Effect of the Mg Content on the Solidification Cracking Susceptibility of the Al-Mg Alloy Laser Welds

J. W. Yoon

Abstract

The solidification cracking susceptibilities of Al-Mg alloy laser welds were assessed using self-restraint tapered specimen crack test. The dependence of cracking susceptibility of Al-Mg alloy laser welds on Mg contents was observed to be similar to that of arc welds in the same materials. The cracking susceptibility of Al-Mg alloy laser welds increased as Mg content increased up to 1.6~1.9 wt.% and then it decreased as Mg content increased further. The peak cracking susceptibility occurred at around 1.6 to 1.9 wt.% Mg for both autogenous and wire feed welds. It was also observed that the cracking susceptibility decreased as the grain size of Al-Mg alloy laser welds decreased, when Mg content was in the range higher than 1.9 wt.%.

Key Words : Al-Mg alloys, Laser welding, Solidification cracking susceptibility, Tapered specimen crack test, Grain size

1. Introduction

It has been reported that the hot cracking including the weld metal solidification- cracking and the heat-affected-zone (HAZ) grain boundary liquidation cracking is one of the defects most frequently encountered when the laser welding aluminum alloys [1,2].

Quantitative cracking tests using the arc welds and castings of binary aluminum alloys such as Al-Mg, Al-Si and Al-Cu tend to show a typical relationship between solidification cracking susceptibility and solute content [3]. As the solute content increases in the binary aluminum alloy castings and arc welds, solidification cracking susceptibility increases, reaching a peak value and then decreases with further addition of solute as can be seen in Fig. 1. The solute content corresponding to the peak cracking susceptibility is usually lower than the maximum solubility observed in the equilibrium phase diagram of each binary aluminum alloys.

Al-Mg alloys are candidate materials for lightweight car body structure and panels due to their good combination of strength and formability. In the case of Al-Mg alloy arc welds and castings, the Mg content corresponding to the peak cracking susceptibility is summarized in Table 1.

The peak cracking susceptibility of Al-Mg alloys usually occurs in the range of 0.5 to 2.75 wt.% Mg when using self-restraint crack tests, while it occurs at an increased range above 4 wt.% Mg when restrained crack tests were used.

The substantial difference of Mg content corresponding to the peak cracking susceptibility between self-restraint and restrained crack test remains unexplained. Thus the solidification cracking susceptibility of Al-Mg alloys remains not fully understood, particularly for the laser welded Al-Mg alloys.

The work described in this paper examined the

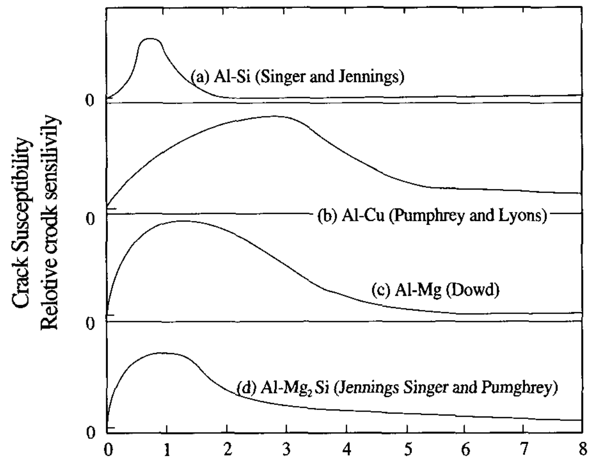


Fig. 1 Effect of alloying content of weld metal on cracking susceptibility in binary aluminum alloy[3].

J. W. Yoon is an Assistant Professor, Department of Advanced Materials Engineering, Dongeui University, Pusan, Korea.
E-mail : jwyoon@hyomin.dongeui.ac.kr, TEL : +82-51-890-1721

solidification cracking susceptibility of Al-Mg alloy laser welds, both with and without filler wires. The relationship between solidification cracking susceptibility and Mg content, and the Mg content corresponding to peak cracking susceptibility were established for the laser welding of Al-Mg alloys.

The effect of grain size on the solidification cracking susceptibility of Al-Mg alloy laser welds was also discussed.

