WELDABILITY TEST OF PRECIPITATION HARDENABLE ALUMINIUM ALLOY EN AW 6082 T6

L. Kolarik, K. Kovanda, M. Valova, P. Vondrous, J. Dunovsky
Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Manufaturing Technology
Prague, Czech Republic

e-mail: ladislav.kolarik@fs.cvut.cz

The article presents results of weldability test of precipitation hardenable aluminium alloys used often for rolling stock production. The research was conducted at Department of Manufacturing Technology, Faculty of Mechanical Engineering, Czech Technical University in Prague. The used material was EN AW 6082 T6. The weldability by GTAW and GMAW welding methods was assessed by Houldcroft`s weldability test (Fishbone test). Using this weldability test susceptibility of the base metal and influence of filler wire selection to solidification cracking was evaluated. As filler wire AlSi5, AlMg4.5MnZr and AlMg5Cr were selected, because they are recommended for selected base metal. During the tests, it was found that to evaluate the susceptibility to solidification cracking GTAW method is much more sensitive than GMAW welding. The results of base metal test had shown that it is very susceptible to solidification cracking. As the filler metal the AlMg5Cr gave the best results, it suppressed solidification cracking the most.

Keywords
Aluminium Alloys, Houldcroft Test, Fishbone Test, Weldability, GTAW, GMAW

1. Introduction

Aluminium is unique relatively young material, which production volume is steadily increasing more than for other metallic materials. Use of aluminium alloys for construction purposes is increasing strongly. This is because of great combination of mechanical, chemical and technological properties of Al alloys that make them suitable for use in almost all industrial areas, e.g. transportation industry [Michna 2005].

There are already more than 120 different Al alloys described in the norms, so dramatic development of brand new Al alloys is not to be expected [Sperlink 2003]. Probably the development will focus on aircraft and cosmic industry, where the main development will be based on known alloys with Li, e.g. Al-Cu-Li, Al-Mg-Li, Al-Li-Zr alloys. For more traditional industrial use there is continuous development of Al-Mg-Si, Al-Mg and Al alloys with Sc. From above cited reasons, the Welding group of Department of Manufacturing Technology is focusing its research of weldability on widely used precipitation hardenable Al-Mg-Si alloys (group 6 according to EN 573).

2. Base metal and filler metal

As base metal (further BM) alloy EN AW 6082 was used. It is often used in the manufacture of transport equipment and is know by brand name Avial. The material was used after heat treatment in the T6 condition (after hardening). According to CR ISO 15608 it belongs to 23.1 weldability group. Chemical composition and mechanical properties are stated at tab. 1.

Suitable filler metals (further FM) for welding of this alloy were selected according to recommendations in the norm EN 1011-4. On the base of stated norm, 3 commercially available materials produced by ESAB Vamberk were selected. Selected filler metals were AlSi5 (OK Autrod 4043), AlMg5Cr (OK Autrod 5356) and AlMg4.5MnZr (OK Autrod 5087). Chemical composition and mechanical properties of these FM are stated at tab. 2 [ESAB 2007]. With use of these FM the susceptibility to the solidification cracking was tested.

3. Weldability tests

One of the main problems occurring during welding of Al alloys are cracks. The most commonly occurring cracks are hot cracks. In

EN AW-6082 (AlMg1Si1Mn)							
Mg	Si	Mn	Fe	Zn	Cu	Cr	Al
0,6 – 1,2 %	0,7 – 1,3 %	0,4 – 1,0 %	< 0,5 %	< 0,2 %	< 0,1 %	<0,25 %	rest
Tensile strength [MPa]		Yield strength [MPa]		Ductility A_{50} [%]		Hardness [HB]	Young modulus [MPa]
Assured	Typical	Assured	Typical	Assured	Typical	Typical	
295	350	240	305	8	11	105	69000

Table 1. *EN AW 6082 T6 – BM chemical composition and mechanical properties*

OK Autrod 4043 (AlSi5)				
Si	Mn	Fe	Zn	Al
5.0 %	< 0.05 %	< 0.60 %	< 0.10 %	rest
Tensile strength – R_m		Yield strength – $R_{p0,2}$		Ductility A_{50}
165 MPa		55 MPa		18 %

