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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

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Abstract

The article presents the innovative GMA welding technology using variable polarity AC and reveals the results following the investigation of the impact of the EN ratio on the structure and HAZ width of overlay welds and joints of high strength steels HCT 600X ZF RBO, HX 420 LAD Z 100 MBO and CPW 800 Z100 MBO provided with special zinc- and zinc-iron-based protective coatings.

Key words: GMAW VP, high strength steels, zinc-coated steel

1. Introduction

The development of modern GMA welding variants is related to the search for appropriate methods for joining advanced engineering materials, often thin and sensitive to heat effect (e.g., coated steels, aluminium and magnesium alloys, nickel alloys). Increasing quality-related users' demands set out for welding technologies are also a reason for the development of new MAG welding solutions. The latest innovative option utilises an electric arc supplied with variable polarity AC. Recently, a number of companies such as Fronius, Cloos and OTC Daihen have developed devices enabling the use of the aforesaid solution in industry practice.

The researchers of Gliwice-based Instytut Spawalnictwa have carried out detailed technological tests of variable polarity AC GMA welding of thin steel plates provided with protective coatings [1, 2]. The tests revealed that the use of variable polarity AC makes it possible to obtain joints characterised by good quality and aesthetic appearance. Modern welding devices (such as OTC Daihen-manufactured DW 300 or Cloos-made Qineo Champ), using synergic lines with variable course of parameters, enable users to produce butt, overlap and T-shaped joints of 0.8 mm-thick plates. Although welding with variable polarity AC is less stable than MAG welding and is accompanied by characteristic sounds, AC-welded joints are characterised by good quality and are usually free from spatters. The tests also revealed that variable polarity AC welding can be applied in the automotive industry. A developed and implemented research programme simulating typical problems occurring in automotive production enabled obtaining good results in welding of coated plates as well as in welding of misfit joints [1–3].

The basic process variables, having the greatest impact on the course, weldability, quality and appearance of joints are technological parameters (wire feeding rate, welding rate, torch inclination angle, arc length) and the ratio of negative constituent fraction in the course of welding current, i.e. the so-called EN (electrode negative) ratio. The change of electrode negative ratio significantly affects the change of arc voltage and amount of heat supplied to a weld. The tests revealed that the most convenient settings of the aforesaid parameters are those equal to 0. An increase in the EN ratio results in smaller penetration depth and leads to arc bridging ability [1, 2]. Welding of thin plates and repairing of very small zinc coating damage requires greater EN ratio in the course of current. An increase in the electrode positive ratio increases process heat input, arc stability and penetration depth [1, 2].

The study presents results of microscopic metallo-

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Table 1. Mechanical properties (lengthwise) of steels under test [4, 5]

Steel grade	Yield strength $R_{p0.2}$ (MPa) min.	Tensile strength R_m (MPa) min.	Elongation A_{80} (%) min.
HCT 600X ZF100 RBO	350	600	16
HX 420 LAD Z 100 MBO	420	470	17
CPW 800 Z100 MBO	680	800	10

Table 2. Chemical composition (%) of steels under test [4, 5]

Steel grade	C max.	Si max.	Mn max.	P max.	S max.	Cr max.	Nb max.	Ti max.	Al max.	Mo max.
HCT 600X ZF100 RBO	0.12	0.30	1.66	0.02	0.004	0.50	–	–	0.020	–
HX 420 LAD Z 100 MBO	0.11	0.50	1.40	0.030	0.025	–	0.09	0.15	$\geq$ 0.015	–
CPW 800 Z100 MBO	0.18	0.80	2.2	0.025	0.010	0.60	0.08	0.18	–	0.40

graphic examinations aimed to determine the impact of electrode negative ratio in the course of current on HAZ width and structure during welding of unalloyed and high strength low-alloy steels.

2. Base and filler metals used in tests

The tests involved the use of three types of high strength steels provided with protective coatings. Table 1 presents the mechanical properties, whereas Table 2 – the chemical composition of steels used in technological tests.

