# SOLIDIFICATION CRACKING SUSCEPTIBILITY OF AL-MG-SI ALLOY LASER WELDS

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**ABSTRACT**

The solidification cracking susceptibilities of Al-Mg-Si alloy laser welds were assessed using the self-restraint tapered specimen crack test. The cracking susceptibility of 6061 and 6082 Al-Mg-Si alloy laser welds was substantially reduced when the filler wire containing high Si such as Al-12 wt.% Si (4047A) was used. The amount of eutectic was observed to affect the solidification cracking of Al-Mg-Si alloy laser welds. Abundant eutectic seems to heal the cracking and reduces the cracking susceptibility, while an initial increase in eutectic liquid leads to the increased cracking tendency.

**KEYWORDS**

Al-Mg-Si alloys, Laser welding, Solidification cracking susceptibility, Tapered specimen crack test, Amount of eutectic

## 1. Introduction

Al-Mg-Si alloys are candidate materials for lightweight car body structure and panels. Hence the laser weldability and post weld properties of these alloys are being exploited by many investigators. It has been reported from the previous investigations[1, 2, 3, 4, 5] that porosity and hot cracking are the defects most frequently encountered when laser welding aluminum alloys. Particularly, hot cracking is serious in the crack susceptible alloys such as Al-Mg-Si alloys. According to Jennings et al.[6], maximum cracking in Al-Mg-Si alloy castings occurs at a composition of 0.25 wt.% Mg and 0.5 wt.% Si. Since the composition of 6061 and 6082 alloys is in the very range of high cracking susceptibility, these alloys are likely to be highly prone to cracking during welding. However, as the content of Mg and Si is increased, the cracking susceptibility of Al-Mg-Si alloys can be decreased. Therefore, it seems that solidification cracking of 6061 and 6082 alloys can be reduced by feeding filler wires of high Si and/or Mg content and thus increasing the content of Mg and/or Si in welds, as proved by various investigation[7, 8, 9, 10]. The work described in this paper examines the solidification cracking susceptibility of Al-Mg-Si alloys, both with and without filler wires. The relationship between solidification cracking susceptibility and the amount of eutectic has been established for the laser welds of Al-Mg-Si alloys as well.

## 2. Experiments

### 2.1 Materials

The solidification cracking susceptibility of Al-Mg-Si alloy laser welds was assessed using 1.6 mm thick 606l sheets and 6.4 mm thick 6082 plates, of which the chemical compositions are shown in Table 1. For wire feed bead-on-plate(BOP) welding filler wires normally used for Gas Metal Arc (GMA) welding were fed along the center line of the tapered specimens. The wire diameter was 1.2 mm and the chemical compositions of the filler wires used are shown in Table 2.

**Table 1** Nominal chemical compositions (in wt.%) of aluminum alloys used (balance aluminum).

| Alloy | Thickness (mm) | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
|---|---|---|---|---|---|---|---|---|---|
| 6061 | 1.6 | 0.62 | 0.25 | 0.23 | > 0.01 | 0.92 | 0.17 | >0.01 | 0.02 |
| 6082 | 6.4 | 0.99 | 0.29 | 0.03 | 0.67 | 0.82 | 0.01 | 0.05 | 0.06 |

**Table 2** Nominal chemical compositions (in wt.%) of filler wires used (balance aluminum).

| Filler wire | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Zr |
|---|---|---|---|---|---|---|---|---|---|
| 99.5Al-Ti | 0.03 | 0.13 | - | 0.002 | 0.001 | 0.001 | 0.02 | 0.14 | - |
| 5154 | 0.25 | 0.4 | 0.1 | 0.1 | 3.5 | 0.25 | 0.2 | 0.2 | - |
| 5556A | 0.09 | 0.34 | - | 0.57 | 5.60 | 0.07 | - | 0.07 | - |
| 5183 | 0.04 | 0.15 | 0.017 | 0.63 | 4.83 | 0.007 | 0.003 | 0.011 | - |
| 5183Zr | 0.11 | 0.18 | 0.003 | 0.70 | 4.60 | 0.07 | <0.01 | 0.12 | 0.12 |
| 4043A | 4.65 | 0.36 | 0.01 | 0.01 | 0.01 | - | 0.01 | - | - |
| 4047A | 12 | 0.8 | 0.3 | 0.15 | 0.1 | - | 0.2 | - | - |