OK Autrod 5356 (AlMg5Cr)				
Si	Mn	Fe	Mg	Al
< 0.25 %	< 0.20 %	< 0.40 %	5.0 %	95 %
Tensile strength – R_m		Yield strength – $R_{p0,2}$		Ductility A_{50}
265 MPa		120 MPa		26 %

OK Autrod 5087 (AlMg4,5MnZr)								
Mg	Si	Mn	Zr	Zn	Cu	Cr	Ti	Al
0.6 – 1.2 %	0.7 – 1.3 %	0.4 – 1.0 %	< 0.5 %	< 0.2 %	< 0.1 %	<0.25 %	0.8 %	rest
Tensile strength – R_m		Yield strength – $R_{p0,2}$			Ductility A_{50}			
280 MPa		130 MPa			30 %			

Table 2. *Filler metals – Chemical composition and mechanical properties*

the weld metal (WM) intercrystalline solidification cracks can occur and in the heat affected zone (HAZ) liquation cracking can occur [Kolarik, 2011a]. Therefore welding research of Al alloys usually concentrates on hot cracking as criteria of base material comparison and filler metal comparison. As weldability tests the for hot cracking evaluation Lehigh test, Houldcroft test, Varestraint test, T-joint test can be listed. Mainly used weldability tests are described in detail by Hrivnak [Hrivnak 2009].

Such weldability tests are considered the main source of weldability data of Al alloys. The tests are used to evaluate BM and also filler metals from the point of view of cracking susceptibility that is defined as length of crack to weld length [Matsuda 1980]:

$$A = \left(\frac{l_t}{l_0}\right).100 \quad [\%] \tag{1}$$

A = crack sensitivity [%], l_t = crack length [mm], l_0 = weld length [mm]

When comparing crack sensitivity the results of the same test should be compared, because different tests give various values of crack sensitivity.

In research preceding to this work the T-joint weldability test was used for evaluating the BM and FM. This weldability is used as fillet welds with 1 layer weld. The results of this test do compare only presence or non-presence of cracks and it was found that this weldability test has quite a low sensitivity. The low sensitivity of this test was proved, when none of 3 welds done by 3 different filler wires, in tab. 2, had shown any cracks [Kolarik 2011b]. On the base of T-joint weldability test no distinction between filler wires could be done.

Because of the fact that on the basis of T-joint weldability test no distinction between filler wires could be done, the next research focused on weldability test with higher sensitivity. As more suitable weldability test Houldcroft weldability test (Fishbone test) was selected [Kolarik 2011a].

3.1 Houldcroft crack susceptibility test

The Houldcroft weldability test (Fishbone test) is suitable for evaluating of solidification cracking of thin materials (2 – 3 mm) welded by GMAW and GTAW methods. It is the most widely used test for this purpose.

This solidification crack sensitivity test uses a sample very similar to the Lehigh weldability test [Davis 2002]. In Houldcroft crack susceptibility test the sample has several slots of various lengths that are perpendicular to the weld. These slots reduce the rigidity

Weldability method	W	W_1	W_2	w	L	l_1	l_2	P	G	t
GTAW (TIG)	44.6	22.3	19	6,4	76	6	70	8,5	1	2
GMAW (MIG)	140	70	60	20	240	20	220	23	3	6

