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Effect of EN Ratio in Welding Current Waveform on the Properties of MIG/MAG Welded Joints Made of Various Structural Materials

Abstract: The article presents the use of VP current for welding thin elements of various structural materials, describes the course of tests and discusses the test results related to the determination of the effect of EN ratio in the current and arc voltage waveforms on the weld geometry, penetration depth and welded joint quality.

Keywords: MIG/MAG, adjustable EN ratio AC welding, galvanised steel, stainless steel, aluminium alloys

Introduction

The development of modern MIG/MAG welding variants is connected, among others, with searching for appropriate methods for joining engineering materials, particularly thin elements (steels with protective coatings, stainless steels, aluminium alloys) sensitive to heat effect. The latest and most innovative MAG welding variant involves current with adjustable EN ratio used for energising the electric arc. Recently a number of companies (Fronius, Cloos, OTC Daihen) have developed devices enabling the use of this welding variant in industrial practice.

Instytut Spawalnictwa in Gliwice has conducted thorough technological research involving EN ratio MAG welding of thin steel elements with protective coatings, corrosion-resistant steels and aluminium alloys. Modern welding equipment utilising synergic lines with variable parameters enable making butt joints, overlap joints and T-joints of materials having thicknesses from 0.8 mm upwards. Although welding with adjustable EN ratio current is less stable than the "conventional" MAG welding and is accompanied by a specific irritating sound, joints welded using this method are characterised by good quality and tend to be free from spatters. It has also been demonstrated that innovative synergic lines with adjustable EN ratio in the current waveform can be used for weldbrazing. The developed research programme simulating problems occurring in the automotive industry has enabled the obtainment of positive results during welding various materials [1, 2].

The basic process variables having the greatest effect on the course and possibility of welding as well as on the quality and aesthetics of joints are technological parameters (arc voltage, current, filler metal feeding rate, welding rate, welding torch inclination angle, arc length) and the content of the negative component in the welding current waveform, i.e. so-called parameter EN Ratio. The change of EN ratio significantly affects the arc voltage and heat input to a joint. Increasing EN ratio decreases the penetration depth and arc bridging

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Table 1. Chemical composition of test materials

Grade	Chemical element content,%													
	C	Si	Mn	P	S	Cr	Nb	Ti	Al	Mo	N	Mg	Fe	Zn	Cu
HCT600X ZF100 RBO1)	0.12	0.30	1.66	0.02	0.004	0.50	-	-	0.020	-	-	-	-	-	-
HX 420 LAD Z100 MBO1)	0.11	0.50	1.40	0.030	0.025	-	0.09	0.15	≥0.015	-	-	-	-	-	-
CPW 800 Z100 MBO1)	0.18	0.80	2.2	0.025	0.010	0.60	0.08	0.18	-	0.40	-	-	-	-	-
X5CrNi18-102)	≤0.07	≤1.00	≤2.00	≤0.045	≤0.015	17.5÷ 19.5	8.0÷ 10.5	-	-	-	≤0.11	-	-	-	-
X6CrTi172)	≤0.05	≤1.00	≤1.00	≤0.040	≤0.015	16.0÷ 18.00	-	0.15÷ 0.80	-	-	-	-	-	-	-
AW-6082*3)	-	0.7÷ 1.3	0.40÷ 1.0	-	-	0.25	-	0.10	rest	-	-	0.6÷ 1.2	0.50	0.20	0.10
AW 5754*3)	-	0.40	0.50	-	-	0.30	-	0.15	rest	-	-	2.6÷ 3.6	0.40	0.20	0.10

1) PN-EN 10346 Flat steel products with continuous fire coating. Technical delivery conditions [3]
2) PN-EN 10088-1. Corrosion resistant steels. Grades [4]
PN-EN 10088-2. High alloy steels (stainless, duplex, acid resistant, heat resistant, super duplex, carbon, boiler, super duplex, inconel, monel and others). Technical delivery conditions for sheets and strips of stainless steels [5]
3) PN-EN 573-1 Aluminium and aluminium alloys. Chemical composition and types of wrought products. Part 1: Numerical designation system
* others in total 0.15 [6]

ability [1,2]. Welding of thin elements requires greater EN ratio in the current waveform. Increasing EP (electrode positive) ratio increases process heat input, arc stability and penetration depth [1,2].

