EXPERIMENTAL INVESTIGATION OF HOT CRACKING SUSCEPTIBILITY OF WROUGHT ALUMINUM ALLOYS

P. KAH, E. HILTUNEN and **J. MARTIKAINEN**
Lappeenranta University of Technology, Lappeenranta, Finland

The process of gas tungsten arc (GTA) and gas metal arc (GMA) welding of heat treatable wrought aluminum alloys 6005-T6 and 6082-T6, filler metal composition and preheating temperature as the main factors affecting the formation of hot cracking are considered. It has been shown in experiments that specimens welded with 5356 filler wire are more prone to hot cracking than those welded with 4043 wire, and GMAW demonstrates less cracks than GTAW due to its lower heat input. The effect of preheating proves to have little or no consequence.

Keywords: *hot cracking, GMAW, GTAW, filler alloys, preheating, alloy 6005, alloy 6082, heat input*

Outstanding in their unique combination of light weight, high strength, high toughness, extreme temperature capability, excellent corrosion resistance and versatility of extruding and recycling capabilities, aluminum alloys have applications in almost every manufacturing sector such as in transportation, construction and building. A typical application of 6005-T6 and 6082-T6 heat-treatable wrought aluminum alloys is structural and architectural. Aluminum-based alloys can be successfully arc welded without any cracking related problems or with only minor ones. There are three areas that can significantly influence the probability of hot cracking in an aluminum welded structure. These are the susceptible base alloy chemistry, selection and use of the most appropriate filler alloy, and choosing the most appropriate joint design. The 6xxx series alloys are very sensitive to cracking if the base metal composition remains close to the filler metal composition. During arc welding, the cracking tendency of these alloys is adjusted to acceptable levels by the dilution of the base material with excess magnesium (by the use of the 5xxx series Al–Mg filler alloys) or excess silicon (by the use of the 4xxx series Al–Si filler alloys).

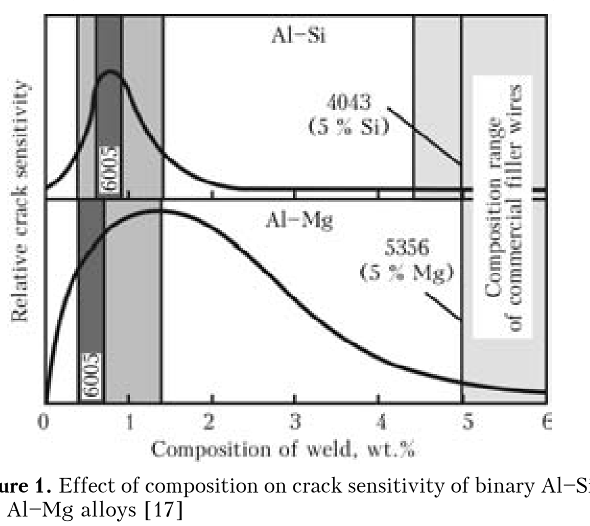

Figure 1. Effect of composition on crack sensitivity of binary Al–Si and Al–Mg alloys [17]

The most appropriate and successful method used to prevent cracking in the 6xxx series base materials is to ensure that an adequate filler alloy is added during the welding operation [1–10].

Much research has been conducted fully understand the main causes of hot cracking with Al–Mg–Si alloys during welding [4–13]. To avoid or minimize the cracking effect it is recommended to use appropriate filler alloys [5–10]. Filler alloys 5356 with 5 % Mg and 4043 and with 5 % Si have been used to compare the effect of filler metal composition on hot cracking. It was concluded that a weld with filler 4043 is less prone to hot cracking than that with filler 5356 due to the narrow solidification temperature range and the lower eutectic temperature of the weld metal which enable the base metal to solidify first (Figure 1). The problem with 4043 filler is that it is easily anodized after welding, producing dark weld metal and a highly visible weld result. This is due to the amount of silicon in the composition. Thus, there is no significant difference in hardness when using either of the two filler alloys. In fact the specimens welded with filler 4043 showed a HAZ that was on average 2 mm wider than those welded with filler 5356 in both GTA (GTAW) and GMA welding (GMAW).