Table 3. *Dimensions of Houldcroft test [Hrivnak, 2009]*

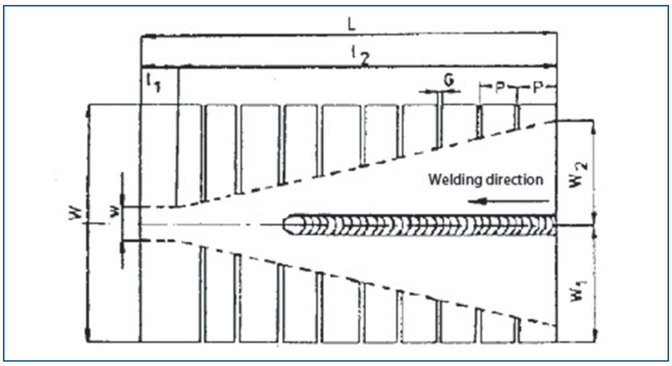

Figure 1. *Schematic of Houldcroft cracks susceptibility test*

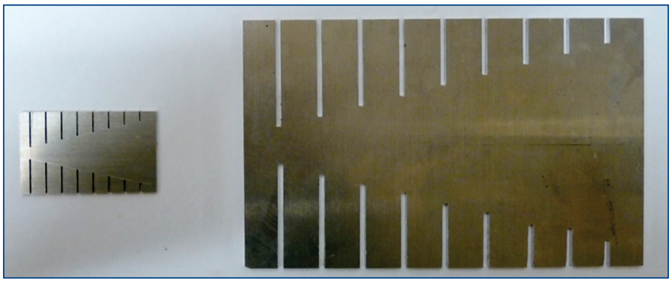

Figure 2. *Comparison of fabricated samples used for Houldcroft test, left side GTAW sample, right side GMAW sample*

of the sample. Then the full penetration weld is done. At the weld beginning the length of slots is minimal, rigidity maximal and the crack will occur. With the increase of the slots length the rigidity of the sample decreases and the crack created at the beginning will cease to exist at some point. The length of created crack is measured and can be used for calculation of A (1) and comparison of solidification cracking susceptibility of different materials.

Dimensions of the sample, dimensions and quantity of slots depend on the sheet thickness and welding method. The used dimensions are stated in table 3 according to recommendation of prof. Hrivnak [Hrivnak 2009].

At figure 2 the size of samples fabricated according to table 3 are shown.

4. Research laboratory

Experiment was done at interdepartmental Laboratory of welding technologies of CTU in Prague (Laboratoř výuky svářečských technologií na ČVUT v Praze) founded by Faculty of Mechanical Engineering in cooperation with other faculties of Czech Technical University.

For the experiment the robotic welding cell, supplied by Migatronic Automation, was used. The GMAW and GTAW welding experiments are done at this work cell. There is a lot of measurement and sensory equipment available, also the off-line programming is possible at this laboratory. The basis of this robotic cell is welding robot Fanuc ArcMate 100iC in combination with 1-axis manipulator (figure 3.). The movement of robot and manipulator is coordinated in real time by a function coordinated motion.

Figure 3. *Robotic welding cell at CTU in Prague*

For GTAW welding the source Migatronic PI320 AC/DC was used. This source has patented system D.O.C. for welding of Al alloys, when the oxide layer needs to be removed. For GMAW welding Migatronic Sigma 400 Pulse was used.

Because the GMAW and GTAW were done by robot at robotic cell, for both welding methods the filler wire of unified diameter 1.2 mm were used.

5. Experimental setup

5.1 GTAW welding setup

The size of the sample was 44.5 x 76 mm and 3 mm thickness. The GTAW welder was setup to weld with AC current and pulsation.

According to [Matsuda 1980] the Houldcroft test for GTAW is suitable for low welding speeds, approximately 300 mm/min for 2 mm

Effective welding current I_f [A]	Pulse current I_p [A]	Base current I_z [A]	Voltage U [V]	Welding speed v_{sv} [mm/min]	Wire feeding rate v_p [m/min] (pulsed)
160	230	90	16.4	300	1.3 / 0.8

Table 4. *GTAW welding parameters*

thick samples. The welding parameters need to be selected to assure full penetration from the weld beginning, so that the crack would occur at the weld start. The parameters for full penetration and crack occurrence were tested on special samples and parameters are stated in table 4.

The tungsten electrode WL20 with diameter 3.2 mm was selected. The shielding gas is Ar, purity 4.6, with flow rate of 17 l/min. For all the samples the same setting was used, the filler wire is the only exception. Prior to welding oxide layer was mechanically cleaned by stainless brush and samples were degreased. The same welding jig was used for GTAW and GMAW welding, figure 4. Run-on, run-off plates were used for both welding methods.