Test Materials and Methodology

The tests involved the use of high strength steels with protective coatings, i.e. zinc+iron HCT600X ZF100 RBO, zinc HX420 LAD Z 100 MBO and CPW 800 Z100 MBO, two types of corrosion-resistant steels, i.e. X5CrNi18-10 of austenitic structure and X6CrTi17 of ferritic structure as well as two aluminium alloys, i.e. AW-6082 and AW 5754. The chemical composition of the materials used is presented in Table 1.

The objective of the tests was to develop material-technological conditions for adjustable EN ratio welding of thin-walled elements enabling the obtainment of the best possible quality of welded joints and the determination of the EN ratio parameter effect on the properties of welds/overlay welds and process.

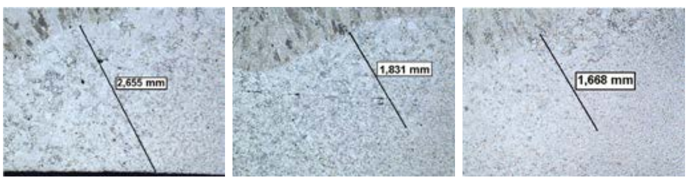
The process technological tests of variable polarity MIG/MAG welding were conducted on a mechanised stand equipped with an OTC Daihen-manufactured DW 300 welding machine. The research methodology included the determination of EN ratio on the geometry of an overlay weld, penetration depth and HAZ width. To this end it was necessary to perform overlay welding tests using constant technological parameters (welding current, overlay welding rate) changing only EN ratio in the 45%÷80% range. Only one overlay weld was made on each test piece. Such an approach was undertaken in order to eliminate the heat effect of subsequent runs. Afterwards the test pieces with overlay welds underwent cross-sectional macroscopic metallographic examination followed by microscopic observation aimed to determine the HAZ width. The HAZ width measurements were performed using a LEICA MEF4M optical microscope provided with a digital image analysis system supported by appropriate software tools.

The next research stage involved technological test related to the welding of the materials mentioned above and the determination of EN ratio on the weld geometry. For this purpose it was necessary to make joints using various EN ratio in the current and arc voltage waveforms. Afterwards, representative joints were subjected to tensile tests and hardness measurements. The related test results are presented below.

Tests of Overlay Welds and Joints Made of High Strength Steels Provided with Protective Coatings

In order to determine the effect of EN ratio on the HAZ structure it was necessary to make a number of overlay welds with various EN ratio settings. Each overlay weld was made on a test piece (50 × 100 × 3 mm) made of the HX420 LAD Z 100 MBO steel. During the tests, technological parameters remained unchanged (welding current 150 A, welding rate 45 cm/min); only EN ratio was modified. Afterwards, each overlay weld was sampled for a metallographic specimen for macroscopic examination. Figure 1 presents the microstructure of the weld and that of HAZ for the neutral and extreme EN ratio settings along with HAZ width measurements. The welding and overlay welding tests were conducted using the PN-EN ISO-A-G3Si1 grade electrode wire having a diameter of 1.2 mm. The shielding gas used was the 92% Ar + 8% CO_2 mixture; the gas flow rate amounted to 12 l/min.

The macroscopic tests revealed that the HAZ is significantly affected by EN ratio in the current waveform – the lower the EN ratio (higher heat input - Fig. 1, test piece A), the greater HAZ width. For extreme EN ratio settings the difference in HAZ widths amounted to almost 1 mm.



45% EN ratio (maximum EP ratio) | 60% EN ratio (neutral setting) | 80% EN ratio (maximum EN ratio)

Fig 1. Microstructures of overlay welds made with various EN ratio settings in current waveform with HAZ widths marked, magnification 25 x, etching Nital

Afterwards, technological welding tests involving joints made of the HCT 600X (1 and 2 mm thick), CPW 800 Z100 MBO (1.5 mm thick) and HX 420 LAD Z 100 MBO (3 mm thick) steels were conducted. The welded joints obtained were subjected to macroscopic metallographic tests, hardness measurements and tensile tests. Table 2 presents the tensile test results; Figure 2 presents the hardness measurement results (Vickers test according to PN-EN 1043-1:2000 under a load of 98.1 N).