### 2.2 Self-restraint tapered specimen crack test

Two $CO_2$ laser welding systems of the laser power, 5 kW for 1.6mm thickness sheet and 10 kW for 6.4mm thickness plate were used. Shape and dimension of a tapered specimen was depicted in Figure 1. Full penetration bead-on-plate (BOP) welding was made from the narrow towards the wide end edge along the longitudinal centerline of tapered specimens. Each BOP welding was actually started at the dummy plate placed in front of narrow start edge and stopped at the other dummy plate placed at the rear of the wide end edge. This enabled full penetration to be achieved at the start edge and thus allowed a crack to initiate at the start edge. The rolling direction of all the specimens was perpendicular to the welding direction. No external restraint was applied during the BOP welding ; each specimen was held by sticky tape on a plate before BOP welding. The plate contained a machined cavity slot through which underbead shielding gas was supplied. At least three specimens were tested at each welding condition to confirm repeatability. Both autogenous and wire feed BOP welding were made along the centerline of the tapered specimens.

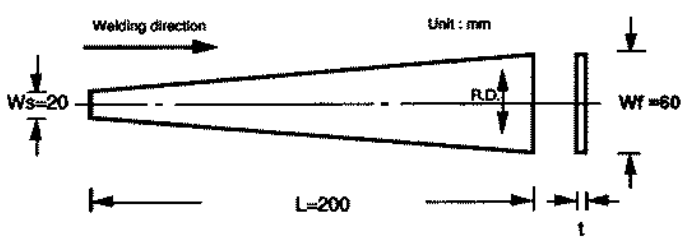



**Fig. 1** Shape and dimension of the tapered specimen.

The welding conditions were selected to give full penetration and were constant for each test unless otherwise stated ; 5 kW laser power and 6 m/min weld speed for 1.6 thick sheet specimens, 8 kW and 2.7 m/min for 6.4 mm thick plate specimens for autogenous BOP welding. For wire feed BOP welding of tapered specimen, various combinations of base alloys and filler wires were tried in order to examine the effect of filler wire composition (i.e. resulting weld metal composition) on weld metal solidification cracking susceptibility.

The length of the longitudinal crack produced along the weld centerline was measured with the aid of dye penetrant. X-ray radiography was also used, particularly for the 6.4 mm thick tapered specimen, to check the exact position of the crack tip. The percentage crack length (PCL), ratio of the measured longitudinal crack length to the weld seam length (i.e. specimen length), was used as an index of cracking susceptibility.

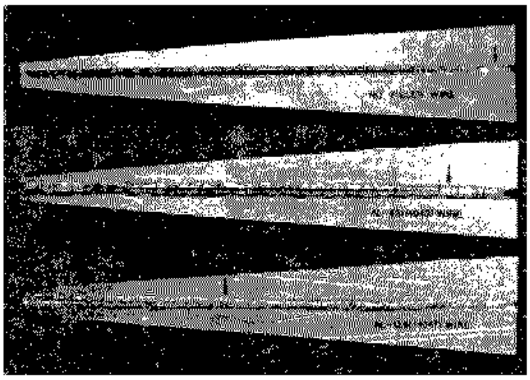
**2.3 Chemical analysis and microanalysis of segregate**

Using the weld sections prepared from crack-free portions of the BOP welds in the tapered specimens, the chemical compositions of the weld metal were determined by inductively coupled plasma (ICP) spectroscopic analysis. Segregates in the weld sections and on the longitudinal as-cracked surfaces, particularly at the crack tip area were examined by optical and scanning electron microscopy (SEM). Microanalysis of the segregates was carried out using Energy Dispersive X-ray analysis (EDX).