Table 1 Mg content corresponding to peak cracking susceptibility of Al-Mg alloys.

Mg content (in wt.%) corresponding to peak cracking susceptibility in Al-Mg alloys	Test Method	References
1.0	Ring casting test	[4] Pumphrey and Lyons (1948)
1.5	T-fillet weld test	[5] Dowd (1952).
0.5-0.75	Patch test	[6] Borland et al.(1962)
<2.75	T-fillet weld test	[3] Dudas et al.(1966)
1.0	Ring casting and GTA spot crater	[7] Nakata et al.(1980)
4.0	Restrained weld	[4] Pumphrey and Lyons (1948)
>4.5	Varestraint test	[8] Lippold (1989)
1.72	Slow bending Trans-varestraint	[9] Arata et al.(1977)

2. Experiments

2.1 Materials

A range of Al-Mg alloys (5005, 5251, 5754 and 5083) and commercially pure grade aluminum (1200) was used to investigate the solidification cracking susceptibility of the Al-Mg alloy laser welds in terms of the Mg content. The thickness of all the Al-Mg alloy sheets investigated was in 2mm. The nominal chemical compositions of each alloy used are summarized in Table 2.

In order to investigate the effect of the weld metal composition, particularly the Mg content on the solidification-cracking susceptibility for Al-Mg alloys, Mg content in weld metal was varied by feeding the filler wires during the tapered specimen crack test. The filler wire used in this study was chosen among the wires normally used for gas metal arc welding.

Various combinations of base alloys and welding wires were made when conducting tapered specimen crack test using filler wires. The diameter of welding wires was 1.2mm and their chemical compositions are summarized in Table 3.

Table 2 Nominal chemical compositions (in wt.%) of aluminum alloys used (balance aluminum).

Alloy (batch)	Si	Fe	Cu	Mn	Mg	Cl	Zn	Ti
1200	0.06	0.27	<0.01	<0.01	<0.02	<0.01	0.01	0.01
5005	0.05	0.37	0.04	0.05	0.77	<0.01	<0.01	-
5251(1)	0.05	0.16	<0.01	0.23	1.91	<0.01	0.04	-
5251(2)	0.14	0.36	0.03	0.25	2.19	0.02	0.05	-
5754(1)	0.06	0.16	<0.01	0.24	3.06	<0.01	<0.01	-
5754(2)	0.06	0.16	<0.01	0.24	3.07	<0.01	0.07	-
5083(1)	0.14	0.29	0.02	0.63	4.46	0.05	0.01	-
5083(2)	0.14	0.30	0.02	0.63	4.54	0.05	0.03	-

Table 3 Nominal chemical compositions (in wt.%) of filler wires used (balance aluminum).

Filler WIre	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
1050A	0.05	0.18	0.002	0.002	0.007	-	0.004	0.001
5154	0.25	0.4	0.1	0.1	3.5	0.25	0.2	0.2
5556A	0.09	0.34	-	0.57	5.6	0.07	-	0.07

2.2 Self-restraint tapered specimen crack test with and without filler wires

The CO_2 laser welding system of 5kW was used for the tapered specimen crack test of the Al-Mg alloy sheets. The used tapered specimen was depicted as in Fig. 2. Full penetration bead-on-plate (BOP) melt-runs were

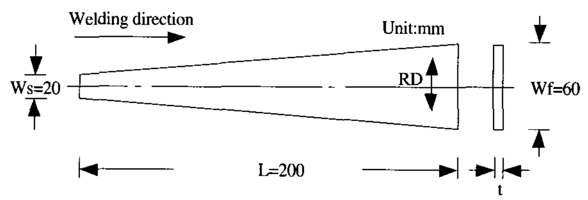


Fig. 2 Shape and dimension of the specimen used in tapered specimen crack test.

made from the narrow edge towards the wide edge along the longitudinal centerline of tapered specimens. Each full penetration melt-run was actually started in a run-on-tap plate placed in front of the narrow edge and stopped in the other run-off-tap plate placed at the rear of the wide edge. This enabled full penetration to be achieved in the beginning at the very narrow edge and thus allowed a longitudinal crack to initiate spontaneously at the narrow edge along the BOP melt-runs. The rolling direction of all the tapered specimens was perpendicular to the bead-on-plate melt-run direction. No external restraint was applied during the bead-on-plate melt-run; each tapered specimen was held loosely by sticky tape on a jig plate that contained a machined cavity slot through which underbead shielding gas was supplied. At least three tapered specimens were tested at each bead-on-plate melt-run condition to confirm the reproducibility of each longitudinal crack length.