GTAW and GMAW were employed to compare different heat inputs, where the heat input in pulsed GTAW was about 4 times higher than that in pulsed GMAW. Some of the test specimens were also preheated to reduce tensile stresses and the cooling rate so as to decrease the liquation cracking effect. Liquation cracking occurs in the partially melted zone (PMZ) of a weld, i.e. just next to the fusion zone. Liquation can occur along the grain boundary as well as in the grain interior. Grain boundary liquation makes the PMZ susceptible to liquation cracking [14, 15]. Hot cracking is a high-temperature cracking mechanism and mainly a function of how metal alloy systems solidify.

The degree of restraint also significantly affects liquation cracking. The more restraint the material shows, the higher is the probability of liquation crack-

Chemical composition of the base aluminum alloys and filler wires, wt.%

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Others	Al
6005	0.6	0.21	0.12	0.15	0.54	0.028	0.01	0.15	Bal.
6082	1.2	0.33	0.08	0.50	0.78	0.14	0.05	0.15	Bal.
Wire								B	
4043	5.0	0.8	0.3	0.05	0.05	0.20	0.10	0.0008	Bal.
5356	0.25	0.4	0.1	0.05–0.20	5.0	0.10	0.14	0.0008	Bal.

ing. Because aluminum alloys have high thermal contraction and, if they are not relaxed to solidify, they develop high tensile stress that tends to tear or open the liquated grains. Selecting a base metal which is fine-grained and less susceptible to liquation cracking, such as a material that does not contain low melting impurities or segregates, can also help to reduce this problem if it is feasible [9, 16].

Experimental procedures. 10 mm thick 6005-T6 and 6082-T6 wrought aluminum alloy specimens have been tested for cracking based on different criteria. First, filler alloys were used to understand their effect on cracking. The actual chemical compositions of the base and nominal composition of filler metals are shown in the Table. The influence of different welding processes, preheating temperatures and the base alloys were examined on hot cracking. Mechanized 90 Hz pulsed GTAW and GMAW with short circuiting droplet transfer were used for all the experiments for good repeatability.

The welding parameters used were as follows:

- ambient temperature of approximately 20 °C, and some of the samples were heated to about 120 °C before welding to examine the effect of preheating;
- welding currents of 172, 210 and 352 A for both base alloys with and without preheating;
- voltages of 17, 22 and 26 V, respectively;
- welding speed of 2.8–10.0 mm/s;
- filler wire feed rate of 0.34–13.50 m/min;
- pure argon (Ar + 0.03 % NO) was used as a shielding gas in both cases, and flow rates were 14 and 10 l/min for GMAW and GTAW, respectively;
- filler wire electrode diameter of 1.2 and 2.4 mm in GMAW and GTAW, respectively;
- stick-out of 15 mm in GMAW;
- bead-on-plate technique was used in all cases.

Sufficient cleaning of the surface was done using a stainless wire brush prior to welding, with the goal of removing all oxides, oils and loose particles from the surface to be welded. This is especially important because of the susceptibility of the aluminum weld to porosity due to hydrogen and the dross due to oxygen. The materials to be welded should be rigid enough in order to prevent them from contracting without restraint during welding. This allowed hot cracking to be occurred during welding and the crack susceptibility to be evaluated [18–20].

For the GTAW tests, the new Fronius Majicwave 5000 Job G/F GTAW machine was used. The pulsed AC from this machine could be adjusted and measured. The ESAB CWF1 wire feeder was used for the wire feeding purpose. In the case of GMAW, the Kemppi Pro GMA 530 welding machine with pulsed AC was used in all the experiments. The resultant welds were cut, polished and etched with a solution of 8 % HF and 12 % HCl in water for microstructural examination by optical microscopy. The transverse cross-sectional area of each weld was determined with a digital camera and a computer using commercial software.

Results and discussion. Macro and micro photos of the weld cross-sections and Vickers hardness tests (3 kg) were performed so as to investigate the cracks and the resultant loss of mechanical properties, i.e. hardness due to welding. Each hardness graph shows the hardness across the weld. The results of experiment that demonstrate the effect on crack sensitivity are shown in Figure 2. The material used was 6005-T6 alloy GTA-welded at I = 300A and v_w = 2.5 mm/s, and no filler metal nor preheating (20 °C) was applied. As can be seen, in welding without filler metal, hot cracks are located in the weld and HAZ.

