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Welding EN AW 7075 Aluminium Alloy Sheets – Low-energy Versus Pulsed Current

Abstract: The article presents test results related to welding thin EN AW 7075 aluminium alloy sheets and the course of technological tests aimed at determining the usability of the CMT and MIG-Pulse methods for welding 2.0 mm EN AW 70775 alloy butt joints. The article also discusses the basic difficulties encountered while welding the 7xxx series alloy and presents the specific character of the welding method employing low arc energy and using pulsed current. The article presents the selected results of strength-related and macroscopic metallographic tests of the welded joints along with their detailed analysis. The study also describes the "circle path" hot crack resistance test; the joints obtained in the test were subjected to detailed microscopic metallographic examination and microanalysis of chemical composition. It should be emphasised that the CMT method enables the obtainment of good quality and aesthetics of welded joints made of the aluminium alloy generally recognised as poorly weldable.

Keywords: EN-AW 7075, CMT, MIG-Pulse, aluminium alloys, thin sheets

Introduction

Increasing popularity of multi-component aluminium alloys (6xxx, 7xxx and 2xxx series alloys) in industry is dictated by the necessity of making lightweight structures simultaneously satisfying strength-related criteria. The same phenomenon can be observed with reference to welded joints made of such alloys which must be characterised by appropriate quality, aesthetics and mechanical properties. Until today, welding of the alloys mentioned above has been performed using the MIG method, and particularly its variant utilising pulsed current. However, using the MIG method for welding thin-walled elements made of high strength, wrought and precipitation hardened aluminium alloys resulted in the production of joints, the quality of which "left much to be desired". The elements were covered with spatters and contained gas pores; the excessive heat input to the material caused angular deformations, reduced joint mechanical properties and favoured the formation of hot cracks. The presence of surface imperfections reduced the aesthetics of the finished product. This, in turn, entailed additional costs connected with the necessity of removing such imperfections.

The national industry relatively seldom makes use of welding 7xxx series alloys (Al-Zn-Mg) - mainly due to technological and metallurgical difficulties [1-3]. Problems accompanying the welding of Al-Zn-Mg alloys can partly be solved by using filler metals of appropriate chemical composition. It is also possible to provide filler

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metals with slight additions of modifiers such as titanium, zircon, boron and chromium, which by reducing the size of weld grains, decrease weld susceptibility to cracking [1,2].

The second half of the 1990s saw the advent of innovative MIG/MAG welding machines developed especially for solving problems which accompany joining thin-walled elements characterised by limited weldability, susceptible to post-weld porosity and sensitive to heat effect. This article presents the comparison and the influence of low-energy (CMT) and pulsed current (MIG-Pulse) methods on the quality, aesthetics, mechanical properties and structure of welded joints made of the Al-Zn-Mg type aluminium alloy.

Test materials

The technological tests of MIG-Pulse CMT welding methods involved making butt joints of 2.0 mm thick 7xxx series alloy sheets (grade EN AW 7075 according to PN-EN 573-3) [6] using the following filler metals according to PN EN ISO 18273 [7]:

- electrode wire AlMg4.5MnZr (Al 5087) ϕ1.2 mm,
- electrode wire AlCu6MnZrTi (Al ML2319) ϕ1.2 mm.

The chemical composition of the parent metal and that of the electrode wires is presented in Tables 1 and 2.

The alloys of 7xxx series are usually welded using the filler metals made of the 5xxx series alloys. As opposed to the most popular AlMg5Cr type filler metal, the AlMg4.5MnZr (Al 5087) electrode wire enables obtaining slightly less advantageous plastic properties, yet compensated by better mechanical properties of the joints. In turn, the AlCu6MnZrTi (Al ML2319) filler metal is used for welding joints of the 2xxx and 2xxx+7xxx series alloys. These filler metals enable the performance of the post-weld precipitation hardening and contain such modifiers as zircon, chromium and titanium which stabilise the structure, prevent the grain growth and reduce weld cracking susceptibility.