The bead-on-plate melt-run conditions were selected to give full penetration and were constant for each test unless otherwise stated; 5 kW laser power and 6m/min welding speed for autogenous melt-runs, 5 kW laser power, 5 m/min welding speed and 4mm/min wire feed speed for wire feed melt-runs.

In addition to autogenous melt-runs, wire feed melt-runs were also carried out with various combinations of base alloys and filler wires in order to examine the effect of filler wire composition (eventually resulting weld metal composition) on the weld metal solidification cracking susceptibility.

The length of the longitudinal crack produced along the centerline of melt-run seam was measured with the aid of dye penetrating. The percentage crack length (PCL), ratio of the measured crack length to the melt-run seam length (i. e. specimen length), was used as an index of the cracking susceptibility.

2.3 Chemical analysis, grain size determination and scanning electron microscopy

The chemical composition of the base alloys, filler wires, and melt-run fusion zone was analyzed using the inductively coupled plasma (ICP) spectroscopic method. In order to measure the grain size of each melt-run fusion zone made by CO_2 laser, polished cross sections and longitudinal sections were etched using electro-etching technique and photos of the polished and electro-etched sections were taken using an optical microscope with polarized light.

These were processed using a computerized image analyzer in order to obtain the average grain size. The as-cracked surfaces on the longitudinal centerline crack of each tapered specimens were also investigated using a scanning electron microscope (SEM) in order to confirm the nature of weld metal solidification cracking and estimate the grain size at the as-cracked surface.

3. Results

3.1 Tapered specimen crack test by autogenous melt-runs

Longitudinal centerline cracks formed along the melt-runs of the tapered specimens made from Al-Mg alloy sheets are shown in Fig. 3.

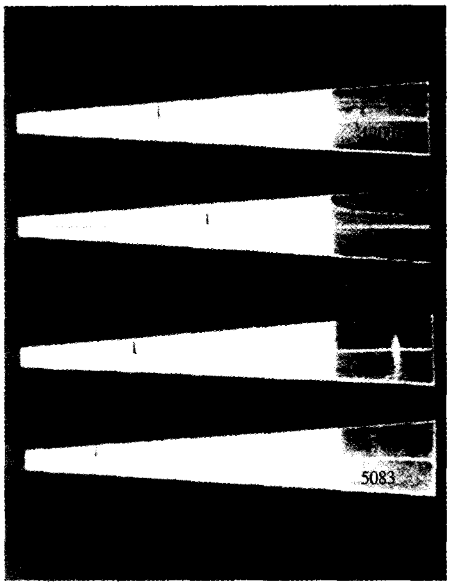


Fig. 3 Tapered crack test specimens which show the variation of longitudinal crack length with the aid of dye penetrating.

The longitudinal crack length was observed to depend on the Mg content. 5083 alloy (4.5 wt.% Mg) exhibited the shortest crack length, while 5251 (1.91 wt.% Mg) showed the longest crack length therein. The PCL values (i. e., the ratio of measured crack length to the whole

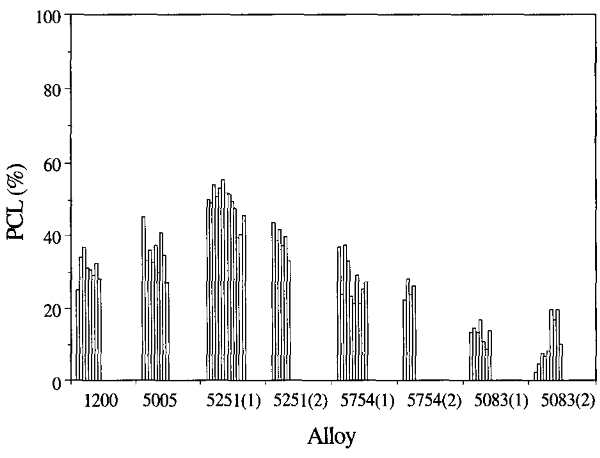


Fig. 4 Variation of weld metal solidification cracking susceptibility of 2 mm thick Al-Mg alloy sheets, as measured by the tapered specimen crack test without filler wires.

