Janusz Rykała, Tomasz Pfeifer

Robotised CMT welding of 6xxx series aluminium alloys

Abstract: The article presents the use of low-energy and standard welding methods (CMT and MIG-Pulse) for joining elements made of hard-to-weld 6xxx series aluminium alloys as well as the course of technological tests aimed at the determination of the usability of the CMT and MIG-Pulse methods for welding butt joints made of 2.0 mm thick sheets. The work also discusses the basic difficulties related to welding 6xxx series aluminium alloys, presents the specific character of welding by means of "typical" and low arc energy methods as well as presents the selected results and analysis of macro/microscopic metallographic tests and strength tests of the welded joints. The authors indicate that CMT welding ensures high quality and aesthetics of welded joints made of aluminium alloys regarded as difficult to weld.

Keywords: aluminium alloys, CMT, MIG-Pulse, low-energy welding

Introduction

The necessity of making lighter structures yet maintaining their original strength triggers the increasingly frequent use of high strength aluminium alloys in various industrial sectors. A related growing demand for welded joints of such alloys requires the former to be characterised by appropriate quality and mechanical properties.

MIG methods applied for welding thin-walled elements made of wrought and precipitation hardened high-strength aluminium alloys have failed to produce fully satisfying results. This is mainly due to significant weld porosity and excessive heat input leading to a considerable deterioration of mechanical properties in the joint area and hot cracking susceptibility. Traditional MIG welding is also characterised by significant spatters and deformations of the joined elements. This deteriorates the aesthetics of finished products and requires labour-consuming post-weld processing or taking measures to prevent these negative phenomena, which in turn, decreases efficiency and complicates the fixtures design and technological processes.

In recent years the research and development undertaken by leading manufacturers of welding equipment have given rise to new MIG/MAG low-energy welding variants (CMT, ColdArc) devised especially to solve problems which accompany joining thin-walled materials of limited weldability, susceptible to post-weld porosity formation and sensitive to heat effect. The publications [1,2] present the principle of

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operation of these methods as well as preliminary test results related to their implementation in welding aluminium alloys, including technological issues and the influence of selected methods on joint aesthetics. This article presents the effect of low-energy CMT welding on the structure of welded joints made of Al-Mg-Si aluminium alloys and their cracking susceptibility.

Tests and results

The technological tests of CMT and MIG-Pulse welding involved making butt joints using 2.0 mm thick Al-Mg-Si alloy sheets (grade EN AW 6082) with an AlMg4.5MnZr electrode wire having a diameter of ϕ1.2 mm (base metal designation according to PN-EN 573-3, metal designation according to PN EN ISO 18273 [3,4]).

Unlike most commonly used filler metals such as Al-Si (AlSi5 and AlSi12) or Al-Mg (AlMg5Cr), the filler metal under investigation is characterised by slightly less advantageous plastic properties, yet by better mechanical properties, ensuring good metallurgical properties of welds as well as enabling post-weld precipitation hardening of joints made of the aforesaid aluminium alloy. The filler metal contains zircon stabilising the structure and preventing the grain growth.

The technological tests involving both welding methods were carried out using a test rig equipped with a TransPuls Synergic 2700 device manufactured by Fronius (CMT) and GLC 553 MC3R produced by Cloos (MIG-Pulse) respectively. In order to ensure the repeatability of test conditions both devices were connected with a ROMAT 310 robot produced by Cloos.

The technological tests of CMT and MIG-Pulse welding have revealed the possibility of using welding parameters which enable obtaining a welded joint characterised by the quality level B according to PN EN ISO 10042 [9]. The technological tests referred to above were supplemented with welding of one-sided stiffened joints in order to measure and compare the angular deformation α of the joints (Fig. 1) made using both methods. For each material system 5 joints were made. The averaged test results are presented in Table 1.

