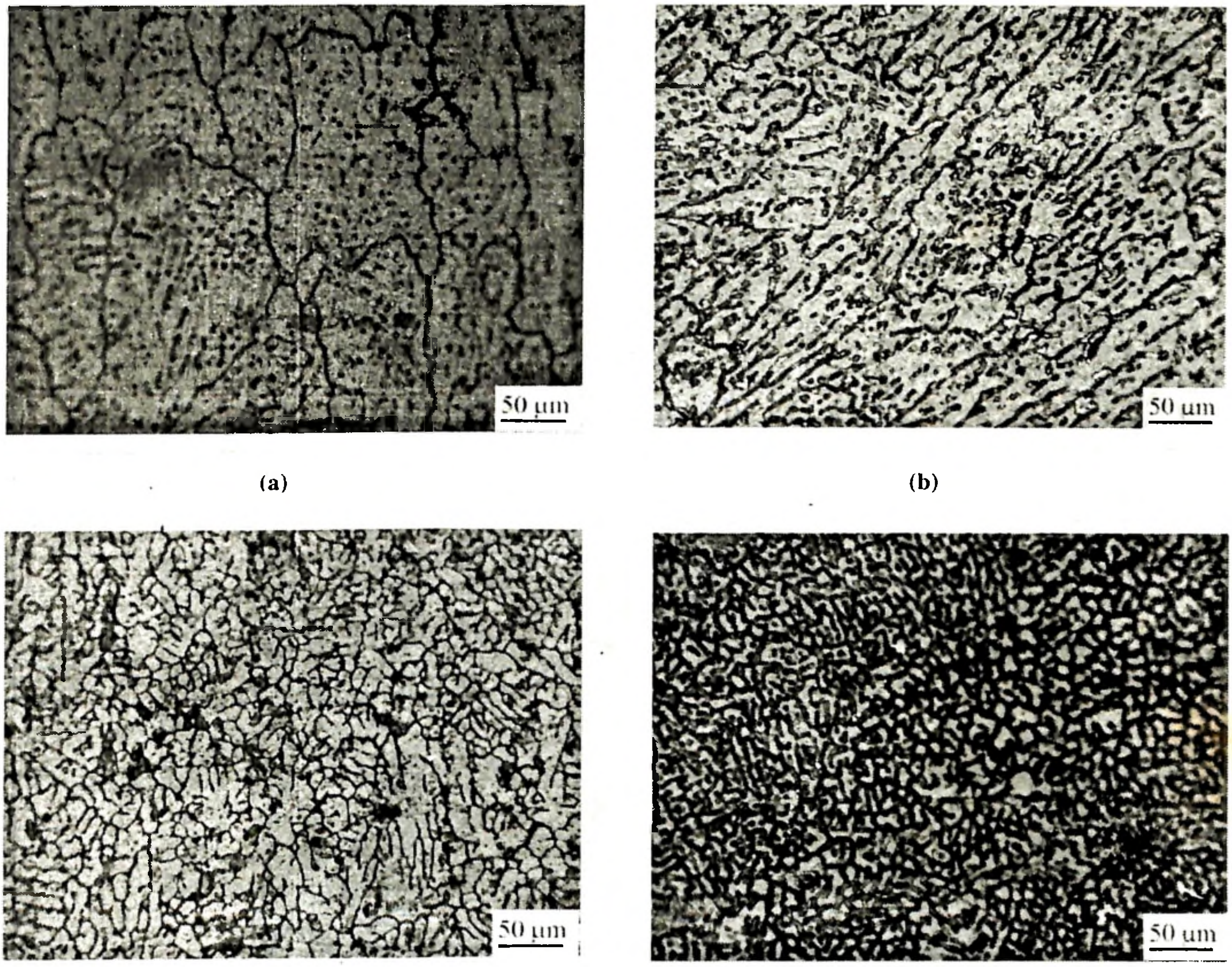
the AA 5356 filler metal. Among the inoculants studied filler metal with 0.5% Sc was observed to provide highest cracking resistance to the weldments of AA 6061 alloy followed by Ti+B.