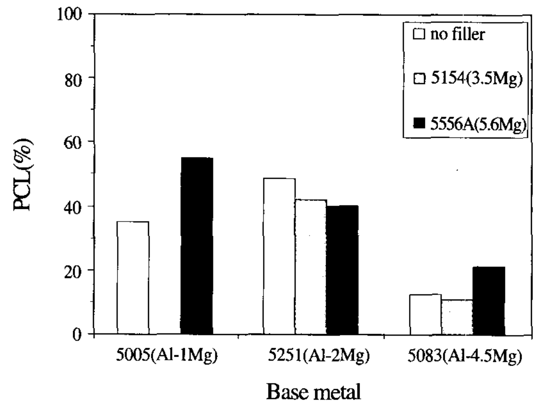
melt-run seam length) are compared with each other as shown in Fig. 4. 5251 alloy (batch 1) containing 1.91 wt.% Mg shows the highest PCL (i. e. the highest cracking susceptibility) and 5083 alloy containing 4.5 wt.% Mg shows the lowest PCL (i. e. the lowest cracking susceptibility) among the Al-Mg alloys investigated. It is noticeable that the cracking susceptibility of pure grade aluminum (1200) lies in between those of these two alloys.

3.2 Tapered specimen crack test by wire feed melt-runs

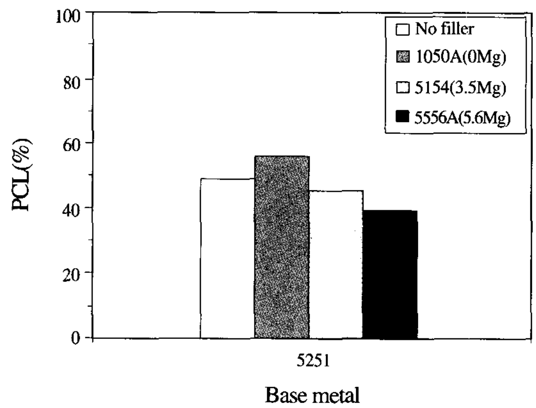
The PCL values obtained from the tapered specimen crack test using various combinations of base alloys and filler wires are summarized in Table 4 together with the

Table 4 Solidification cracking susceptibility of 2mm thick Al-Mg alloys. Results of tapered specimen crack test with filler wires.

Base alloy	Filler wire	Laser power (kW)	weld speed (m/min)	wire feed speed (m/min)	Mg content in weld (wt.%)	Average PCL (%)
5005	5556A	5	5	4	1.9	54.8
5251	5154	5	5	4	2.8	41.8
5251	5556A	5	5	4	2.9	40.3
5083	5154	5	5	4	4.3	11.1
5083	5556A	5	5	4	4.4	21.8
5251	1050A	5	6	2	1.6	56.0
5251	5154	5	6	2	2.2	43.0
5251	5556A	5	6	2	2.8	39.6



a) laser power 5kW, weld speed 5m/min, wire feed speed 4m/min



(b) laser power 5kW, weld speed 6m/min, wire feed speed 2m/min

Fig. 5 Variation of weld metal solidification cracking susceptibility of 2mm thick Al-Mg alloy sheets with filler wires, as measured by the tapered specimen crack test with filler wires.

resulting weld metal Mg content. The variation of average PCL values for each base alloys with filler wires is shown in Fig. 5. When tapered specimens made from 5005 alloy were BOP melted with the addition of 5556A filler wire, the average PCL value was increased 55% compared with 35% PCL for the autogenous melt-run (Fig. 5(a)). The Mg content of the wire feed melt-run fusion zone made with 5556A was 1.9 wt.%, while that of autogenous melt-run was 0.77 wt.%.