The macroscopic metallographic tests conducted did not reveal the presence of any imperfections. The tensile test results revealed that

Table 2. Tensile test results for but joints

Steel grade	Material thickness, mm	Rm, MPa	Min. Rm according to PN-EN 10346, PN-EN 10 152, MPa
HCT 600X ZF 100 RBO	1,0	628.2	600
		614.6	
		618.7	
HCT 600X ZF 100 RBO	2,0	642.1	600
		632.8	
		613.5	
HX 420 LAD Z 100 MBO	3,0	511.2	470
		512.2	
		514.0	
CPW 800 Z100 MBO	1,5	807.2	800
		805.1	
		804.4	

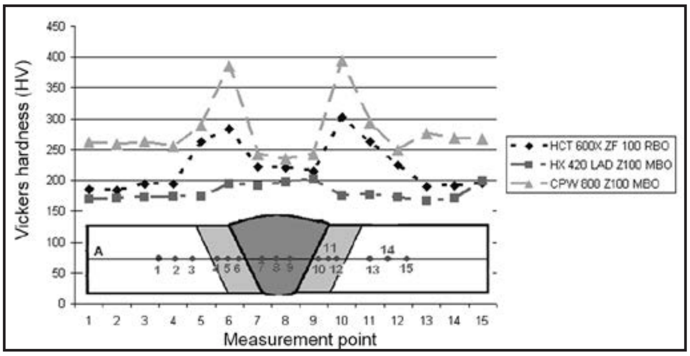


Fig. 2. Hardness measurement results for selected butt joints made of the HCT 600X ZF 100 RBO, HX 420 LAD Z100 MBO and CPW 800 Z100 MBO steels

all the test pieces ruptured in the parent metal. The results obtained meet the minimum tensile strength requirements for each of the steels tested. It can be stated that the use of a synergic line with adjustable EN ratio makes it possible to obtain good quality joints meeting requirements for the individual parent metals (Table 2).

The hardness measurement results revealed that the weld hardness was comparable with that of the parent metal. The hardness of HAZ increased in relation to the parent metal. In the joints made of the CPW 800 Z100 MBO steel the HAZ hardness increased up to approximately 400 HV; in the remaining cases the hardness did not exceed 350 HV. The values mentioned above are permissible according to PN-EN ISO 15614-1:2008. The hardness increase observed for the materials tested indicates that the welding process was performed properly. The results obtained also indicate that the structural changes which took place in the HAZ during welding do not adversely affect the operational properties of the joints.

Tests of Overlay Welds and Joints made of Corrosion-resistant Steels

Tests of overlay welds and joints made of austenitic steel

The tests performed were analogous to those concerning the overlay welding and welding of steels having protective coatings. The parent metal was in the form of test pieces made of the X5CrNi18-10 steel (50 × 150 × 2 mm). Figure 3 presents the macrostructures of the overlay welds obtained. Figures 4÷6 present the measurements performed in the central part of the overlay weld, i.e. where fusion into the material was the deepest.

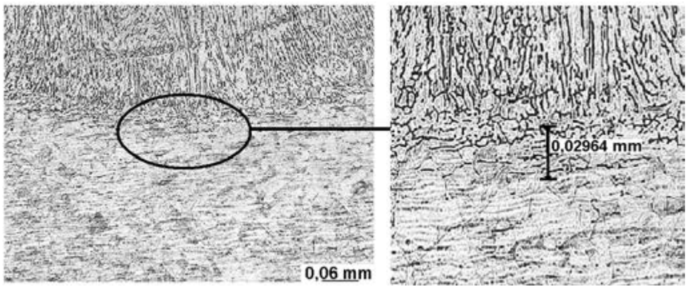


Fig. 4. Microstructure of the overlay weld made of the X5CrNi18-10 steel with 60% EN ratio, electrolytic etching