**3. Results**

**3.1 Variation of cracking susceptibility with filler wires**

Center-line longitudinal cracks typical of those formed in the tapered specimens made of 6.4 mm thick 6082 alloy are shown in Figure 2. The length of longitudinal cracks depends on the filler wires used.



No filler wire

Al-5 wt.% Si (4043A)

Al-12 wt.% Si (4047A)

**Fig. 2** Variation of longitudinal center-line crack length with different filler wires in tapered specimens made of 6.4 mm thick 6082 Al-Mg-Si alloy.

PCL values for 6.4 mm thick 6082 alloy and 1.6mm thick 6061 alloy are shown in Figures 3 and 4, respectively. Longitudinal crack length (i.e. cracking susceptibility) primarily depends on the composition of the filler wires used. The Al-12 wt.% Si (4047A) filler wire is the most effective in reducing the cracking susceptibility of Al-Mg-Si alloys among the fillers used. The effect of Al-5 wt.% Si (4043A) wire on reducing the cracking susceptibility was not substantial although the Al-5 wt.% Mg (5556A) filler wire reduced the cracking susceptibility of 1.6 mm thick 6061 alloy to some degree, but not as much as the Al-12 wt.% Si (4047A) filler. The reduction of cracking susceptibility in the 1.6 mm thick 6061 alloy laser welds made with 5556A (Al-5 wt.% Mg) filler appears to be due to increased equiaxed grains in the weld center regions[11]. When filler wires having low solute contents like 99.5Al-Ti or 5154 (Al-3.5 wt.% Mg) were used, weld metal solidification cracking susceptibility was not reduced, On the contrary, the 99.5Al-Ti filler wire increased the cracking susceptibility of the Al-Mg-Si alloy. In this study the degree to which each filler wire affects the cracking susceptibility of Al-Mg-Si alloy could be assessed quantitatively when the tapered specimen crack test was used.

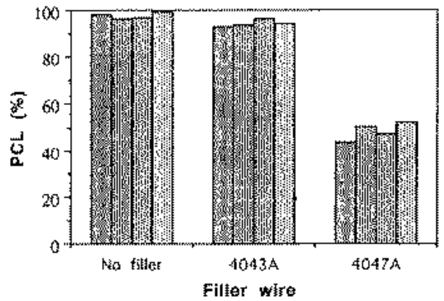



**Fig. 3** Variation of weld metal solidification cracking susceptibility of 6.4 mm thick 6082 Al-Mg-Si alloy with filler wires, as measured by the tapered specimen crack test.

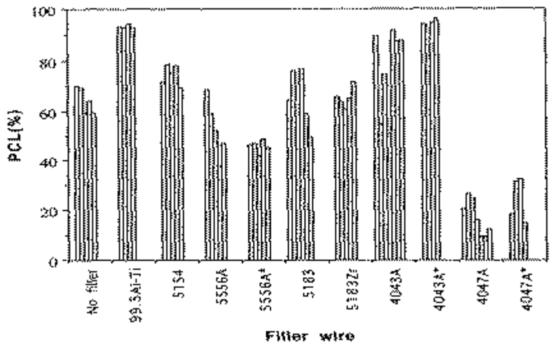
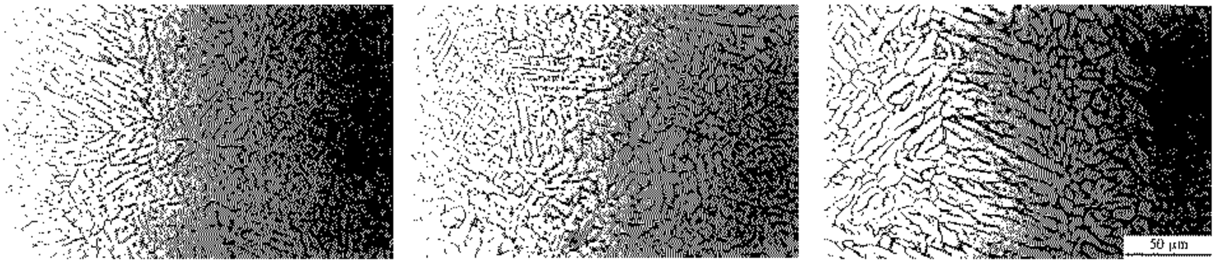