Methodology

The technological tests involving both welding methods were performed on the station equipped with a Fronius-manufactured Synergic 2700 device (CMT) and Cloos-manufactured GLC 553 MC3R device (MIG-Pulse) integrated with a Cloos-manufactured ROMAT 310 robot.

The testing methodology was similar for both joining methods. An important criterion for the selection of welding parameters was the elimination of porosity appearing on the surface of welds at an excessively high welding rate. Due to the significant number of factors affecting the quality of welded joints the window of welding parameters ensuring the satisfaction

Table 1. Chemical composition of the parent metal

Alloy designation		Content of chemical elements [%]								
Numerical	Chemical symbol	Zn	Mg	Cu	Fe	Si	Mn	Cr	Zr+Ti	Ti
EN AW 7075	AlZn5.5MgCu	5.10÷ 6.10	2.10÷ 2.90	1.20÷ 2.00	to 0.50	to 0.40	to 0.30	0.18÷ 0.28	to 0.25	to 0.20

Table 2. Chemical composition of the electrode wires

Alloy designation		Content of chemical elements [%]								
Numerical	Chemical symbol	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr
Al 5087	AlMg4.5MnZr	0.25	0.4	0.1	0.7÷ 1.1	4.5÷ 5.2	0.05÷ 0.25	0.25	0.15	0.1÷ 0.25
Al ML2319	AlCu6MnZrTi	0.06	0.18	6.36	0.29	0.01	-	0.02	0.11	

of the quality level B requirements according to PN-EN ISO 10042 [8] is very narrow. In addition, the CMT method recommended for making joints of thin-walled elements favours the "relatively easy" welding technology development. In turn, making proper joints of 2.0 mm thick sheets using the MIG-Pulse method required labourious trials and more precise technological settings. The welding technological tests, visual tests (VT) and penetrant tests (PT) demonstrated the possibility of using welding parameters enabling the obtainment of welded joints characterised by the quality level B according PN EN ISO 10042 for both welding methods mentioned above.

Tests and Results

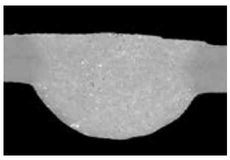
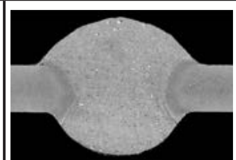
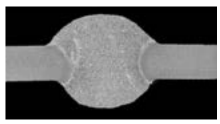
The visual tests revealed that the CMT welded joints had welds with the more uniform and convex face in comparison with the joints obtained using the MIG-Pulse method. The higher weld face of the CMT welded joints can be ascribed to the character of the CMT method and, more exactly, to the software in the form of synergic lines characterised by lower arc voltage values and higher current values in comparison with the MIG-Pulse method synergic lines. The size of the face was also affected by the smaller number of spatters present on the CMT welded sheets.

Fig. 1. View of the welded joint made of the 2.0 mm thick EN AW 7075 alloy, a) - b) MIG-Pulse, c) CMT

The surface of all the joints made was covered with a poorly removable oxide layer (Fig. 1). The layer was more intense and significantly wider while using the AlMg4.5MnZr electrode wire and the MIG-Pulse method. Attempts to remove this layer from the surface of welded aluminium sheets by means of a cloth saturated with acetone proved very labourious or even impossible (necessity of mechanical working) in the case of the pulsed current welded joints. On the CMT welded joints the oxide layer was considerably thinner and easy to remove. In addition, the surface of the CMT welded joints contained fewer spatters. Recently, the aesthetics of aluminium joints, particularly in thin-walled structures, has become an important assessment criterion additionally favouring the CMT method. The difficulty removing the oxides from the joint surface was probably due to the heat input to the elements joined. This in turn justified the conclusion that in spite of similar current and arc voltage settings for both methods, the linear energy in both processes differed significantly.

Visual and penetrant testing did not reveal the presence of any hot cracks, which was confirmed by the results of metallographic examination (Table 3).

Table 3. Results of macroscopic metallographic examination of the 2.0 mm thick EN-AW 7075 aluminium welded joints.