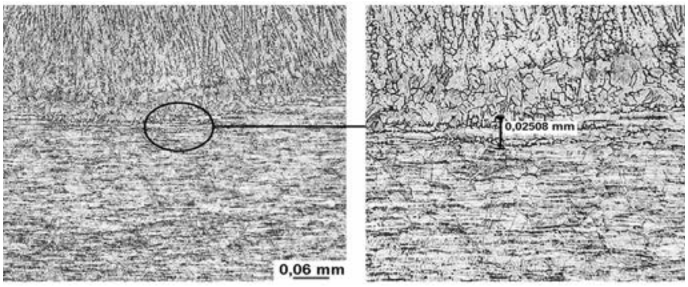


Fig. 5. Microstructure of the overlay weld made of the X5CrNi18-10 steel with 80% EN ratio, (maximum EN ratio), mag. 200x, electrolytic etching

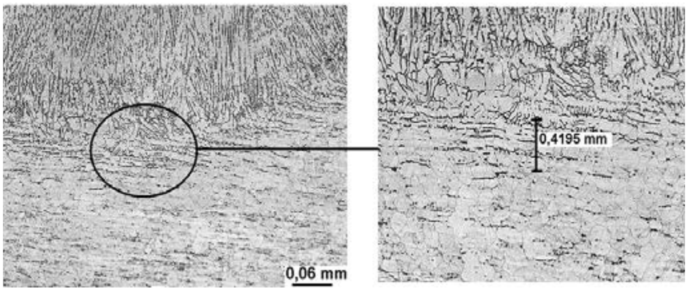
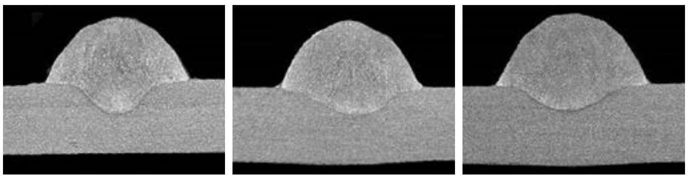


Fig. 6. Microstructure of the overlay weld made of the X5CrNi18-10 steel with 45% EN ratio, (maximum EP ratio), mag. 200x, electrolytic etching

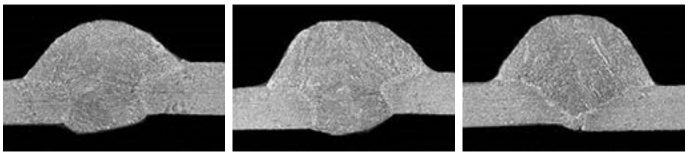


45% EN ratio (maximum EP ratio) | 60% EN ratio (neutral setting) | 80% EN ratio (maximum EN ratio)

Fig. 3. Macrostructure of the overlay welds made of the 2 mm thick X5CrNi18-10 steel, mag. 5.0x. etching with Adler's reagent

The test revealed that the deepest penetration accompanied the minimum EN ratio (45%). For other settings the penetration depth was smaller. The metallographic examinations revealed that the HAZ was characteristic of welded joints made of austenitic steels. The HAZ was composed of the Partially Melted Zone (PMZ) and of the recrystallization zone. The HAZ did not reveal the presence of the traditional fusion line; therefore, the combined width of the PMZ and that recrystallization zone were adopted as the HAZ width. The width measurements of these zones revealed that for the maximum EN ratio (80%) the HAZ width was smaller than in the overlay weld made with the minimum EN ratio (45%). The tests conducted confirmed that also in the case of austenitic steels the change of EN ratio in current and arc voltage waveforms enables modifications of heat input to the workpiece [7].

The next research stage involved technological tests of the welded joints made of the 1 mm thick X5CrNi18-10 steel with various EN ratio settings. During the tests, similarly as in the case of the overlay welds, process parameters remained the same and only EN ratio was subject to modifications. Figure 7 presents the macrostructure of the joints made with EN ratio 45%, 60% and 80% settings in the current waveform. The technological tests revealed that the welding process was stable for each EN ratio setting, yet the highest EN ratio setting was accompanied by greater spatter.