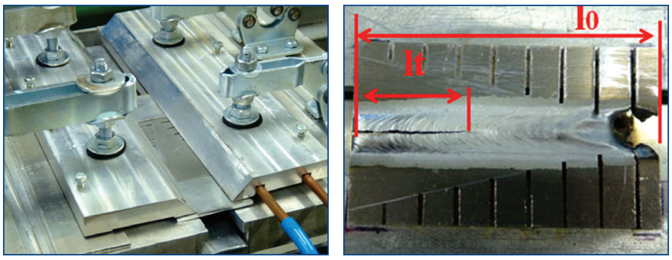

Figure 4. *Welding jig (left), sample after GTAW welding (right)*

5.2 GMAW welding setup

The size of welding samples needed to be adapted for GMAW welding, so the sample size was 140 x 240 mm, 3 mm thick. The polarity DC (+) was used to get proper arc cleaning effect (direct current, electrode positive). Three different currents were used, noted at table 5.

Sample	Weldingcurrent I [A]	Voltage U [V]	Welding speed v_{sv} [mm.min^{-1}]	Wire feeding rate v_p [mm.min^{-1}]
A	130	21.2	550	7.6
B	145	22	550	8.7
C	160	22.4	550	9.6

Table 5. *GMAW welding parameters*

It was found that to reach solidification crack occur at the weld beginning is more difficult with GMAW compared to GTAW, probably because of weld size and amount of filler wire in the WM.

The shielding gas is Ar, purity 4.6, with flow rate of 15 l/min. Prior to welding oxide layer was mechanically cleaned by stainless brush and samples were degreased.

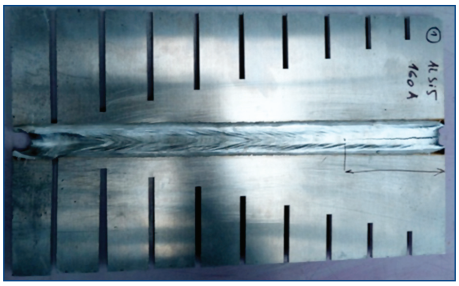

Figure 5. *Sample after GMAW welding*

6. Results of the experiment

GTAW welding made full penetration welds for each of 3 filler materials plus 3 welds on BM without filler wire (12 samples for GTAW). With GMAW welding assessing BM only was not possible, so for each of 3 filler metals 3 samples were welded (3 different current settings) (9 samples by GMAW). After the welding the length of occurring cracks was measured, the lengths were compared for different fillers and the solidification cracking susceptibility ratio was calculated.

6.1 GTAW experimental results

The measured crack lengths for each sample and the solidification cracking susceptibility ratio for each filler metal are noted in the table 6. On the base of this table the graphs at figure 6 and figure 7 were created.

Sample: A, B, C – three samples for each filler	Filler metal	Length of the crack l_f [mm]	Average length of crack for each filler metal l_f [mm]	Cracking susceptibility ratio $A = (l_0/l_f).100$ [%]
1A	Without filler wire	32	33.3	43.8
1B		34		
1C		34		
2A	AlMg4.5MnZr (OK Autrod 5087)	34	33	43.4
2B		33		
2C		32		
3A	AlSi5 (OK Autrod 4043)	26	26	34.2
3B		25		
3C		27		
4A	AlMg5Cr (OK Autrod 5356)	8	7.6	10.5
4B		8		
4C		7		