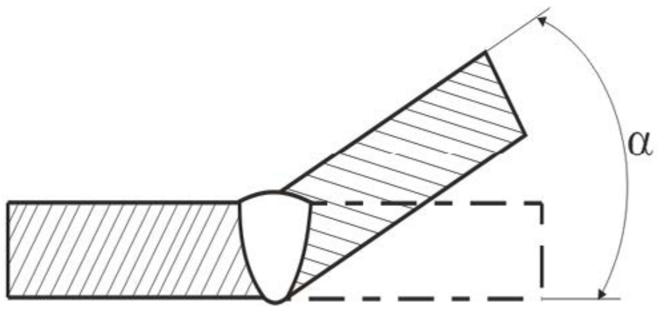


Fig. 1. Joint angular deformation

Table 1. Measurements of angular deformations α in joints made of EN-AW 6082 aluminium alloy using CMT/MIG-Pulse methods

Welding method	Angle of deformation α* [°]
MIG-Pulse	8.5
CMT	5.5

* - mean from measurements of 5 welded joints

The research also involved hot crack resistance tests of CMT and MIG-Pulse welded samples made of 4.0 mm thick EN-AW 6082 aluminium sheets using the Houldcroft method. Sheets were subjected to three overlay welding tests carried out with each of the methods. In order to obtain proper penetration in the base metal (a slight material bulge visible on the sample from the root side) overlay welding was carried out with the same conditions and parameters.

a)

b)

Fig. 2. Result of Houldcroft test carried out with MIG-Pulse method a) face; b) root

a)

b)

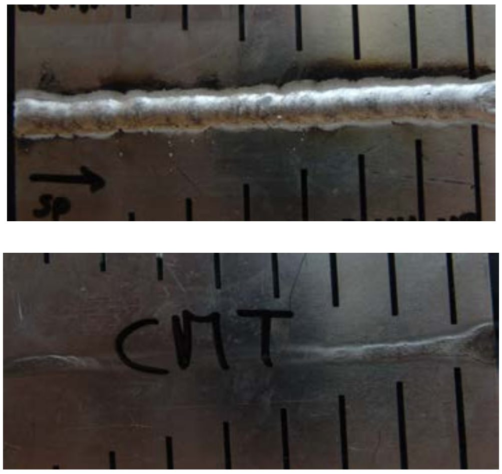


Fig. 3. Result of Houldcroft test carried out with CMT method a) face; b) root

None of the three CMT-welded samples made of the EN-AW 6082 alloy revealed cracks, whereas the MIG-Pulse welded samples had slight cracks from the root side. At the subsequent stage of the tests the welded joints made of 2.0 mm thick sheets underwent a heat treatment (solutioning followed by artificial ageing). Afterwards, the joint samples (both before and after heat treatment) were subjected to metallographic tests. The macroscopic metallographic photographs are presented in Figures 4 and 5.

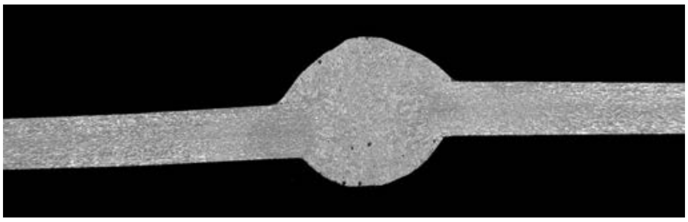


Fig. 4. Macrostructure of CMT welded joint made of 2.0 mm thick EN AW 6082 alloy, filler metal AlMg4.5MnZr ϕ1.2 mm, mag. 5x

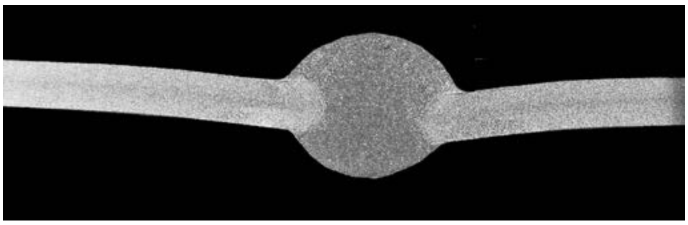


Fig. 5. Macrostructure of CMT welded joint made of 2.0 mm thick EN AW 6082 alloy after heat treatment, filler metal AlMg4.5MnZr ϕ1.2 mm, mag. 5x

The selected samples were also subjected to microscopic metallographic tests (light microscopy and scanning electron microscopy). The results of the tests are presented in Figures 6 and 7.