Effect of filler alloys. Qualitative evaluation was used to present hot cracking test susceptibility; thus, the extent of cracks due to the filler alloys was simply assessed by an observation of the intensity of cracks in the weld cross-section using high magnification of

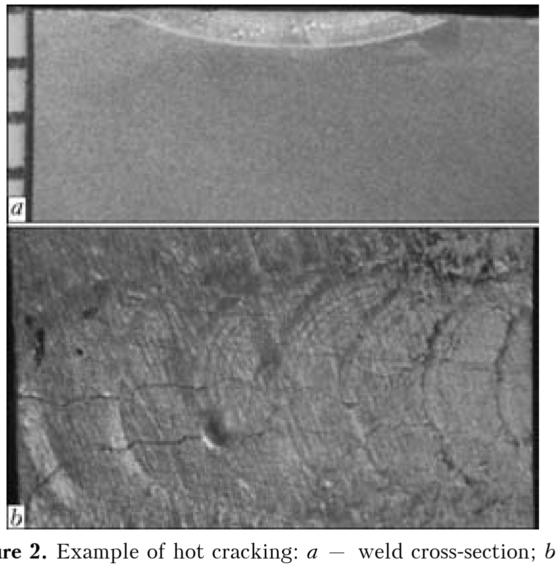

Figure 2. Example of hot cracking: *a* — weld cross-section; *b* — from top view

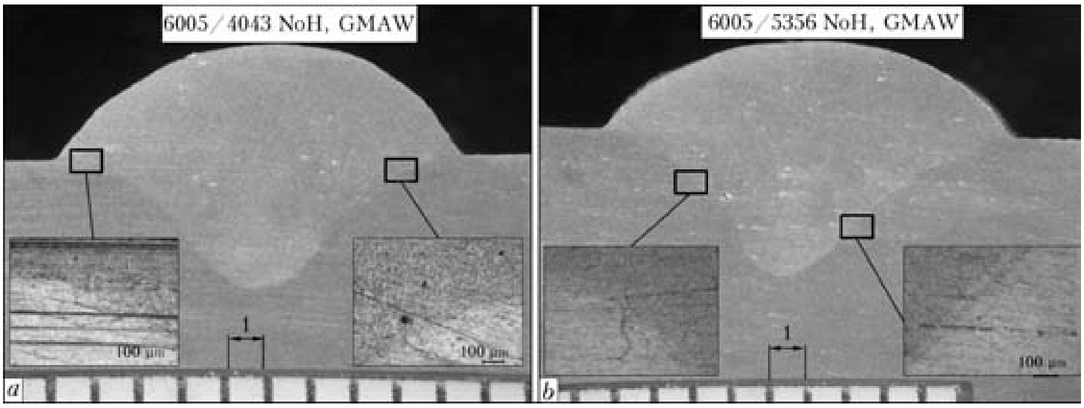

Figure 3. Macro- and microsections demonstrated the effect of filler metal on liquation cracking (here and in Figures below NoH — not preheated sample)

X100. Figure 3, *a* and *b*, show the macrographs of the weld obtained at heat input Q = 440 and 426 J/mm on alloy 6005 with fillers 5356 and 4043, respectively. Open liquation cracks are evident along the outer edge and the root of the weld. The effect of these filler wires on the reduction of cracks can be seen from the macrophotos (see Figure 3), and their influence on hardness can be observed from the graphs of hardness tests (Figure 4).

As can be seen from Figure 4, on the whole the hardness distributions are similar in the weld, HAZ and base metal. Figure 4, *a* and *b*, respectively present the hardness distributions for alloy 6005 specimens GTA- and GMA-welded without preheating. The minimum values in both GTAW and GMAW for those welds using filler 4043 are less than *HV*3-60. If 6082 alloy is welded with the same filler wires, the situation is different. The hardness distribution goes below *HV*3-60 and slightly above *HV*3-80. Thus, there is no significant difference in hardness when using either of the two filler alloys. In fact the specimens welded with filler 4043 showed a HAZ that was on average 2 mm wider than those welded with filler 5356 in both GTAW and GMAW. Fewer and smaller cracks can be observed in the joint that was GMA-welded with 4043 filler wire (see Figure 4, *a*). Hence, it can be concluded that 4043 filler wire is preferable to 5356 from the viewpoint of liquation cracking susceptibility in the GTAW and GMAW of the 6005 alloy.