Note: Total length of the weld is the same as total sample length. l_0=76 mm

Table 6. *GTAW welding – Houldcroft test results*

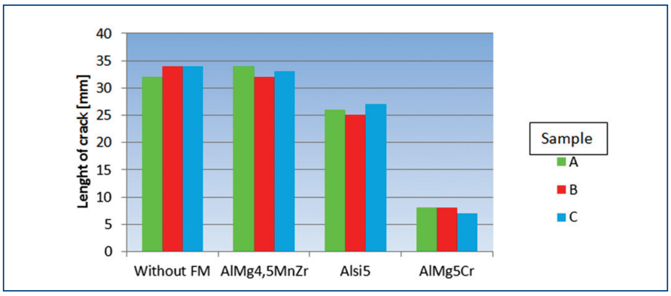

Figure 6. *GTAW – length of the measured cracks, filler metal influence*

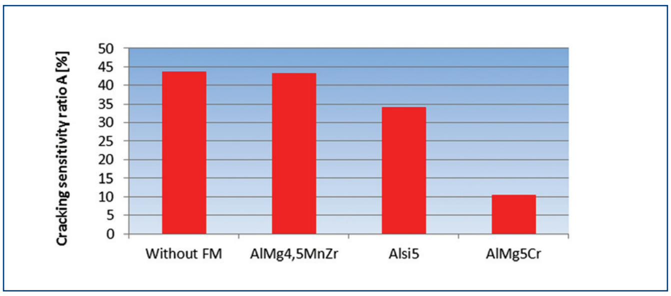

Figure 7. *GTAW – cracking susceptibility ratio, filler metal influence*

Sample (current)	b	D	h_1	h_2
1A (130 A)	8	5	2,4	1
1B (145 A)	7	5	2,5 – 3,1	1,5
1C (160 A)	9 – 10	8 – 9	3,9 – 5 *	-(1,6 – 1,8)
2A (130 A)	8,5 – 9	6,5	0,5 – 1,1	1,6 – 1,8
2B (145 A)	10	11	-(0,9 – 1,1)	2,6
2C (160 A)	14	14	-(0,5 – 1)	2
3A (130 A)	7 – 8	5 – 5,5	2,1	1,6 – 2,8
3B (145 A)	8	6,5	1,2 – (–1,2)	3,5 – 4,1
3C (160 A)	9	8	0,8 – 0,3	2,9 – 3,4
*Note: * burn through was noticed at the sample; b = weld width, d = root width, h_1 = bead reinforcement, h_2 = root reinforcement*				

Table 7. *GMAW welding – size of the weld bead*

Sample	Filler metal	Crack length l_1 [mm]	Cracking susceptibility A =(l_0/l_1).100 [%]
1A (130 A)	AlMg4.5MnZr (OK Autrod 5087)	0	0
1B (145 A)		46	19.3
1C (160 A)		55	22.9
2A (130 A)	AlSi5 (OK Autrod 4043)	0	0
2B (145 A)		49	20.4
2C (160 A)		64	26.7
3A (130 A)	AlMg5Cr (OK Autrod 5356)	0	0
3B (145 A)		27	11.25
3C (160 A)		32	13.3
Note: Total length of the weld (l_0)is same as sample length 240 mm			

Table 8. *GMAW welding – Houldcroft test results*

6.2 GMAW experimental results

For the low current setting (130 A) the solidification cracks did not occur. Only at higher current setting (145, 160 A) the cracks were created and their length could be measured. Still the cracks were not as easily visible as for GTAW welding, so the penetration test was used to indicate the cracks and make measurement more precise. The examples of penetration test are at figure 8.

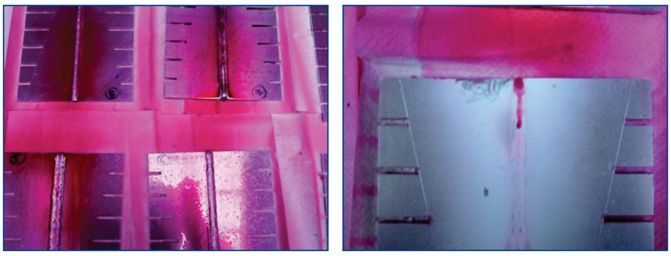

Figure 8. *GMAW welded samples after penetration test*

The sizes of the welds produced by GMAW at different welding parameters are at the table 7 as measured along the whole length of the weld. The length of the cracks as measured after penetration test, calculated solidification cracking susceptibility ratio are at table 8. On the base of measured data, graphs at figure 9 and 10 were created.

7. Discussion of the results

The base metal EN AW 6082 (AlMg1Si1Mn) crack sensitivity ratio found by GTAW welding is A = 43.8 %. As upper limit for crack sensitivity evaluated by Houldcroft test is usually considered A=35 % [Davis 2002]. From stated data, comparison of measured and upper limit values shows (43.8 %>35 %) that the base metal cracking susceptibility can be evaluated as high and needs to be lowered. This can be achieved by use of proper filler metal.