45% EN ratio (maximum EP ratio) | 60% EN ratio (neutral setting) | 80% EN ratio (maximum EN ratio)

Fig. 7. Macrostructure of the joints made of the 1 mm thick X5CrNi18-10 steel welded with various EN ratio settings in the current waveform, mag. 5.0x. etching with Adler's reagent

The technological and metallographic macro and microscopic examinations revealed that increasing EN ratio degenerates the weld shape, i.e. the face becomes excessively convex. The maximum EN ratio results in the lack of penetration. The increase in EP (electrode positive) ratio enables the obtainment of the proper face shape. However, the maximum EP ratio is accompanied by significantly higher heat input, which may cause local burn-throughs. The technological and metallographic macroscopic examinations revealed that for butt joints the negative EN ratio setting (greater EP ratio) is the most convenient as it enables the obtainment of high quality joints and proper geometry welds and prevents the formation of welding imperfections. The microscopic metallographic tests revealed that, similarly as in the case of overlay welds, the welded joints did not have a typical fusion line and the HAZ was composed of the PMZ and of the recrystallization zone [7]. The smallest HAZ width results from welding with the highest EN ratio in the current and arc voltage waveforms. The tests did not reveal the presence of microcracks in the HAZ, and particularly in the PMZ.

For comparative purposes the technological tests also involved welding with a standard arc. The tests were conducted using the same current-voltage parameters and the same filler metal feeding rate. Figure 8 presents the macrostructures of the joints made.

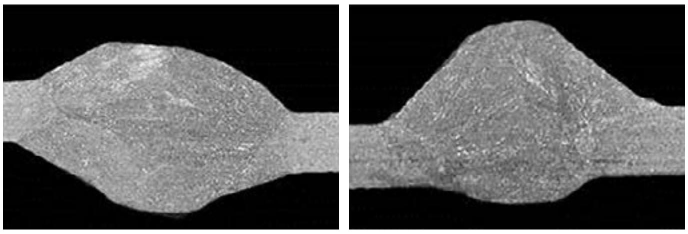
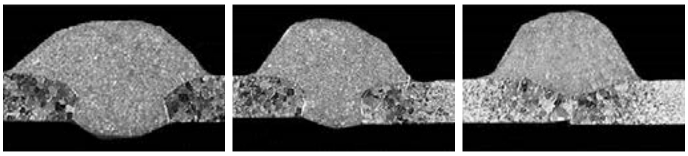


Fig. 8. Macrostructure of the joints made of the 1 mm thick X5CrNi18-10 steel welded with the standard arc, mag. 5.0x. etching with Adler's reagent

The technological tests revealed that at the same filler metal wire feeding rate welding current was higher by over 10A, which caused the excess penetration bead in the weld root. In turn, using the current as in the case of the variable polarity current arc resulted in the formation of a weld having a very disadvantageous shape with excess weld face penetration. The reason for this imperfection was overly low arc voltage caused by the synergic line used. Only after correcting the arc voltage it was possible to obtain a properly shaped joint.

The next stage of research involved the technological tests and tests of the properties of butt joints made of 1 mm thick X6CrTi17 ferritic steel. The tests involved the use of the same electrode wire as the one used during welding the austenitic steel. The first stage of investigation included tests aimed to determine the effect of EN ratio on the weld geometry. The following stage involved the determination of the best possible welding parameters as regards the joint quality. During this test the quality level B according to PN-EN ISO 5817 as was adopted by the quality criterion. The welded joints were made using constant technological parameters, only EN ratio was modified. The EN ratio settings were 45%, 60% and 80% with 45% and 80% being the extreme settings. The tests were performed in the same manner as in the case of the austenitic steel tests – the same parameters and welding consumables (wire+gas) were used. Figure 9 presents the macrostructure of the joints made with the 60% setting of EN ratio as well as with the extreme settings of this parameter, i.e. 45% and 80%.



45% EN ratio (maximum EP ratio) | 60% EN ratio (neutral setting) | 80% EN ratio (maximum EN ratio)

Fig. 9. Macrostructure of the joints made of the 1 mm thick X6CrTi17 steel, mag. 5.0x. etching with Adler's reagent

The technological tests revealed that the use of variable polarity current for joining thin elements made of acid resistant ferritic steel enables the obtainment of joints characterised by very good quality. Similarly as in the case of the austenitic steel, the welding process was stable and without spatter; the weld face was smooth and even, and the root was properly shaped. The use of higher EN ratio in the current waveform results in the excess weld face penetration. In ferritic steels this effect is significantly more visible due to a different surface tension value and greater heat conductivity. Only the use of the maxim EN ratio setting enabled the obtainment of the properly shaped face.