**Fig. 4** Variation of weld metal solidification cracking susceptibility of 1.6 mm thick 6061 Al-Mg-Si alloy with filler wires, as measured by the tapered specimen crack test (All tests were measured at laser power of 5kW, weld speed of 5 m/min and wire feed speed of 5 m/min except tests* made at laser power of 4.5kW, weld speed of 5.5 m/min and wire feed speed of 2 m/min).

### 3.2 Effect of segregation of secondary phases on the cracking susceptibility

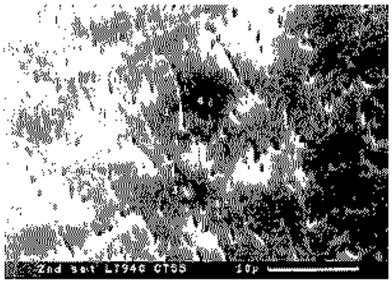
Figures 5 and 6 are optical and scanning electron micrographs of autogenous and wire feed BOP cross-sections in the tapered specimens for the 6082 and 606l alloys, respectively. Particularly in the wire feed BOP welds made with Al-12 wt.% Si filler wires, segregation of a secondary phase increased at the cell or grain boundaries compared to the autogenous and other wire feed BOP welds made with Al-5 wt.% Si or Al-5 wt.% Mg fillers. Microanalysis using EDX shows that the Si content increases in the weld metal as the Si content of the filler wires increases (Figure 6).

Segregates are highly enriched with Si and the segregation is greater when the Al-12 wt.% Si filler wire is used. However, segregation of Mg at the cell or grain boundaries is not apparent. It seems that Mg is uniformly distributed throughout the weld metal, even in the case of the wire feed BOP welds made with Al-5 wt.% Mg filler. Si is rejected from solidifying dendrites as solidification proceeds due to its limited solubility (e.g. maximum solubility of Si in the Al-Si binary system is 1.8 wt.%) and is concentrated at the cell or grain boundary, while the uniform distribution of Mg in weld metals seems likely to occur because of its relatively high solubility (e.g. maximum solubility of Mg in Al-Mg binary system is 14.9 wt.%). Substantial amounts of

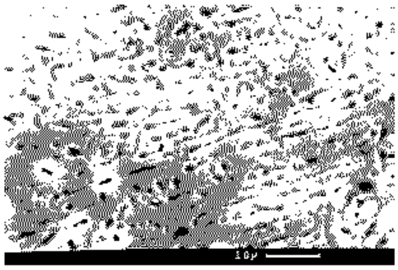



(a) Autogenous weld without filler (b) Wire feed weld with Al-5 wt.%Si (4043A) wire (c) Wire feed weld with Al-12 wt.%Si (4047A) wire

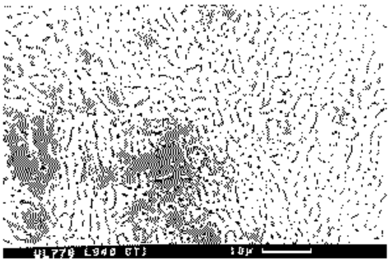
**Fig. 5** Optical microstructures of bead-on-plate welds in 6.4 mm thick 6082 Al-Mg-Si alloy.