As can be seen from Table 3 that the highest TCL was observed in the CC welds made with reference filler. Addition of Ti+B to the filler metal reduced the cracking susceptibility to ~ 75%, Zr addition reduced the sensitivity to ~ 56% and Sc addition reduced cracking susceptibility to a maximum extent of ~ 80%. Similar trend was observed in PC welds. However, the cracking susceptibility was reduced to greater extent with inoculant additions reaching a maximum reduction in HAZ cracking susceptibility of around 92% in the case of 0.5% Sc addition. In the case of titanium and zirconium around 82% and 76% reduction in the cracking susceptibility was observed, respectively. These results suggest that the addition of grain refiners (inoculants) to the reference filler metal have strong influence in reducing the HAZ cracking of AA 6061 alloy welds. Least cracking susceptibility in AA 6061 alloy can be achieved by using pulsed current with 0.5% Sc added AA 5356 filler metal.

Current pulsing was found to refine the weld solidification structure in all welds (made with and without filler metal modification), Fig. 2a-d. Addition of 0.5% Sc to the AA5356 filler metal resulted in maximum refinement in the weld microstructure as shown in Fig. 2d. Microstructural studies revealed significant cracking in the PMZ of all the welds. Welds made with reference filler (AA5356) without inoculants addition metal showed severe cracking. Significant reduction in the severity of cracking was observed with inoculants addition to filler metal. Filler metal with 0.5% Sc addition showed minimum cracks among the filler metals studied. These results showed a significant effect of the weld-metal composition on PMZ cracking in partial-penetration welds in alloy AA6061. The regions in the vicinity of PMZ cracks were analyzed for their chemical composition using EDX and the results are presented in Table 4.

The microstructure of partially melted zone of AA 6061 alloy welded with reference filler metal (AA 5356) is shown in Fig. 3. The cracks were intergranular in nature with rounded edges (Fig. 3a). The EDX analysis of the crack (Table 4) showed high concentration of Mg and/or Si and was found to decrease as we approach crack tip. Similar crack features were observed in the case of other welds made with modified filler (with inoculants) as shown in Fig. 4. However, the Mg and Si concentrations were considerably reduced when the filler metal was modified with inoculants. Maximum reduction in the concentration of these elements at the cracks was observed with 0.5% Sc addition.

The PMZ cracks were opened at room temperature and the fracture surfaces were observed under SEM to correlate with the microstructural observations. Figure 5 shows the fracture surface of the PMZ cracks in the welds made with reference filler metal. The fracture path was intergranular within a few grains of weld fusion boundary. The crack surface near the fusion boundary had the smooth and rounded features showing some solidification structure (Fig. 5a). At some distance from the fusion boundary the solidification structure was till present. However, no solidification structure was observed at the end of the crack tip. Comparing these features with the fracture features of cracks observed in the welds made with 0.5% Sc added filler (Fig. 6) showed that solidification structure still exists but to a lesser extent, in isolated place only.



(a) (b) (c) (d)

Figure 2 Weld microstructures of type AA6061 alloy
(a) reference filler, CC, (b) reference filler, PC, (c) reference filler with Ti+B addition, PC, (d) reference filler with Sc addition, PC.

DISCUSSION

Sever cracking was observed all the welds made with AA5356 filler except welds made with addition of inoculants to reference filler. Several mechanisms have been proposed by which the HAZ liquation occurs: constitutional liquation, eutectic reaction and invasion or diffusion from the weld metal of elements composing the low melting temperature compounds. In the present investigation the cracking is attributed to penetration of molten metal from the weld metal along the grain boundaries in the PMZ. The observation of solidification structure in the fracture surface indicates that the crack surface was melted when the crack was developed. High concentration of Mg near the cracks in the case of reference filler metal shows that there existed a thin layer rich in Mg on the crack surface. It is known from the solidus lines of Al-Mg-Si ternary system [14] high concentration of Mg and Si at the grain boundaries/interdendritic regions could lower the solidus temperature locally and make the grain boundaries more susceptible to liquation cracking during welding. In