Electrode wire	MIG-Pulse	CMT
AlMg4.5MnZr (Al 50987) ϕ1.2 mm		
AlCu6MnZrTi (Al ML2319) ϕ1.2 mm		
Mag. 4x		

The joint surface seemed free from the 2017 type imperfections according to PN EN ISO 6520-1, yet radiographic tests (RTG) detected their presence.

The amount of porosity in the welds was in accordance with PN EN ISO 10042:

– 1-2% of the weld cross-section area projection on the radiogram for the AlMg4.5MnZr filler metal, making the welded joints meet quality level B or C,
– ≤1% of the weld cross-section area projection on the radiogram for the AlCu6MnZrTi, filler metal, making the welded joints meet quality level B.

The imperfection in the form of excess weld face penetration was restricted in quality level C according to PN-EN 10042, therefore it was acceptable by standard PN-EN ISO 15614-2:2008 concerned with the qualification of aluminium alloy welding technologies. The surface of the metallographic specimens contained an acceptable amount of small-diameter gas pores comparable for both methods.

The limitation of porosity and the absence of hot cracks in the joints was obtained due to low linear energy applied and, primarily, due to the appropriate welding rate and the use of rich composition electrode wires. The elimination of the imperfections was also due to the characteristics of both welding methods – ensuring more precise liquid metal transfer in the arc in comparison with the classical MIG method.

In order to look more precisely into the aspect of various heat input to the material for similar or identical settings of technological parameters in both welding methods, the technological tests mentioned above were supplemented with additional tests consisting in welding one-side stiffened joints aimed to measure and compare the angular deformation α of the joints (Fig. 2). For each material system 5 joints were made. The averaged test results are presented in Table 4.

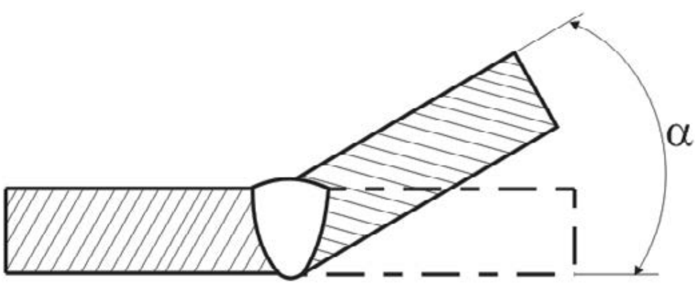


Fig. 2. Joint angular deformation

Table 4. Measurements of angular deformations α in joints made of EN-AW 7075 aluminium alloy using the CMT and MIG-Pulse methods

Welding method	Thickness [mm]	Deformation angle α* [°]
MIG-Pulse	2.0	9.0
CMT	2.0	6.5
* - mean from measurements of 5 welded joints		

The measurements conducted clearly indicated the lower value of angular deformation for the CMT welded joints. This was due to the lower heat input to the joining zone and due to the weld geometry differences resulting from the specific character of individual welding methods (see the macroscopic metallographic specimens) (Fig. 3-6). The higher heat input to the joint in the MIG-Pulse method, if compared with that observed in the CMT method, was responsible for the greater angle α and for the greater hot crack susceptibility of the joints made of the EN AW 7075 alloy.

The next stage involved "circle path" hot crack resistance tests [2,4,5]. The values of the technological parameters used were close to those adjusted while making the butt joints. For each electrode wire, five welding trials were performed. The selected "circle path" test results are presented in Figure 3.