Fig. 6. Microstructure of CMT welded joint made of 2.0 mm thick EN AW 6082 alloy, HAZ view (on the right – base metal, on the left - weld), filler metal AlMg4.5MnZr ϕ1.2 mm, etching with Keller's reagent, mag. 100x

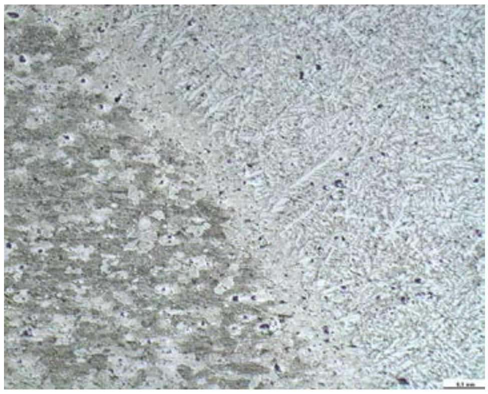
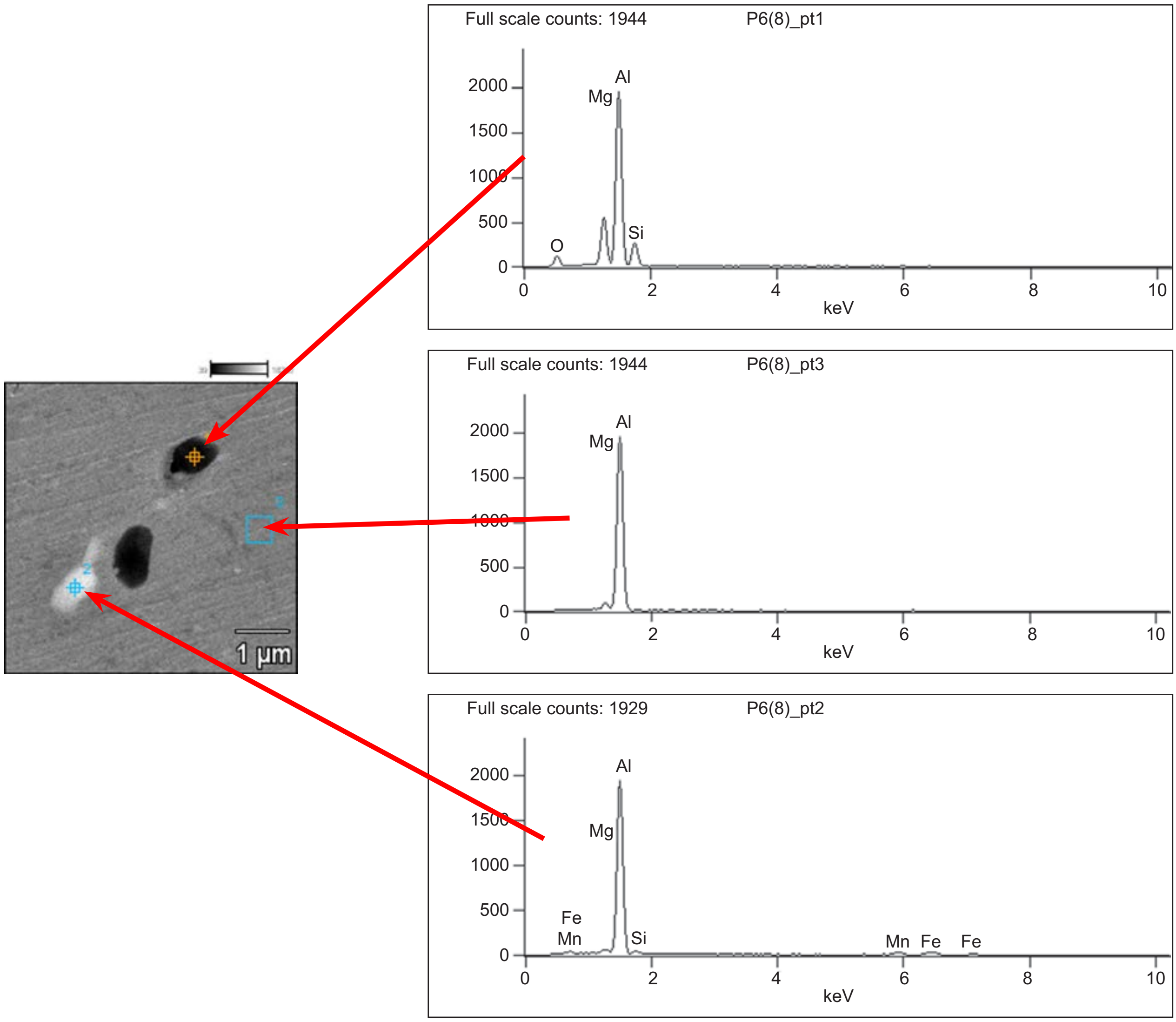