Due to greater heat conductivity, welding of ferritic steel butt joints requires higher current than that used for austenitic steels. Additional technological settings enabled the development of the optimum welding parameters as regards the joint quality. Figure 10a presents the joint macrostructure. For comparative purpose another welded joint was made using the standard arc (Fig. 10b).

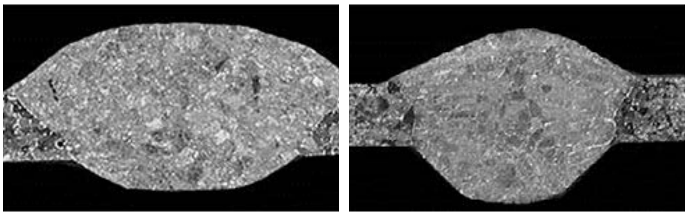


Fig. 10. Macrostructure of the joints of the 1 mm thick X6CrTi17 steel made using VP welding variant (a) and the standard arc (b), mag. 6.0, etching with Adler's reagent

The comparative technological tests involving welding with the standard arc revealed that with the same parameters the process was less stable, with significantly greater spatter and greater heat input to the material. This was demonstrated by the greater excess penetration bead on the root side (Fig. 10 b), the greater grain size in the HAZ and by the greater HAZ width.

Summarising the tests, it can be stated that using variable polarity current enables obtaining good quality welded joints of thin elements made of 1 mm thick corrosion-resistant steels. The decisive influence for the quality of joints can be ascribed to EN ratio in the current and arc voltage waveforms. The maximum EN ratio enables significant heat input limitation.

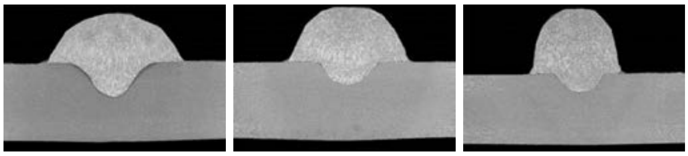
Tests of Overlay Welds and Joints Made of Aluminium Alloys

The technological VP MIG welding tests were performed on the test rig used in the previous tests. The parent metals used were 1÷4 mm thick AW 6082 (AlSi1MgMn) and AW 5754 (AlMg3) aluminium alloys according to EN 573-3. The filler metal used was the AlMg4.5Mn0.7Zr (PN-EN ISO 18273 - Al5083) electrode wire having a diameter of 1.2 mm. The shielding gas was argon provided with a constant flow rate of 14 l/min.

The testing methodology included the determination of EN ratio effect on the penetration depth and HAZ width. To this end it was necessary to conduct overlay welding tests using constant technological parameters (overlay welding current I=100 A, overlay welding rate v_s=50 cm/min.) and changing EN ratio in the range analogous to that applied in the previous tests. The parent metal used was 4 mm thick EN AW 6082 aluminium alloy (40×100 mm).

The next stage involved technological welding tests and determination of EN ratio on the weld geometry. For this purpose it was necessary to make butt joints of 2 mm thick AW 6082 aluminium alloy with various EN ratio in the current and arc voltage waveforms (from 45% to 80%). During the tests, welding parameters remained unchanged (welding current I=70 A, welding rate v_s = 50 cm/min.). Figure 11 presents exemplary photographs of overlay welds made using constant current parameters and variable EN ratio in the current and arc voltage waveforms. Figures 12÷14 present the results of microscopic tests along with HAZ width measurements for EN ratio = 45%, 60% and 80% [8].

The technological tests involving overlay welding and welding with adjusted EN ratio revealed that if welding parameters are constant, the decrease in EN ratio in relation to EN ratio = 60% (setting designated as "0" on the control panel) increases the weld face width, reduces weld face reinforcement height and increases the excess penetration bead on the root side. In turn, the increase in EN ratio in welding current significantly improves the joint quality; the face is higher and the excess penetration bead on the root side is smaller. The excessive EN ratio leads to the excessively high weld face reinforcement and disadvantageous shape. Increasing EN ratio in the current and arc voltage waveforms reduces heat input to the joint. The best quality is achieved with the slight EN ratio advantage in the waveform (approximately 60 - 65%).