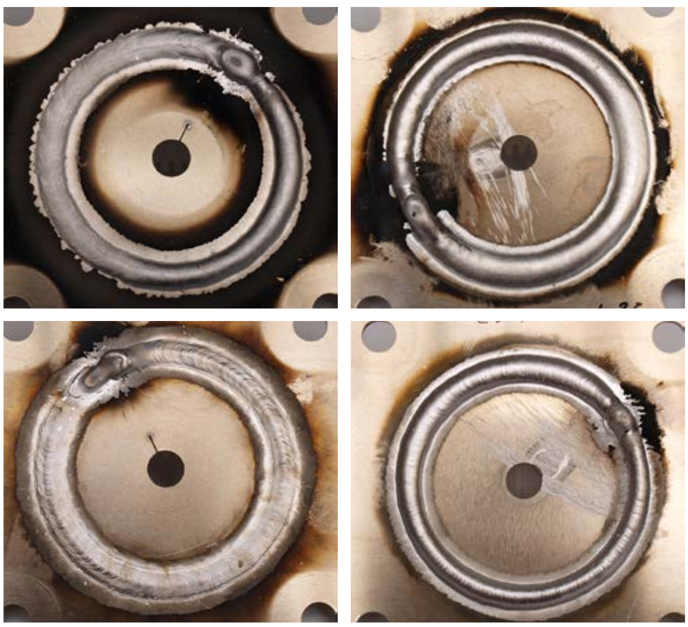
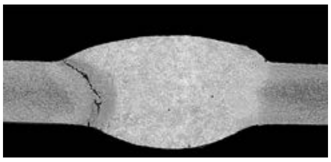
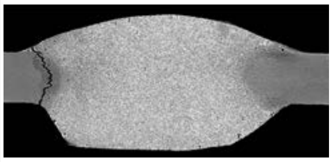
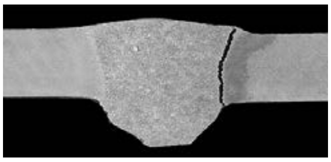
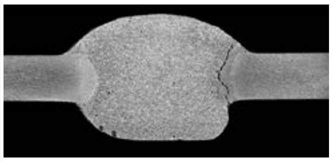


Fig. 3. "Circle path" test results for the MIG-Pulse method (a,c) and CMT (b,d) performed using the a),b) AlMg4.5MnZr; c),d) AlCu6MnZrTi electrode wires

The visual tests revealed differences in weld shapes in each of the test pieces. Differences were also present with reference to the butt joints. In the case of the "circle path" tests, a greater amount of black tarnish was present on the MIG-Pulse test pieces welded with the AlMg4.5MnZr (Al 5087) filler metal than on those made using the CMT method (Fig. 3). The tarnish was also more difficult to remove from the surface of the pulsed current welded test pieces. The cracks formed on the test pieces were measured using a protractor and a magnifying glass (6x). The results are presented in Table 5.

Table 6. Results of macroscopic metallographic tests of the 2.0 mm thick EN AW 7075 aluminium joint metallographic specimens made during the "circle path" test

Electrode wire	MIG-Pulse	CMT
AlMg4.5MnZr (Al 50987) ϕ1.2 mm		
AlCu6MnZrTi (Al ML2319) ϕ1.2 mm		

Photographs magnified x4

Table 5. Measurement results of the cracks formed in the "circle path" tests

Filler metal and diameter	AlMg4.5MnZr (Al 50987) ϕ1.2 mm		AlCu6MnZrTi (Al ML2319) ϕ1.2 mm	
Welding method	MIG-Pulse	CMT	MIG-Pulse	CMT
Crack [°]	27	34	127	none
	69	31	129	19
	46	21; 29**	56	21
	49	none	54	16; 11**
	32	27	67*	18; 16**

* - in addition to a crack the test piece also contained a burn-through imperfection
** - two separate cracks were detected in the test piece
none – joint surface was free from any cracks

The visual and macroscopic tests (Table 6) revealed that in the CMT welded test pieces all the cracks were located in the area near the weld (partially melted zone). The MIG-Pulse welded joints also contained cracks present in the weld and a burn-through (in one case). These imperfections could be ascribed to the greater heat input to the welding area in the case of the MIG-Pulse method. The visual inspection of the joints revealed that the cracks formed in the CMT welded test pieces were characterised by narrower gaps, and in most cases the cracks were significantly shorter than those formed in the joints welded using the MIG-Pulse method. The longest and shortest cracks were formed while welding with the Al ML2319 electrode wire, which indicates the greater sensitivity of the 7xxx+2xxx material system to the heat input to the joint in comparison with the 7xxx+5xxx joint.