Effect of welding process. The dependence of the intensity of cracks on GTAW and GMAW processes can be found by comparing Figure 5, *a* and *b*. There are cracks and few smaller cracks in Figure 5, *a*, but only one large crack and fewer small cracks in Figure 5, *b*. But there can be more cracks, including invisible cracks. Accordingly there are more cracks in the GTA-welded specimens than in the corresponding GMA-welded ones. Thus, the GMA-welded samples demonstrate less cracks and higher or similar hardness values with a narrower HAZ than those in GTA-welded ones (Figure 6). The difference in the hardness values of the GTA- and GMA-welded specimens is significant especially (of about *HV*3-9 on average) for 6082 alloy (Figure 6, *c* and *d*). The smallest (of about *HV*3-1.5) difference in hardness values can be observed in the 6005 alloy (Figure 6, *a* and *b*). The width of the HAZ in GTA-welded joint is 4–5 mm greater than that in GMA-welded joint due to the higher heat input.

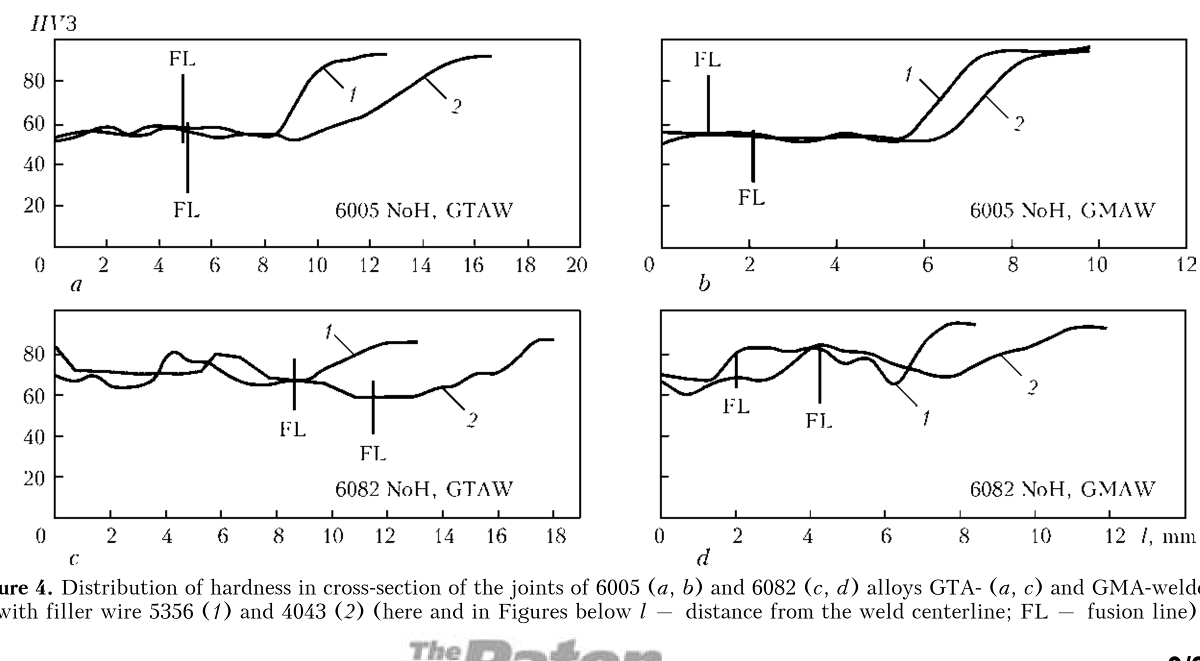

Figure 4. Distribution of hardness in cross-section of the joints of 6005 (*a*, *b*) and 6082 (*c*, *d*) alloys GTA- (*a*, *c*) and GMA-welded (*b*, *d*) with filler wire 5356 (*1*) and 4043 (*2*) (here and in Figures below l — distance from the weld centerline; FL — fusion line)