Fig. 7. Microstructure of CMT welded joint made of 2.0 mm thick EN AW 6082 alloy after heat treatment, HAZ view (on the right – base metal, on the left - weld), filler metal AlMg4.5MnZr ϕ1.2 mm, etching with Keller's reagent, mag. 100x

The tests also included microanalysis of the chemical composition of the aluminium alloy joints using a HITACHI S-4200 scanning microscope featuring a NORAN VOYAGER 3500 X-ray microanalysis system and an EDS spectrometer. The tests of the chemical composition were conducted with an electron beam accelerating voltage of 15keV.

The weld structure of the joints made of EN AW 6082 alloy contained dendrites of a solid solution of magnesium in aluminium α-Al and slight precipitates of intermetallic phases on the boundaries of these dendrites. The analysis of the metallographic test results related to the samples in the state before the heat treatment have revealed that the light intermetallic globular phases present in the weld contain Si (approximately 3% by weight), Mn (approximately 55% by weight to 7.2% by weight) and iron (approximately 10-11% by weight). Combined with aluminium these elements can form phases Al_3Mg_2, Al_3Fe and $AlMg_2Mn$. In turn, dark globular phases contain Mg and Si (probably the phase of Mg_2Si). The samples after the heat treatment contain slight light phase precipitates (rich in Mg, Si, Mn and Fe) on the dendrite boundaries as well as dark phases also located on the dendrite boundaries. The dark phases have the form of discontinuous lattices containing mainly Mg and Si. These are, similarly as in the samples before the heat treatment, Mg2Si phase, yet of another morphology.

The research also involved tensile strength tests of CMT and MIG-Pulse welded joints prior to and following heat treatment (according to PN-EN ISO 4136 [5]) (results marked in grey and with an asterisk) as well as bend tests carried out in accordance with PN-EN ISO 5173:2010 [6]. The tensile test results related to the welded joints are presented in Table 2 (value $R_m(w)$ is the mean from three tests). Table 2 also presents