For 5251 which was BOP melted with 5154 and 5556A filler wires, average PCL values were 42 and 40%, respectively, which were lower than 49% PCL for autogenous melt-run.

In this case, the cracking susceptibility of wire feed melt-run decreased compared to those of autogenous melt-run, and the Mg content of the wire feed melt-runs was 2.8 wt.% (for 5154 wire) and 2.9 wt.% (for 5556A wire), while that of autogenous melt-run was 1.9 wt.% Mg (Fig. 5(a)). When the same procedure was carried out for 5251 alloy with the addition of filler wires, 1050A, 5154 and 5556A, but using a slightly different melt-run condition (i. e. 5kW laser power, 6m/min. weld speed, and 2 m/min. wire feed speed), average PCL values were 56, 43 and 40%, respectively (Fig. 5(b)). The Mg content of the corresponding wire feed weld metal 1.6, 2.2 and 2.8 wt.%, respectively. Thus the maximum cracking susceptibility of Al-Mg alloy laser welds lies at 1.6 to 1.9 wt.% Mg.

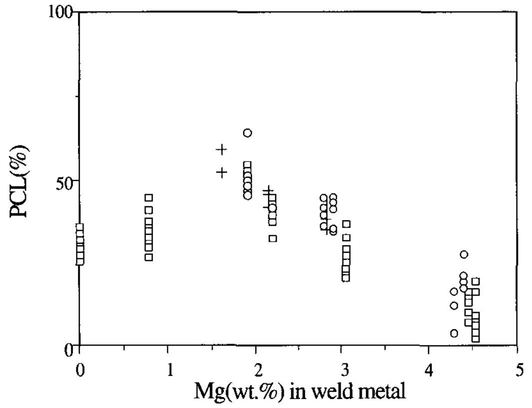
When tapered specimens made from 5083 alloy were melt-run welded with the addition of filler wires, 5154 and 5556A, average PCL values of wire feed melt-runs were 11 and 22%, respectively, while PCL values of the autogenous melt-runs was 13%. The Mg contents of the autogenous and wire feed welds was in the range of about 4.2 to 4.4 wt.%. It is noted that the peak cracking susceptibility of Al-Mg alloy laser melt-runs occurred at

1.6 to 1.9 wt.% Mg when the tapered specimen crack test was conducted using filler wires. Thus the result obtained in the crack test with wire feed melt-runs was consistent with that obtained in the crack test without filler wires (i. e. autogenous melt-run).

4. Discussion

4.1 Effect of Mg content on the solidification cracking susceptibility of Al-Mg alloy laser melt-runs

PCL values of autogenous and wire feed melt-runs were correlated with Mg content in the weld metal as shown in Fig. 6.



□ autogenous welds ; laser power 5kW, welding speed 6m/min
○ wire feed welds ; laser power 5kW, welding speed 5m/min, wire feed speed 4m/min
+ wire feed welds ; lase powerr 5kW, welding speed 6m/min, wire feed speed 2m/min

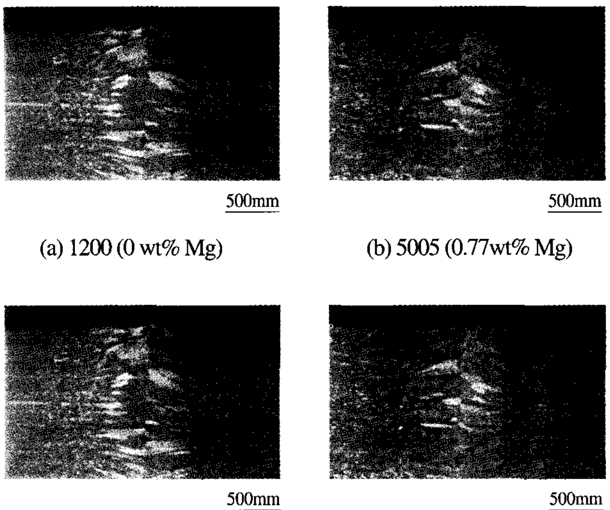
Fig. 6 Variation of weld metal solidification cracking susceptibility of autogenous and wire feed welds of Al-Mg alloys with Mg content.