The macroscopic tests revealed that the CMT welded joints had welds of significantly bigger cross-section area, which was due to significantly higher welding technological parameters in relation to those applied during MIG-Pulse welding and due to the more precise manner (lower wire losses due to lower spatter) of feeding a liquid filler metal to the weld pool in the CMT method. Similarly as in the butt joint tests, the surface of the metallographic specimens contained the acceptable amount of small-diameter gas pores comparable for both methods. In most test pieces the excess penetration in the weld root was observed. The analysis of the test results demonstrated that the use of the CMT method reduces or eliminates the risk of liquation crack formation for both filler metals used.

The next stage involved the tensile tests of the welded joints according to PN-EN ISO 4136 and bend tests performed in accordance with PN-EN ISO 5173. The results $R_m(w)$ is the average of five test pieces.

In all the joints the rupture took place in the HAZ or in the weld. The joints welded with both methods using the AlMg4.5MnZr filler metal were characterised by a tensile strength

Table 7. Welded joint tensile test results and the tensile strength of the EN AW 7075 alloy parent metal.

Filler metal and diameter	Welding method	$R_m(w)^{1)}$ [MPa]	$R_m(pm)^{2)}$ [MPa]
AlMg4.5Mn-Zr ϕ1.2 mm	MIG-Pulse	257	540
	CMT	266	
AlCu6MnZr-Ti ϕ1.2 mm	MIG-Pulse	240	
	CMT	298	

Remarks:
$^{1)}$ $R_m(w)$ – welded joint tensile strength tested,
$^{2)}$ $R_m(pm)$ – parent metal tensile strength according to 485-2:2007

in the range of 250-270 MPa. The test pieces of the joints welded using the low-energy method and the AlCu6MnZrTi wire revealed the $R_m(w)$ values to be in the range of 285-305 MPa. The pulsed current welded test pieces were characterised by the lowest values – approximately 240 MPa. In the joint bend tests the required angle of 1800 was not obtained. The angle was not obtained in the bend tests of the parent metal either – the test pieces cracked having exceeded a bend angle of 1200. The higher bend angle results were obtained for the joints made using the CMT method and the AlCu6MnZrTi filler metal wire, yet they did not exceed the value of 900. The bend tests of the parent metal and of the joints revealed the limited weldability of the EN-AW 7075 alloy. The overly low plastic properties of the joints tested can be responsible for the formation of the intermetallic phases in the HAZ. The analysis of the bend test results justifies the conclusion that the use of the CMT method for welding the EN-AW 7075 alloy joints improves their plastic properties.

At the final stage, the test pieces with visible cracks (Table 1), made using the AlCu6MnZrTi filler metal, were subjected to metallographic examination using a light microscope (LM) and a scanning electron microscope (SEM). For the metallographic examination with the light microscope the test pieces were included in the conductive thermohardening resin and next subjected to grinding and polishing following the procedure developed by the Institute of Materials Science at the Silesian University of Technology. The metallographic specimens prepared in this manner underwent etching in the 2% HF reagent. The exemplary results of the observation performed using an Olympus-made GX-71 light microscope in the light field technique are presented in Figure 2.

The structural tests with greater magnification were conducted using a Hitachi S-3400N scanning electron microscope on unetched metallographic specimens in the back-scattered electron technique (BSE) showing the difference in chemical compositions. The exemplary structures are presented in Figure 4.