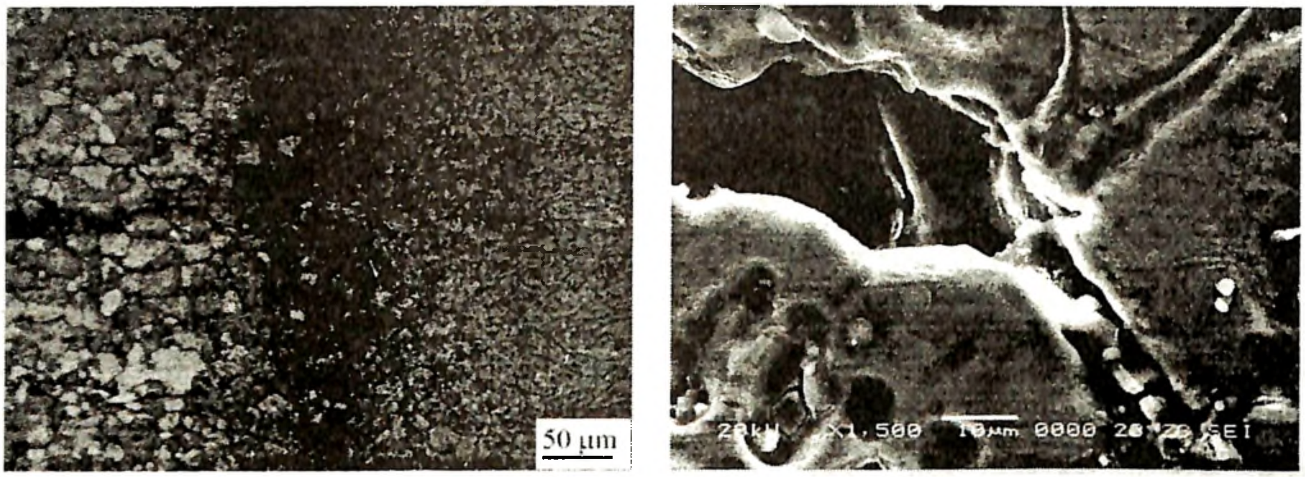


Figure 3 Microstructure of partially melted zone of AA 6061 alloy welded with reference filler metal (AA 5356), (a) optical microstructure, (b) SEM micrograph showing the crack at higher magnification.

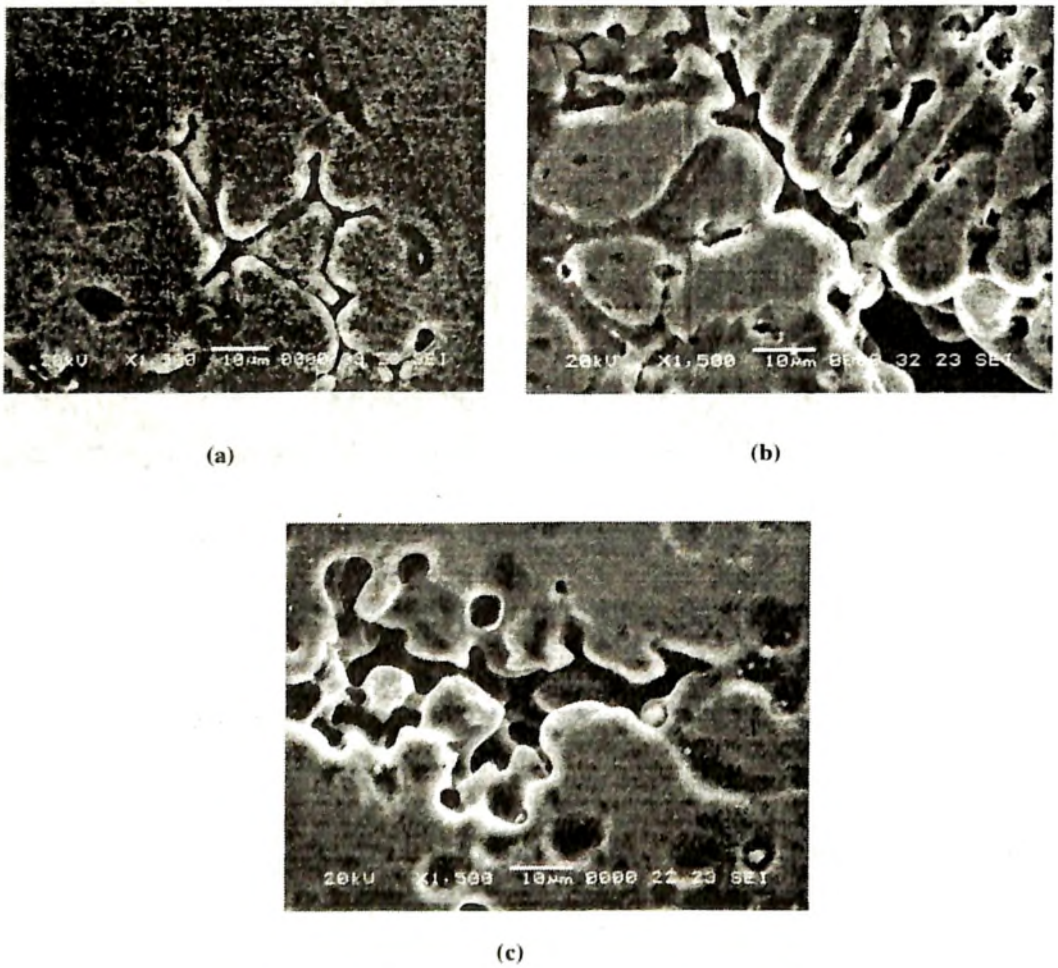


Figure 4 SEM micrographs showing crack morphology,
(a) welds made with Sc added filler, (b) welds made with Ti added filler, (c) welds made with Zr added filler.