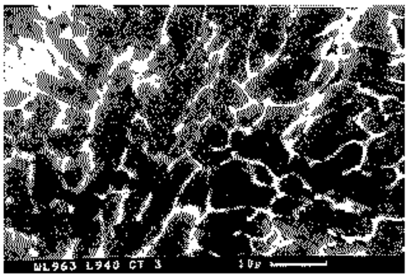
(a) Autogenous weld without filler



(c) Wire feed weld with Al-5 wt.%Si (4043A) wire



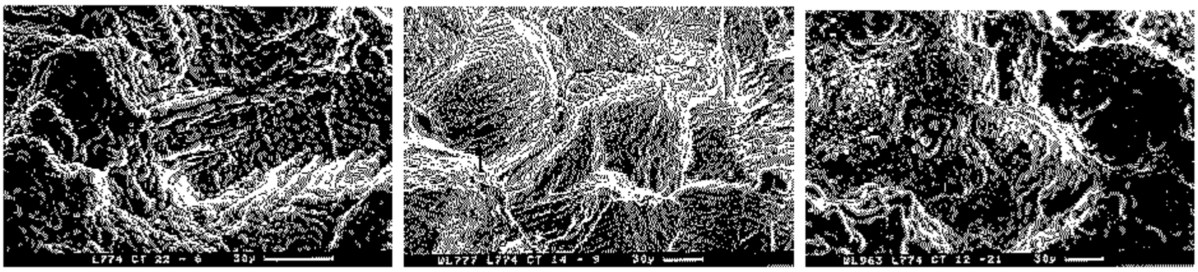
(b) Wire feed weld with Al-5 wt.%Si (5556A) wire



(d) Wire feed weld with Al-12 wt.%Si (4047A) wire

| Filler Wire | Over-all weld metal | Dendritic arm | Cell boundary |
|---|---|---|---|
| No filler | 0.6 wt.% Si | - | 0.18~0.65 wt.% Si |
| Al-5 wt.% Si | 1.3~2.2 wt.% Si | 0.52 wt.% Si | 1.0~4.6 wt.% Si |
| Al-12 wt.% Si | 3~6.6 wt.% Si | 0.96~1.7 wt.% Si | 2.9~10.2 wt.% Si |

**Fig. 6** Scanning electron micrographs of welds and variation of Si content in each area of 1.6 mm thick 6061 Al-Mg-Si alloy laser welds as measured by EDX.



(a) Autogenous weld without filler (b) Wire feed weld with Al-5 wt.%Si (4043A) wire (c) Wire feed weld with Al-12 wt.%Si (4047A) wire

**Fig. 7** Scanning electron micrographs of longitudinal as-cracked surfaces along the bead-on-plate welds in tapered specimens made of 6.4 mm thick 6082 Al-Mg-Si alloys.

segregate were also observed on the longitudinal as-cracked surfaces in the BOP welds in the tapered specimen, as shown by SEM fractography, particularly when Al-12 wt.% Si filler wire (4047A) was used (Figure 7). The amount of segregate was aparently abundant on the longitudinal as-cracked surfaces when using a high Si containing filler wire. However, little trace of segregation was observed on the longitudinal as-cracked surfaces in the autogenous BOP welds in the tapered specimens.

**4. Conclusion**

In the autogenous BOP welds of Al-Mg-Si alloys (at low solute content), little segregate occurs on the longitudinal as-cracked surfaces and solid-solid interlocking (cohesion) is prevalent. When Al-5 wt.% Si filler wire is used (at intermediate solute content), low melting eutectics form on the longitudinal as-cracked surface and the cracking susceptibility increases. When Al-12 wt.% Si filler wire is used, abundant amounts of eutectic form at the longitudinal as-cracked surfaces and the cracking susceptibility is substantially decreased. It seems that an abundant amount of liquid at grain boundaries is beneficial in reducing the cracking susceptibility. Therefore, the existence of liquid during solidification plays an important role in solidification cracking of laser welded Al-Mg-Si alloys.

**Acknowledgement**

The authors would like to thank TWI for their provision of $CO_2$ laser welding facilities.

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