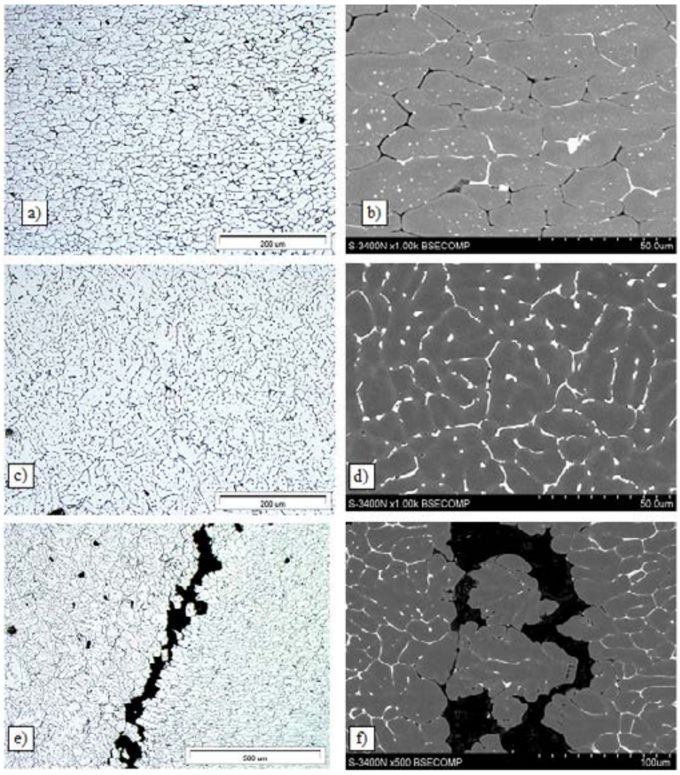
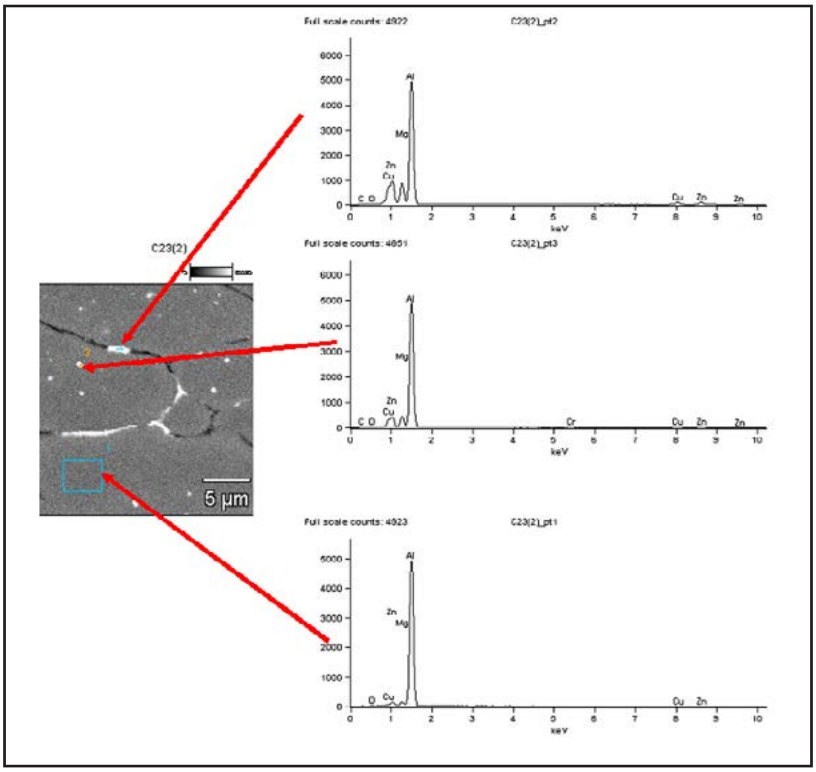


Fig. 4. Microstructure of the CMT welded joint in the "circle path" tests: a),b) HAZ, c),d) weld, e),f) crack detected in the fusion line area

The results of the tests conducted using the light and electron microscopes (Fig. 4) confirmed that the hot cracks were present in the area near the weld, i.e. so-called partially melted zone (PMZ), and had the liquation character (Fig. 4e,f). The smaller amount of precipitates in the crack areas indicates the segregation of zinc and magnesium in these areas, which could lead to the lack of precipitation hardening and result in lower mechanical and plastic properties. The welds of the test pieces made using both methods contained the lattice with the comparable amount of precipitates, yet in the case of the CMT test piece weld it was possible to additionally observe the greater amount of fine globular precipitates. The pulsed arc current welded test piece contained the smaller amount of greater size globular precipitates. The low-energy method welded test piece HAZ contained fewer precipitates on the grain boundary, yet more fine precipitates inside the grains than in the test piece made using the MIG-Pulse method.