45% EN ratio (maximum EP ratio) | 60% EN ratio (neutral setting) | 80% EN ratio (maximum EN ratio)

Fig. 11. Macrostructure of the overlay welds made using the synergic line with adjustable EN ratio in the welding current waveform. Welding current: 100 A, arc voltage between 15.5 V and 23.0 V, etching with Keller's reagent

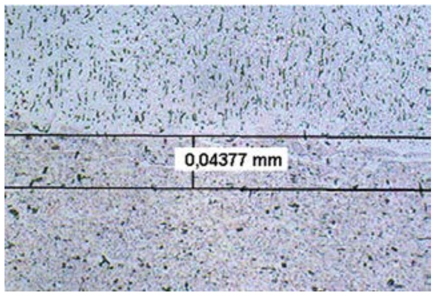


Fig. 12. Microstructure of the overlay weld made with 60% EN ratio setting, mag. 200x, etching with Keller's reagent

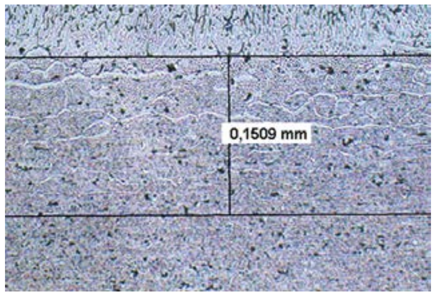


Fig. 13. Microstructure of the overlay weld made with 45% EN ratio setting, mag. 200x, etching with Keller's reagent

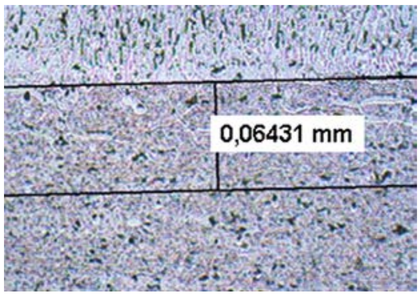
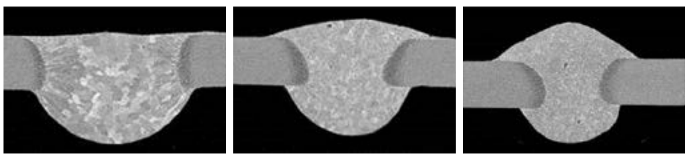


Fig. 14. Microstructure of the overlay weld made with 80% EN ratio setting, mag. 200x, etching with Keller's reagent



45% EN ratio (maximum EP ratio) | 60% EN ratio (neutral setting) | 80% EN ratio (maximum EN ratio)

Fig. 15. Macrostructure of the joints welded using the synergic line and various EN ratio settings, etching with Keller's reagent

The next testing stage involved HAZ width measurements. The tests revealed that greater EN ratio does not significantly increase the HAZ width with differences being so slight that they can be regarded as restricted within the limit of measurement error (0.044 and 0.064 mm for EN ratio = 60% and EN ratio = 80% respectively) (Fig. 12÷14). In turn, increasing EP (Electrode Positive) ratio significantly widens the HAZ (over three times for the maximum EP ratio). However, it should be noticed that the HAZ is still quite narrow as its width does not exceed two tenths of a millimetre).

The tensile tests of the welded joints were performed according to PN-EN ISO 4136. The tensile strength criterion adopted was that referred to in PN-EN ISO 15614-2. Following the provisions of the standard mentioned above, the tensile strength of a welded joint made of the 6xxx series aluminium alloys subjected to natural and artificial ageing should amount to 0.6 and 0.7 of the parent metal in the PWHT state respectively. The tensile test results are presented in Table 3 along with the strength of the parent metal according to PN-EN 485-2 and the minimum required tensile strength of joints welded in accordance with PN-EN ISO 15614-2.