In autogenous melt-runs, where the Mg content was varied from 0 to 4.54 wt.%, the peak cracking susceptibility occurred at 1.9 wt.%, while in the wire feed melt-runs, where the Mg content of weld metal was varied from 1.6 to 4.4 wt.%, the peak cracking susceptibility occurred at around 1.6 to 1.9 wt.% Mg. Thus the Mg content corresponding to peak cracking susceptibility was consistent for both autogenous and wire feed melt-runs. Moreover, the Mg content corresponding to peak cracking susceptibility measured in this work for laser welds using a self-restraint tapered specimen crack test (i. e. 1.6 to 1.9 wt.%) is comparable to that (i. e. 0.5 to 2.75 wt.% Mg) for arc welds or castings of Al-Mg alloys associated with other type of self-restraint crack tests.

In summary, the cracking susceptibility of Al-Mg alloys laser welds initially increased as Mg content was increased and then it declined with further increase in Mg content, for both autogenous and wire feed melt-runs, as is the case for arc welds or castings (see Fig. 1). Hence when using the self-restraint tapered specimen crack test, the solidification cracking susceptibility could be discriminated quantitatively for Al-Mg alloy laser welds and the result was similar to those obtained using other self-restraint crack test associated with castings or arc welding.

4.2 Solidification structure, grains size and cracking susceptibility

Since longitudinal centerline cracks in the tapered specimens usually propagate along the longitudinal centerline of the melt-runs, the solidification structure, particularly grain size in the weld center region, will influence the solidification cracking tendency. It is well known that a refined grain structure can accommodate the local strain and thus reduce cracking susceptibility [10].



(a) 1200 (0 wt% Mg) (b) 5005 (0.77wt% Mg)

(c) 5251 (1.9 wt% Mg) (d) 5754 (3.1 wt% Mg)

Fig. 7 Variation of weld metal solidification structures of Al-Mg alloy laser welds.

The solidification structures of crack-free portions from autogenous melt-runs in the tapered specimens are shown in Figs. 7 and 8. In the autogenous melt-runs, as the Mg content increased from 0 to 4.5 wt.% Mg, the portion of refined grains increased at the weld center region. When the Mg content is nil, as for the 1200 alloy, a columnar grain structure dominates the fusion zone, and the columnar grains tend to grow in the direction of heat dissipation and finally meet each other at the weld center region with little nucleation of equiaxed grains.

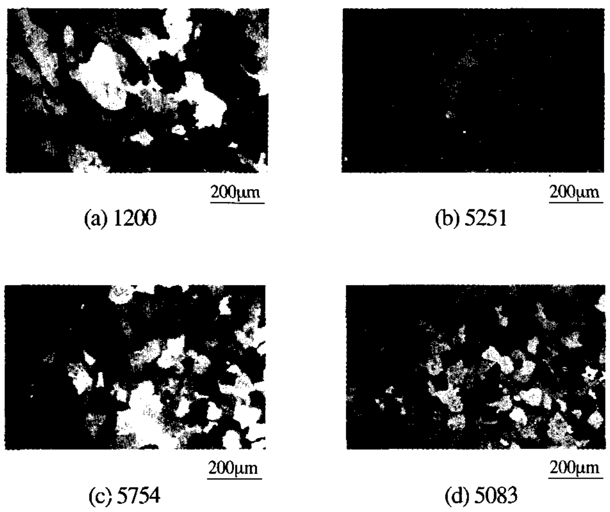


Fig. 8 Variation of grain size at the weld center region of the longitudinal sections in Al-Mg alloy laser welds.