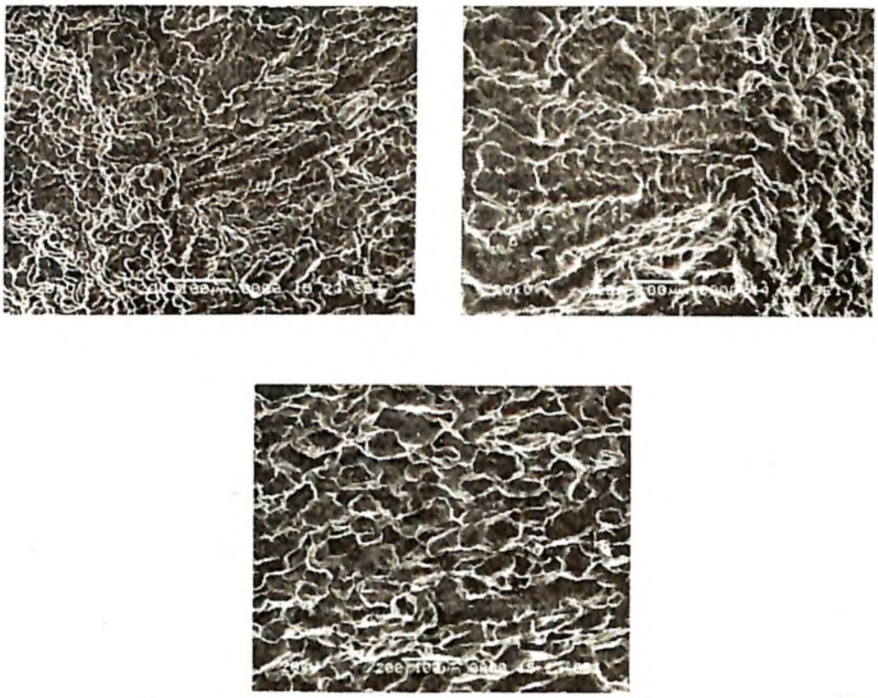


Figure 5 Fracture features of HAZ cracks of AA6061 alloy welds made with AA5356 filler, (a) near fusion boundary, (b) middle of the crack, (c) near the end of crack.

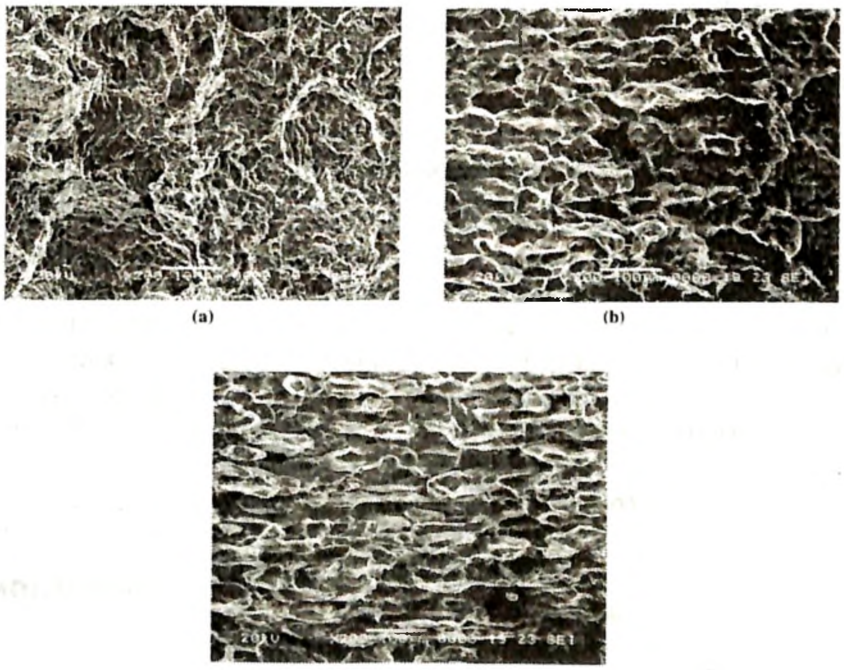


Figure 6 Fracture features of HAZ cracks of AA6061 alloy welds made with AA5356 filler containing 0.5% Sc, (a) near fusion boundary, (b) middle of the crack, (c) near the end of crack.