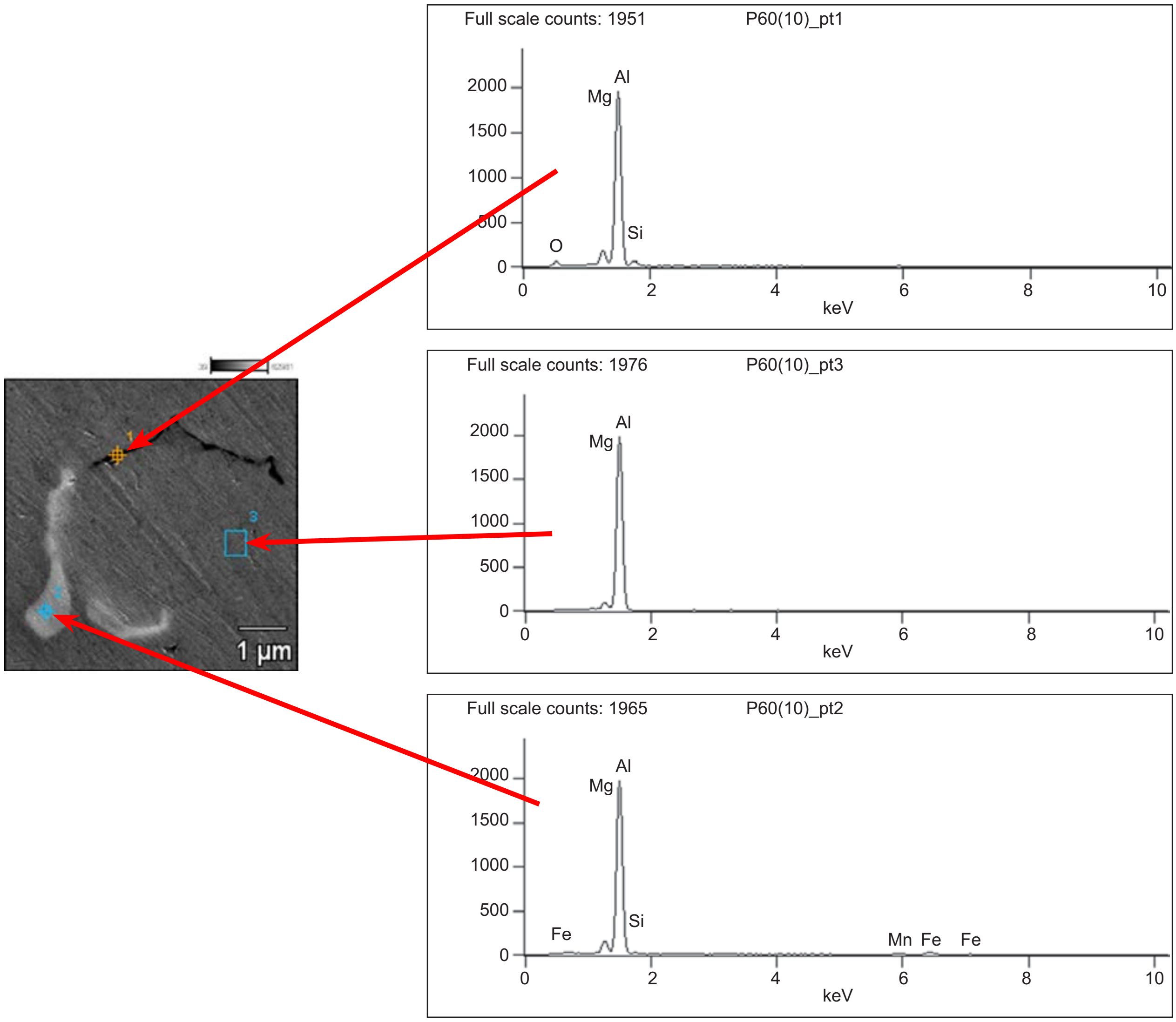
Weight%	Mg-K	Al-K	Si-K	Mn-K	Fe-K
pt1	14.53	68.16	17.31	-	-
pt2	2.25	77.27	3.25	7.21	10.01
pt3	2.77	97.23	-	-	-
Atom%	**Mg-K**	**Al-K**	**Si-K**	**Mn-K**	**Fe-K**
pt1	15.99	67.54	16.48	-	-
pt2	2.74	84.66	3.42	3.88	5.30
pt3	3.06	96.94	-	-	-

Fig. 8. Results of EDS chemical composition microanalysis of CMT welded EN-AW 6082 alloy joint weld area

the strength of the base metal in accordance with PN-EN 485-2:2007 [7] and the minimum required tensile strength of the welded joints in accordance with PN-EN ISO 15614-2 [8].

Analysis of results and concluding remarks

The MIG-Pulse welded joints are characterised by worse aesthetics in comparison with the CMT welded joints. During the visual testing no imperfections such as porosity were detected, yet the view of the face implied the presence of gas pores just underneath its surface, which was confirmed by radiographic tests. In the case of the tests involving the CMT method non or reduced numbers of gas pores in the joints were detected. The surfaces of the MIG-Pulse welded joints contain an oxide layer difficult to remove and slight traces of spatters. The surface of the CMT welded joints does not contain spatters nor does it contain the post-weld layer of oxides, or if it does, the layer is thinner and easy