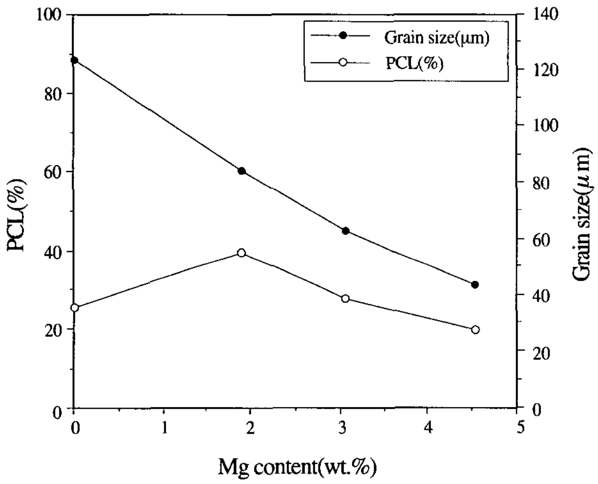


Fig. 9 Variation of solidification cracking susceptibility and grain size with Mg content of Al-Mg alloy laser welds.

The corresponding microstructures along the longitudinal centerline sections at the crack-free melt-run seams are shown in Fig. 8. The grain size measured from Fig. 8 and the corresponding cracking susceptibility for each Al-Mg alloy laser welds were correlated with Mg content in Fig. 9. As the Mg content increased, grain size decreased, although the cracking susceptibility showed a peak value at 1.9 wt.% Mg. The solidification cracking susceptibility of pure grade 1200 aluminium (0 wt.% Mg) is not the highest, even though the average grain size in the fusion zone is the coarsest among the alloys investigated. Hence factors other than grain size also seem to affect the weld metal solidification cracking.

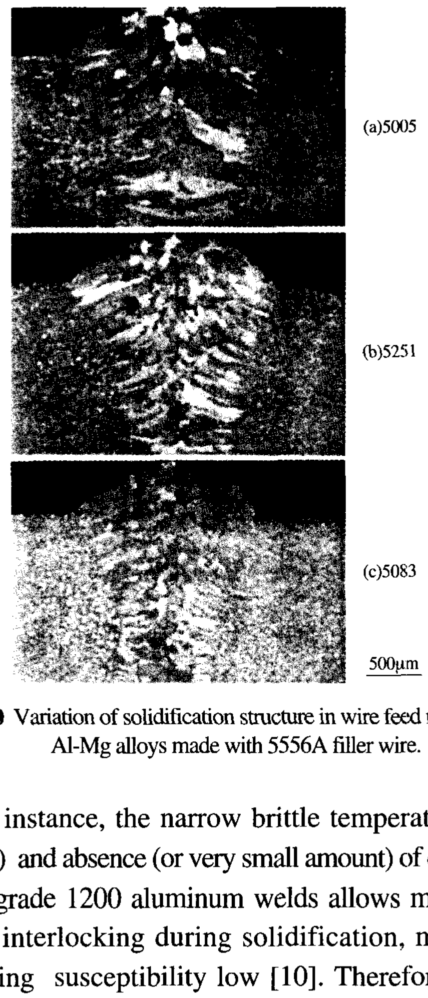


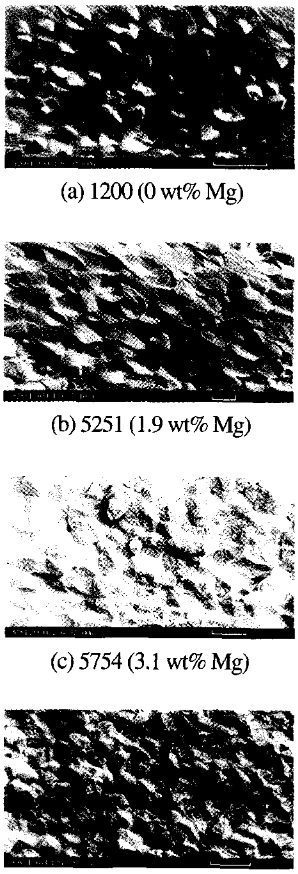
Fig. 10 Variation of solidification structure in wire feed melt-runs in Al-Mg alloys made with 5556A filler wire.

For instance, the narrow brittle temperature range (BTR) and absence (or very small amount) of eutectic in pure grade 1200 aluminum welds allows more solid-solid interlocking during solidification, making its cracking susceptibility low [10]. Therefore various factors such as grain size, BTR and the nature and amount of eutectic all affect the cracking susceptibility interrelatedly.