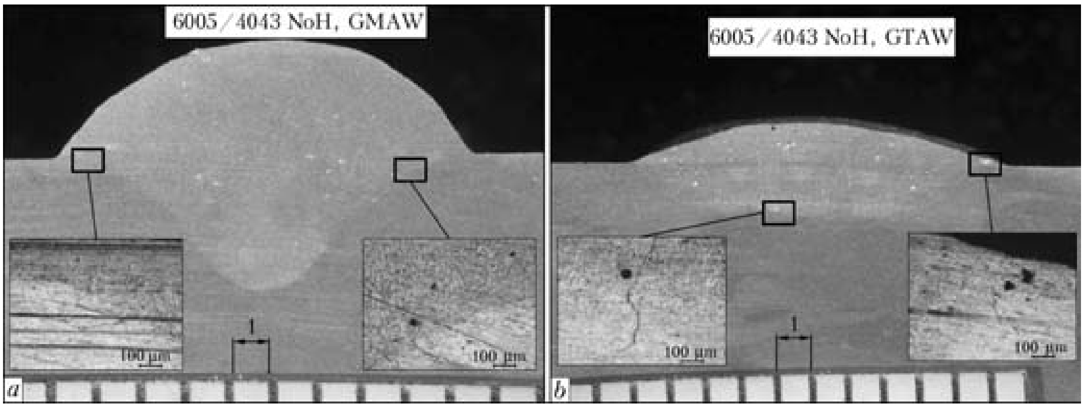

Figure 5. Macro- and microsections of the 6005 alloy joints GMA- (*a*) and GTA-welded (*b*) with 4043 filler at heat input of 440 (*a*) and 1290 (*b*) J/mm

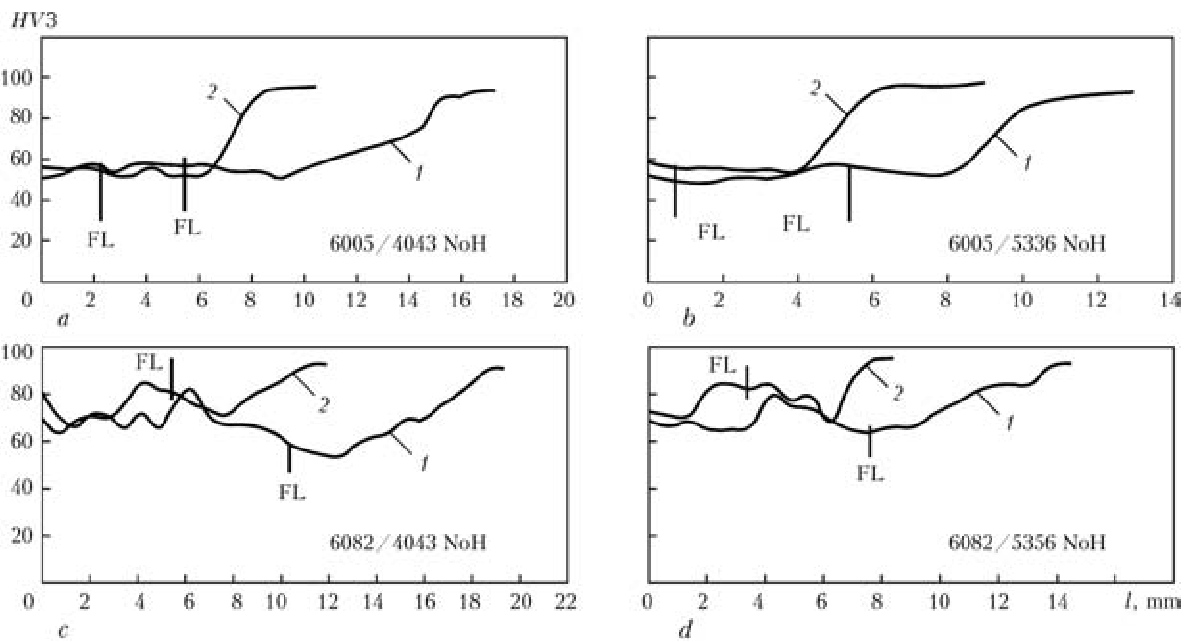

Figure 6. Distribution of hardness in cross-section of the joints of 6005 (*a*, *b*) and 6082 (*c*, *d*) alloys GTA- (*1*) and GMA-welded (*2*) with filler wire 4043 (*a*, *c*) and 5356 (*b*, *d*)