Afterwards the HITACHI S-3400N scanning microscope provided with a NORAN VOYAGER SYSTEM SIX X-ray microanalysis system was used to conduct the microanalysis of the chemical composition of phase precipitates in the test pieces. The tests were performed on flat cross-sections at an electron beam accelerating voltage of 15keV. The selected EDS microanalysis results are presented in Figure 5.



Mas.%	Mg-K	Al-K	Cr-K	Cu-K	Zn-K
C23(2)_pt1	1.5	90.6		1.3	6.5
C23(2)_pt2	9.8	54.8		14.7	20.7
C23(2)_pt3	5.6	67.9	0.6	11.6	14.2
Atom%	Mg-K	Al-K	Cr-K	Cu-K	Zn-K
C23(2)_pt1	1.8	94.8		0.6	2.8
C23(2)_pt2	13.5	68.1		7.8	10.6
C23(2)_pt3	7.3	79.7	0.4	5.8	6.9

Fig. 5. Results of the microanalysis of the chemical composition of the precipitates in the HAZ of the CMT welded joint made using with the AlCu6MnZrTi electrode wire

The chemical composition analysis revealed that the structure of the parent metal of the EN-AW 7075 test pieces welded with the AlCu6MnZrTi filler metal was composed of grains of a zinc solid solution in aluminium α-Al and precipitates of intermetallic phases rich in silicon, magnesium, copper and iron. The precipitates on the dendrite boundaries in the MIG-Pulse weld contained Mg (approximately 3.8% by weight), Cu (approximately 14.5% by weight) and Zn (approximately 10.7% by weight). These chemical elements can form the Al_2Cu or Al_3Mg_2 phases. The weld made using the CMT method contained precipitates located inside the grains and on the grain boundaries and containing Mg (approximately 3.6% by weight), Cu (approximately 36.8% by weight) and Zn (approximately 4.1% by weight), being probably the Al_2Cu phase, as well as traces of silicon (approximately 0.4% by weight). The HAZ of the test pieces made using both methods contained variously shaped and sized precipitates on the grain boundaries, i.e. Mg - approximately 9-12% by weight, Cu - approximately 14-16% by weight and Zn - approximately 20-22% by weight. In addition, the test piece made using the low-energy method was characterised by the greater amount, if compared with that of the pulsed current welded test piece, of fine globular precipitates inside grains and containing significant amounts of magnesium, copper and zinc as well as traces of chromium (approximately 0.6% by weight), which can indicate the presence of the Al_2Cu or Mg_2Zn phase. In conclusion, it can be stated that the structure of the aluminium alloy joints tested was characteristic of the material systems used, and that differences in the amount, size and shape of the precipitates present in the weld and HAZ resulted from the method applied (different heat input to the joint, i.e. solutioning operation).

Conclusions

The analysis of the technological, strength-related and metallographic test results obtained has enabled the formulation of the following conclusions:

1. The CMT and MIG-Pulse welding methods enable the obtainment of 2.00 mm thick EN AW 7075 aluminium alloy butt joints characterised by good quality and mechanical properties. The best aesthetics and lowest porosity require the use of the CMT method and of the AlCu6MnZrTi electrode wire.
2. The obtainment of welded joints characterised by good quality and mechanical properties requires the precise adjustment of welding parameters. In the MIG-Pulse method the adjustment of appropriate welding parameters is significantly more difficult than while welding using the CMT method. The joints welded using the CMT method and the AlCu6MnZrTi filler metal were characterised by the highest (>300 MPa) values of R_m(w) in the transverse tensile test.
3. The bend tests revealed that the use of the CMT method for welding joints made of the EN-AW 7075 alloy enables the obtainment of the highest plastic properties.
4. The "circle path" tests revealed that the use of the CMT method reduces the formation of liquation hot cracks. The use of the AlCu6MnZrTi filler metal prevents the formation of cracks in CMT welded joints made of the EN AW 7075 alloy significantly better than in the case of the AlMg4.5MnZr filler metal.

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