A similar effect of grain size on cracking susceptibility was also observed in the wire feed melt-runs of Al-Mg alloys, 5005, 5251 and 5083 made with 5556A wire. As the Mg content decreased in the order of 1.9 to 2.9 and 4.4 wt.%, the grain size in the weld center region decreased as shown in Fig. 10 and the corresponding PCL decreased in the order of 54.8 to 40.3 and 21.8%, respectively.

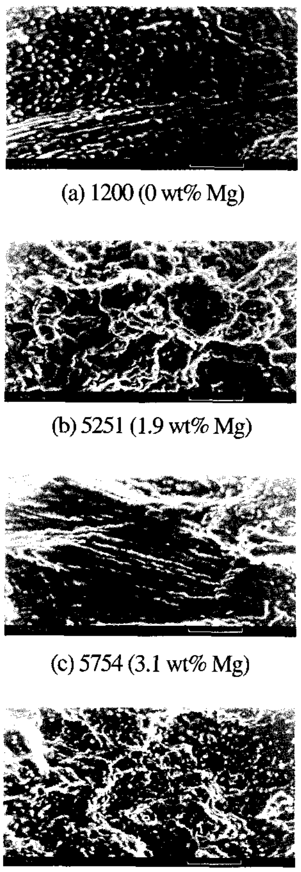
The effect of grain size on the solidification cracking susceptibility was also confirmed by the grain structures shown in the as-cracked surfaces in the melt-run of Al-Mg alloy tapered specimens. SEM fractography of the longitudinal crack surfaces in autogenous melt-runs of the tapered specimens are shown in Fig. 11. Fig. 12 is the magnified image of the as-cracked surfaces shown in Fig. 11 which show that the longitudinal cracking is intrinsically intergranular one and thus the cracking occurred at the final stage of solidification. As the Mg content in the weld metal increased, more refined grains were observed on the as-cracked surfaces.

In the refined grain structure such as 5083 alloy laser welds, considerable development of an interlocked network of crystals seems to endow the weld with increased resistance to the action of tensile stress/strain, thus reducing the solidification cracking susceptibility. Moreover, since the solidification structures are more refined, the local strains around a propagating solidification crack tip also could be accommodated more effectively, as



(a) 1200 (0 wt% Mg)
(b) 5251 (1.9 wt% Mg)
(c) 5754 (3.1 wt% Mg)
(d) 5083 (4.5 wt% Mg)

Fig. 11 SEM fractographs of as-cracked surfaces in tapered specimens of Al-Mg alloys



(a) 1200 (0 wt% Mg)
(b) 5251 (1.9 wt% Mg)
(c) 5754 (3.1 wt% Mg)
(d) 5083 (4.5 wt% Mg)

Fig. 12 Magnified SEM fractographs of as-cracked surfaces in tapered specimens of Al-Mg alloys

was suggested by Pumphrey et al. [11]. Therefore, a reduced grain size will improve the resistance of weld metal to solidification cracking.

5. Conclusion

For both autogenous and wire feed laser welds, the cracking susceptibility of Al-Mg alloys initially increased as Mg content was increased and then it declined with further increase in Mg content, as was observed in the arc welds and castings of Al-Mg alloys. Peak cracking susceptibility occurred at 1.6 to 1.9 wt.% Mg in both autogenous and wire feed welds of Al-Mg alloys when the tapered specimen crack test was used in conjunction with CW CO_2 laser welding.

The grain size in the fusion zone was observed to affect the weld metal solidification cracking susceptibility. For Mg contents above 1.9wt.% Mg, the cracking susceptibility decreased as the grain size decreased. In the range of Mg contents less than 1.9 wt.%, the variation of cracking susceptibility with Mg content can be explained by factors other than grain size. The lower cracking susceptibility of 1200 pure grade aluminum (0 wt.% Mg) compared to 5251 alloy (1.9 wt.% Mg), although the grain size of the 1200 aluminum is the coarsest, seems to be due to the narrowest brittle temperature range or freezing range and the absence of eutectic. Therefore, various factors including grain size affect the cracking of Al-Mg alloy laser welds interrelatedly.

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