2.1. HCT 600 X ZF 100 RBO

The steel is obtained as a result of appropriately conducted cooling after annealing from the range of temperature coexistence of ferrite and austenite phases. The structure of this material is composed of fine-grained polygonal or acicular ferrite with "spots" of martensite; martensite content being 5–40 %. The structure also contains slight amounts of retained austenite. Soft ferrite ensures good formability, whereas martensite is responsible for high strength of steel. The properties of steel also depend on the ratio of the aforesaid phases as well as on the size of a grain. A significant difference between yield strength and the ultimate tensile strength, i.e., the so-called reinforcement coefficient, results in lower spring effect after cold forming. The steels are therefore characterised by the ease of cold- and stretch forming. The material was additionally covered with zinc and iron coating providing better quality. The coating was applied by immersing a steel product in a bath containing a minimum of 99 % zinc. Afterwards, the plate underwent annealing which led to iron diffusion through zinc. As a result, a matt-grey zinc-iron alloy layer was formed; the iron content being between 8 % and 12 %. The steel in question is usually supplied in the state following oil passivation, the purpose of which is to prevent corrosion in the future. The thickness of the protective layer is between 5 μm and 12 μm (preferably 7 μm), its mass being $100\,\mathrm{g\,m^{-2}}$. The aforesaid material is used in automotive industry, replacing unalloyed steels and conventional high strength steels. The application of HTC steel in welded structures allows the creation of resistant framework with reduced mass [6].

2.2. HX 420 LAD Z100 MBO

The steel belongs to a group of high-strength steels intended for cold plastic forming and is immersion-refined with zinc coating. Due to the foregoing, the steel is 2–3 times more resistant to atmospheric corrosion and more aesthetic than hot galvanised steels. The steel has also a surface of enhanced quality (due to oiling). The areas of application include automotive industry, mainly inner and outer parts as well as equipment elements [5].

2.3. CPW 800 Z100 MBO

This high strength hot rolled steel [4], owing to alloying agents and rolling process, has a fine-grained, ferritic-bainitic-martensitic structure. The material is characterised by high strength, hardness and abrasion resistance, yet it is also excellent for cold forming and is known for its good weldability. In automotive industry the steel is usually used in the production of safety features such as bumpers, chassis elements, door-reinforcing beams, profiles, body reinforcements [4].

The tests were conducted using one of the most innovative variable polarity AC welding methods, developed by Cloos company and known as Cold Process. Welding and surfacing tests were carried out with an electrode wire ISO 14341-A-G3Si1 (dia. 1.2 mm);

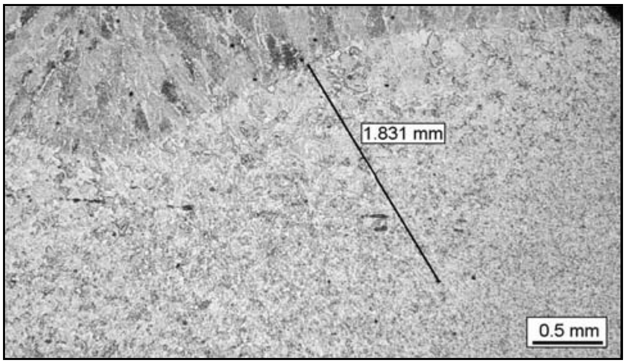


Fig. 1. Microstructure and HAZ width measurement result for neutral setting of variable constituent ratio. Magnification 25×. Etchant: Nital.

shielding gas being a mix of 92 % Ar + 8 % CO2 (PN--EN ISO 14175 M20-ArC8); flow rate: 12 l min^{-1}.

3. Course and results of tests

In order to determine the impact of EN ratio in the course of current on HAZ structure, it was necessary to form a number of overlay welds; in doing so one had to use various settings of the parameter in question. Each overlay weld was built up on a separate test piece made of 3 mm-thick plate made of steel HX420 LAD Z 100 MBO. During the tests, technological parameters (welding current 150 A, welding rate 45 cm min^{-1}) stayed the same. Only the value of variable constituent ratio was modified (non-dimensional value, set within the range from 50 to –50). Afterwards, each overlay weld was sampled for a metallographic specimen for microscopic tests (grinding, polishing and etching with Nital). The test pieces were observed with a Leica-manufactured light microscope MEF4M featuring digital image analysis. Figures 1–3 present the microstructure of the overlay weld and HAZ for the neutral (= 0) as well as extreme EN ratio settings along with HAZ width measurement results.

The microscopic metallographic tests revealed that overlay welds produced with the tool Qineo Champ 450 (Cloos) are characterised by good quality and are free from welding imperfections. The structures of the overlay welds are characteristic of the applied electrode wire (G3Si1) and base metal (bainite, ferrite on former austenite boundaries). The microscopic tests revealed that the width of HAZ is strongly related to the electrode negative ratio in the course of current. The lower the electrode negative ratio (higher heat input), the wider the HAZ is. In case of extreme settings of the electrode negative ratio, the difference in HAZ width amounted to more than 1 mm.