The measured data of BM cracking susceptibility are in accordance with known fact that precipitation hardenable Al alloys are often susceptible to solidification cracking, because of their chemical composition. On the base of this fact these precipitation hardenable Al alloys are often welded by non-hardenable filler

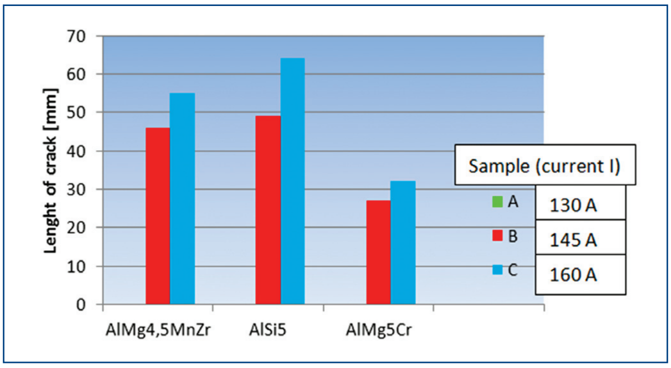

Figure 9. *GMAW – length of the measured cracks, filler metal influence*

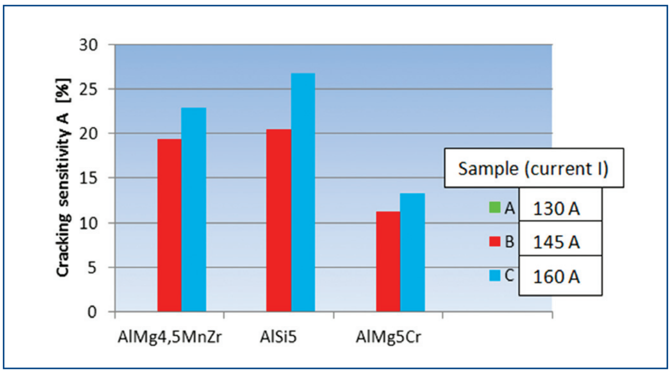

Figure 10. *GMAW – cracking susceptibility ratio, filler metal influence*

wires alloyed with higher amount of Mg and/or Si, according to norm EN 1011-4.

The best experimental results for GTAW welding were gained with filler AlMg5Cr, where resulting cracking susceptibility was A = 10.5 %. With the filler AlSi5 measured cracking susceptibility was A = 34.2 % and with filler AlMg4.5MnZr it was A=43.4 %.

According to [Kolarik 2008] using AlMg4.5MnZr gives the best mechanical properties of the weld metal, but according to current results this wire is not good with regard to solidification cracking, because measured crack sensitivity ratio with this FM was bad, similar to the ratio measured for BM.

For GMAW welding the best results were again with AlMg5Cr, where A = 13.3 %. Then is AlMg4.5MnZr with A = 22.9 %, and last is AlSi5 with cracking susceptibility ratio A = 26.7%.

Some differences between cracking ratio measured for welds done by GTAW and GMAW welding suggest that the cracking susceptibility is influenced also by welding method, e.g. heat input, sample size. The important is that best results of FM AlMg5Cr are supported by results of GTAW and GMAW also.

8. Conclusions

Houldcroft test for evaluating solidification crack sensitivity was employed during welding of Al alloy EN AW 6082 without and with filler wire. As a welding methods GMAW and GTAW welding were used. The results had shown that more proper for Houldcroft test evaluation is GTAW welding, because it has much higher sensitivity because of precise parameters setting, small size of test sample, ease of test execution and data evaluation. Also by GTAW the BM crack sensitivity without filler metal can be evaluated.

Measured crack sensitivity of the EN AW 6082 is very high (A=44 %), there is risk of solidification cracking and because of this fact it needs to be lowered by selection of proper filler metal.

It was proved that selection of proper filler material can strongly suppress solidification cracking susceptibility of the BM. By both welding methods it was found that the best results to suppress solidification cracking have been reached using AlMg5Cr filler metal alloyed with 5 % Mg that lowered cracking susceptibility significantly (A_{GTAW}=10.5 %, A_{GMAW}=13.3 %).

To suppress solidification cracking, filler metals with higher amount of Mg and/or Si (approx. 5 %) are often used [EN 1011-4]. According to our best results with the AlMg5Cr, we want to conclude that alloying with high amount of Mg (5%) can positively influence solidification cracking very much.

Acknowledgment

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Contacts:

Dipl. Ing. Ladislav Kolarik, IWE, Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Manufacturing Technology, Technicka 4, Praha 6, 166 07, Czech Republic
tel.: +420 224 352 630, +420 224 310 292
e-mail: ladislav.kolarik@fs.cvut.cz