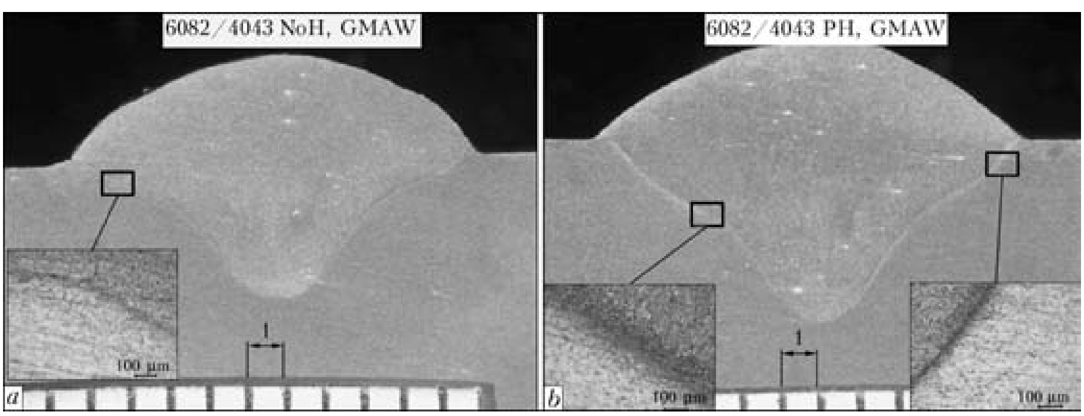

Figure 7. Macro- and microsections of the 6082 alloy joints GMA-welded using 4043 filler without (*a*) and with (*b*) preheating at heat input of 440 J/mm

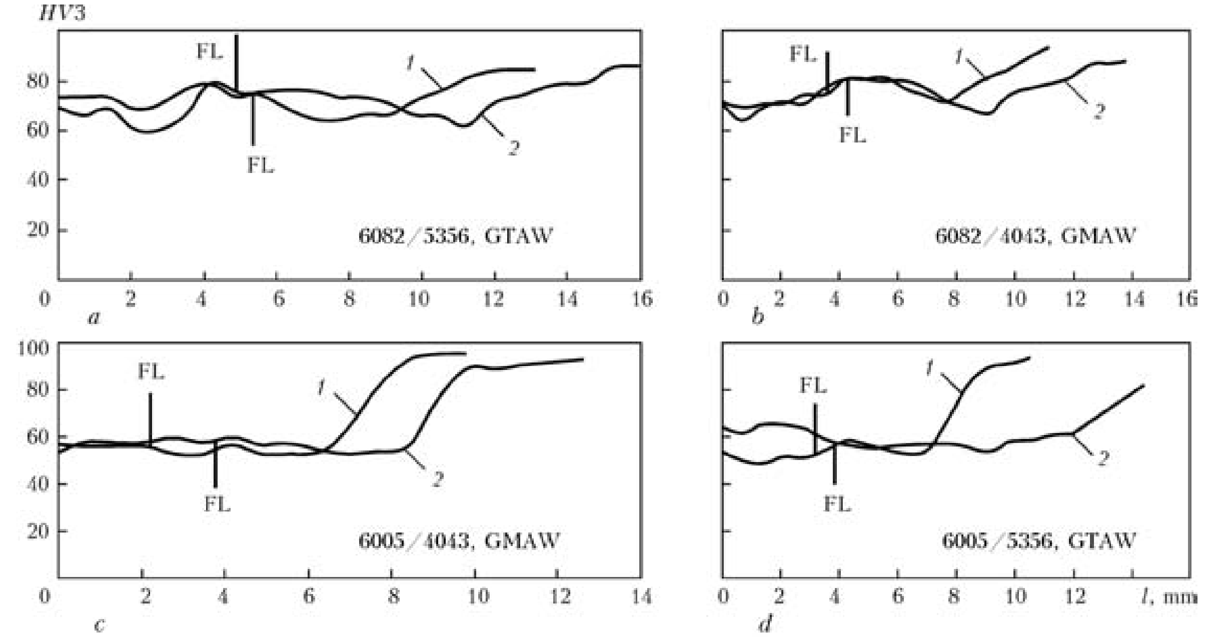

Figure 8. Distribution of hardness in cross-section of the joints of 6082 (*a*, *b*) and 6005 (*c*, *d*) alloys GTA- (*a*, *d*) and GMA-welded (*b*, *c*) using filler wire 5356 (*a*, *d*) and 4043 (*b*, *c*) without (*1*) and with (*2*) preheating