alloy 6061 coarse Mg_2Si particles and Al-Mg_2Si eutectic were reported to be present in alloy 6061 and in the PMZ of the alloy, respectively [15-17]. Since there is no grain boundary liquid in the base metal, most of the grain boundary liquid in the PMZ could have come from the weld pool. If an alloy is heated to above its solidus, it is quite common for melting to start at grain boundaries and this will happen in the HAZ near the fusion boundary. From the present results it is apparent that the weld metal would have solidified before any such constitutional liquated boundaries. The shrinkage strains produced by solidification of the weld metal could have parted the liquated boundaries in the PMZ.

Current pulsing has been used in the past, both in GTA and gas metal arc welding, for obtaining grain refinement in the weld fusion zones of wrought alloy weldments. Significant refinements of the solidification structure and a transition from columnar to equiaxed growth have been reported in aluminium alloys [18,19 14,15]. The pulsing of the welding current has several effects on weld pool solidification. It mainly affects the temperature distribution in the weld pool. The periodic variations of energy input into the weld pool cause thermal fluctuations, these being dependent on the pulsing frequency. They also result in additional fluid motion, which enhances the convective forces already existing in the weld pool. A further consequence of the induced flow patterns in the weld pool is that the thermal gradients in front of the solid–liquid interface are reduced. Due to the temperature fluctuations inherent in pulsed welding, there will be continual change in the weld pool size and shape. All these factors could influence the weld metal solidification process and in turn the microstructure. The cyclic temperature variations that occur at the solidification front owing to the pulsed current can cause remelting and breaking off of the growing dendrites. This is aided by the mechanical action of the weld pool turbulence in bringing the dendrite fragments ahead of the solid–liquid interface. These fragments then become sites for heterogeneous growth, which eventually block the columnar growth process. The PMZ cracking susceptibility is low in PC welds compared to CC welds. The finer structure in the fusion zone and consequent increase in the interdendritic / grain boundary area would have reduced the cracking tendency in PC welds. This is because the increased area could reduce the amount of boundary films/liquids, which form during welding. The reduction in the amount of boundary phases/films are thought to reduce the PMZ cracks.

The grain refinement of aluminium alloy castings through heterogeneous nucleation is well documented and inoculation of castings is also practiced industrially. The micrographs of the inoculated welds (Fig. 2c-d) show that, although all the three inoculants resulted in considerable grain refinement, Sc and Ti+B were slightly more effective than Zr. It is known in the case of aluminium alloy castings that the introduction of boron in addition to titanium yields better performance; this is usually ascribed to the role of TiB_2 as an additional nucleant as well as to the effect of boron in lowering the solubility of Ti in liquid aluminium. This latter behaviour shifts the peritectic point towards the aluminium end of the phase diagram, thus enabling the titanium aluminide crystals to be thermodynamically stable even at very low levels of Ti addition [20, 16].

The inoculant addition to the filler metal result in an appreciable reduction in cracking susceptibility. This is clearly highlighted in a decrease both in total crack length and maximum crack length. Among the inoculants tried, Sc and Ti+B have led to a more pronounced effect than Zr. The degree of reduction in cracking susceptibility is qualitatively in line with the degree of grain refinement achieved by the use of each of the inoculant types. This observation indicates that the improvement in weldability can be directly related to the refinement of solidification structure. The increase in grain boundary volume due to grain refinement reduces the peak concentration of the segregating elements responsible for cracking as can be seen from the reduced Mg concentration at the crack surfaces (Table 4). The decrease in the segregation (or Mg concentration) decreases the effective freezing temperature range and hence the cracking tendency [21, 17]. The other possible reason could be that the smaller grain structure allows for the strain in the weld to be distributed among more grains and across their boundaries [22, 18].

CONCLUSIONS

1. The refinement of the solidification structure by the use of inoculants and current pulsing led to a reduction in PMZ cracking tendency of AA6061.

2. The use of Sc and Ti+B resulted in a greater refinement in the solidification structure and consequent reduction cracking severity.

3. The PMZ cracking resistance was relatively maximum with Sc addition to AA5356 filler compared to Ti+B addition.

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