The tensile tests revealed that all the welded joints satisfied the minimum strength-related criteria. In most cases the rupture took place in the weld, which was due to the fact that the strength of the filler metal used for welding high strength joints was lower than that of the parent metal (therefore the rupture usually takes place in the weld). In the case of many Al-Mg2Si eutectic clusters located in the HAZ or just near the fusion line, as a result of liquation cracks occurring in such places, the rupture can take place in the HAZ or directly in the fusion line, giving significantly lower tensile strength results. The results obtained were close to those received while testing joints made using low-energy methods, such as CMT and Cold Arc [9, 10, 11].

Table 3. Tensile test results, parent metal tensile strength and minimum required welded joint strength

Alloy grade	Thickness, mm	Filler metal grade and diameter	$R_m(w)$l, MPa	$R_m(pm)$, MPa	$R_m(w)_{min}$, MPa
EN AW 6082	2.0	AlMg4.5MnZr ϕ1.2 mm	211	280	196
			221		
			208		
	1.0		199		
			217		
			205		

Remarks:
$R_m(w)$ – welded joint tensile strength,
$R_m(pm)$ – parent metal tensile strength,
Min. $R_m(w)$ – minimum required welded joint tensile strength (0.7 x Rm(pm)).

Conclusions

1. The use of the synergic line with adjustable EN ratio for welding thin-walled elements made of steels provided with protective coatings, corrosion resistant steels and aluminium alloys enables the obtainment of joints characterised by very good quality and aesthetics and can be successfully used as an alternative method to pulsed arc welding and standard arc welding.

2. In addition to the basic technological parameter, the basic factor affecting the process, joint quality and penetration depth is EN ratio in the current waveform.

3. The use of the synergic line enables welding thin steel elements with protective coating of thicknesses from 0.8 mm upwards and ensures the obtainment of good quality, good aesthetics as well as high mechanical and plastic properties of joints.

4. The welded joints made of the X6CrTi17 and X5CrNi18-10 steels using pulsed arc welding with adjustable EN ratio are characterised by the different HAZ structure.

5. The advantage EN of ratio used in the welding current

and arc voltage waveforms reduces the HAZ width and PMZ width (while welding aluminium alloys).

References

1. Kiszka A. Pfeifer T.: The effect of electrode negative (EN Ratio) in GMA welding on the structure and properties of the joints made of high strength steels with protective coatings. Kovove Materialy vol. 51, issue 2.
2. Pfeifer T., Kiszka A. Spawanie blach dla przemysłu motoryzacyjnego metodą MAG ze zmienną biegunowością (AC Pulse). Przegląd Spawalnictwa, 2012, nr 2.
3. PN-EN 10346 Wyroby płaskie stalowe powlekane ogniowo w sposób ciągły. Warunki techniczne dostawy.
4. PN-EN 10088-1. Stale odporne na korozję. Gatunki stali odpornych na korozję
5. PN-EN 10088-2. Stale wysokostopowe (nierdzewne, duplex, kwasoodporne, żaroodporne, superduplex, węglowe, kotłowe, super duplex, inconel, monel i inne). Techniczne warunki dostawy dla blach/arkuszy i taśm ze stali odpornych na korozję.
6. PN-EN 573-1 Aluminium i stopy aluminium. Skład chemiczny i rodzaje wyrobów przerobionych plastycznie. Część 1: System oznaczeń numerycznych.
7. Tokarski M.: Metaloznawstwo metali i stopów nieżelaznych w zarysie. Wydawnictwo Śląsk, 1985 r.
8. Pfeifer T.: Zastosowanie prądu o zmiennej biegunowości do spawania stopów aluminium metodą MIG. Biuletyn Instytutu Spawalnictwa, 2014, nr 2
9. Adamiec J., Pfeifer T., Rykała J.: Modern methods of aluminum alloys welding. Solid State Phenomena, Vol. 176 (2011).
10. Adamiec J., Pfeifer T., Rykała J.: CMT and MIG-Pulse robotized welding of thin-walled elements made of 6xxx and 2xxx series aluminium alloys. Solid State Phenomena, Vol. 176 (2012).
11. Matusiak M., Pfeifer T.: Badanie warunków technologicznych spawania stopów aluminium nowymi niskoenergetycznymi metodami oraz ich wpływu na emisję zanieczyszczeń do środowiska. Praca badawcza Instytutu Spawalnictwa nr Dc-16, Gliwice 2008 r.