Effect of preheating. Preheating helps in minimizing hot cracking by reduces stresses during cooling. Thus, lower heat input can also be used. Preheating is heating the whole base metal or part of it up to a desired temperature before welding, if it is recommended. This preheating temperature is mostly found in the welding specification procedure for the alloy at hand, but generally it can range from 110–140 °C for most commercial aluminum alloys. Preheating can be done in a furnace if the structure is small, and a bank of heating torches, electrical strip heaters or induction heaters can be required if the structure is larger. The major benefit of preheating is the lower cooling rate for weld and base metal, which leads to better ductility and more resistance to cracking. Especially for highly restrained structures and joints it minimizes the shrinkage stresses in the weld and the adjacent base metal, besides slow cooling enables hydrogen to diffuse before it makes a problem after solidification [21–23]. Al–Mg–Si alloys are sensitive to overheating which can form liquation cracking in the HAZ, so proper care has to be taken when preheating [12].

Figure 7 shows macro and micro photos of the samples GMA-welded with 4043 filler with and without preheating. It was noticed that with preheating, the penetration tends to be slightly deeper than without preheating. The reduction of cracks due to preheating is not remarkable, as can be seen when comparing Figure 7, *a* and *b*. Even though in the case of the 6005 specimen preheated and GTA-welded with filler 5356, the size of the cracks decreases somewhat, but there is still approximately the same number of cracks.

The hardness profiles in Figure 8 demonstrate that there is not more than the *HV*3-1.5 difference in the hardness at preheating and without it, and there is the 1–2 mm wider HAZ in the preheated specimens. When preheating, the softened area enlarges due to the rise in the temperature.

In all three cases, when we combined both the loss of hardness and number of cracks formed, without considerable hardness differences, the intensity of cracks is less when using the 4043 filler than the 5356 one, as well as with the GMA-welded specimen as

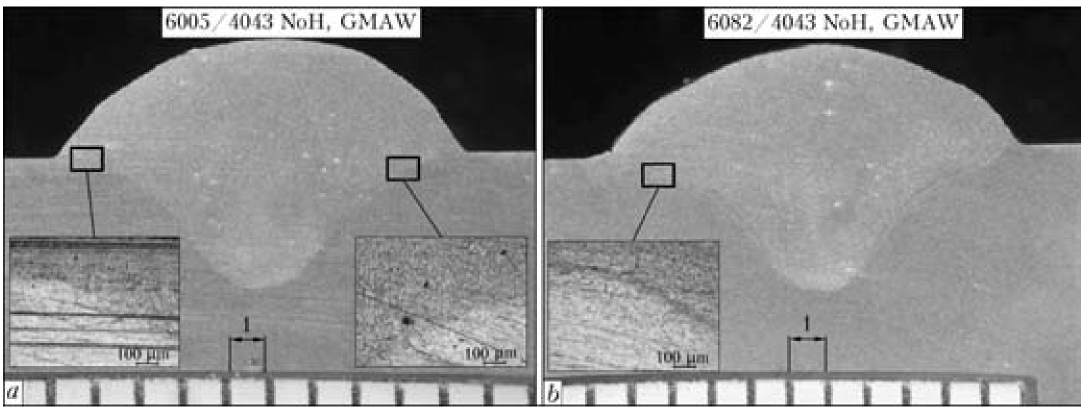

Figure 9. Macro- and microsections of the 6005 (*a*) and 6082 alloy joints (*b*) GMA-welded with 4043 filler without preheating

with the GTA-welded ones. However, the effect of preheating does not show any reduction in the number of cracks.

Effect of base metal. Thus, it follows that according to this experiment the 6082 base alloy is less susceptible to liquation cracking than the 6005 one (Figure 9) at equal heat input $Q = 440$ J/mm in both cases.

CONCLUSIONS

1. The 6082 alloy base metal is less susceptible to liquation cracking than the 6005 alloy.

2. When assessing the liquation cracking susceptibility in GTAW and GMAW of 6005 and 6082 base alloys, GMAW results in fewer liquation cracks and higher or similar hardness with a narrower HAZ than GTAW.

3. The 4043 and 5356 filler metals are immune to solidification cracking, even though liquation cracking can occur.

4. Preheating has little significant effect on avoiding liquation cracks.

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