Weight%	Mg-K	Al-K	Si-K	Mn-K	Fe-K
pt1	6.18	86.81	7.01	-	-
pt2	5.44	81.90	1.27	3.71	7.69
pt3	2.80	97.20	-	-	-
Atom%	**Mg-K**	**Al-K**	**Si-K**	**Mn-K**	**Fe-K**
pt1	6.84	86.46	6.70	-	-
pt2	6.37	86.49	1.29	1.92	3.92
pt3	3.10	96.90	-	-	-

Fig. 9. Results of EDS chemical composition microanalysis of CMT welded EN-AW 6082 alloy joint weld area after heat treatment

to remove. This aspect can be explained by the specific character of the CMT method and lower heat input to the joint area. Although it is not possible or extremely difficult to determine the real value of linear energy in both methods, practical confirmation of the conclusion is quite simple. Directly after welding, the CMT welded joints can be removed from the fixtures barehanded, unlike the MIG-Pulse welded joints; the temperature of the CMT welded joints after welding was lower.

This can be confirmed by the measurements of angular deformations in the one-sided stiffened joints. The joints welded using the CMT method have a smaller angular deformation, which is caused by smaller heat input supplied to the joint area and differently shaped welds. The macroscopic tests have revealed that the CMT welded joints, if compared with the MIG-Pulse welded ones, are characterised by a more uniform penetration and by welds having regular elliptic faces. The "flat-face" effect and a greater root in the MIG-Pulse welded joints results from the specific character of this method due to a higher arc voltage (and accordingly lower current), in spite of comparable linear energy values (calculated in the conventional manner).

The surface of the joints is free from hot cracks, typical of such base metals, yet the metallographic specimens of the MIG-Pulse welded joints contain microcracks along grain boundaries. The hot crack resistance tests carried out with the Houldcroft method have confirmed that the use of the CMT method decreases the possibility of hot crack occurrence in welded joints made of high strength aluminium alloys. However, the reduction of hot cracks can be primarily ascribed to a well selected filler metal, low linear energy and characteristic features of both methods, causing a more precise liquid metal transfer in an arc in comparison with the classical MIG method.

The detailed metallographic tests have revealed that the structure of the aluminium alloy joints is characteristic of the material system used and the heat treatment applied. The analysis of the chemical composition has not indicated quantitative differences as to the amount of precipitates of individual elements and phases depending on the welding method.

Table 2. Results of tensile tests, base metal strength and minimum required welded joint strength

Alloy (welding method)	Rm(w)[1)] [MPa]	Rm(pm)[2)] [MPa]	Rm(w)[3)] [MPa]
EN AW 6082 (MIG-Pulse)	215.7	280	min. 186
	412.2*		
EN AW 6082 (CMT)	232.3		
	468.6*		

Where
1) Rm(w) – tested tensile strength of a welded joint,
2) Rm(pm) – base metal tensile strength according to 485-2:2007,
3) Rm(w) – minimum required tensile strength of a welded joint according to PN-EN ISO 15614-2:2008,
* – results of the samples after the heat treatment.

The tensile strength tests have revealed that all the welded joints meet the minimum strength-related criteria. In the case of the joints made with both methods the rupture took place in the base metal. The same situation was observed in the joints subjected to heat treatment. The tensile strength test results do not differ significantly (approximately 10-20 MPa) for both welding methods, yet in most material systems better R_m(w) results were obtained when CMT welding was used. The strength tests results of the joints after heat treatment indicate the proper course of the former in the case of the EN AW 6082 alloy. The bend tests of the CMT and MIG-Pulse welded joints preceding and following the heat treatment have produced positive results.

The analysis of the results of technological, strength and metallographic tests have led to the formulation of the following conclusions:

1. The CMT and MIG-Pulse methods enable welding butt joints of 2.0 mm thick sheets characterised by very good quality and mechanical properties.

2. All the CMT welded joints were characterised by higher aesthetics in comparison with the MIG-Pulse welded ones. Presently, aesthetic joint appearance is an important assessment criterion in industry.

3. CMT welding requires smaller heat input, which minimises angular deformations and reduces/eliminates hot crack generation if compared to MIG-Pulse welding with similar settings of current-voltage parameters.

4. Properly conducted heat treatment enables obtaining EN AW 6082 alloy joints characterised by strength only slightly lower than that required for S355 grade steel joints.

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