The microscopic metallographic examination was followed by technological welding tests of butt and overlap joints made of steel HCT 600X (1 and 2 mm

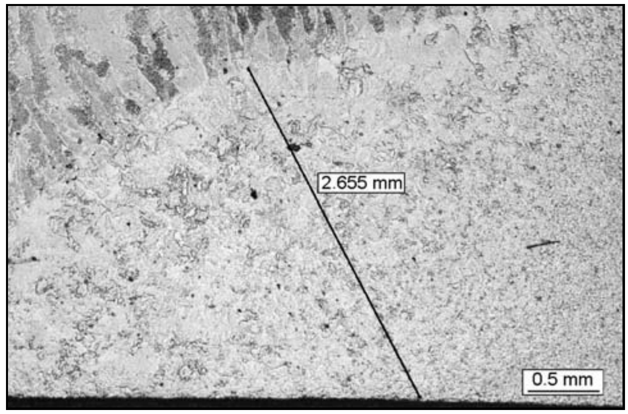


Fig. 2. Microstructure and HAZ width measurement result for minimum electrode negative ratio. Magnification 25×. Etchant: Nital.

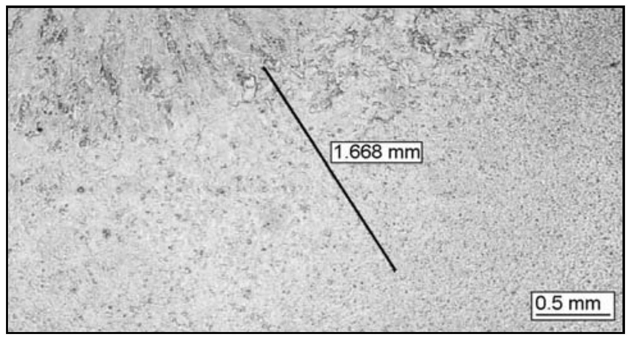
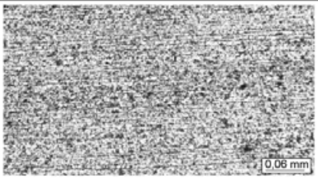
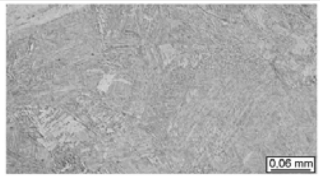
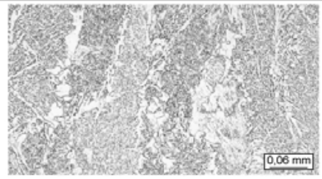
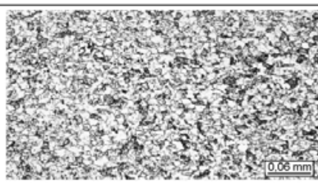
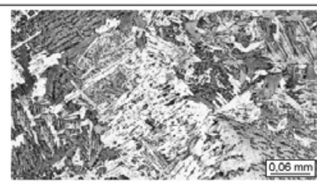
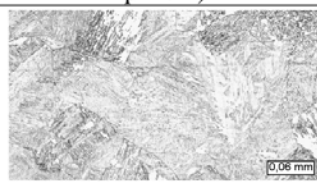
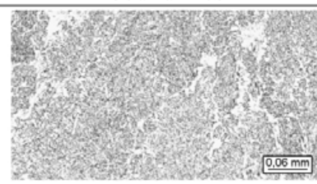


Fig. 3. Microstructure and HAZ width measurement result for maximum electrode negative ratio. Magnification 25×. Etchant: Nital.

in thickness), CPW 800 (1.5 mm in thickness) and HX 420 LAD (3 mm in thickness). The joints underwent macro- and microscopic metallographic tests, hardness measurements and tensile tests. Table 3 presents the results of the microscopic metallographic tests of selected joints made of the steel grades under test. The results include the areas of base metal, weld and HAZ. Table 4 presents the results of tensile tests, and Fig. 4 those of hardness measurements (carried out using Vickers hardness tests acc. to PN-EN 1043-1:2000 under a load of 98.1 N).

The microscopic metallographic tests of the joints did not reveal any imperfections. No micro-cracks or blowholes were observed in any area of the joint. The structure of the weld is typical of welds made with electrode wire G3Si1 and is usually composed of bainite with coarse-grained ferrite on former austenite grain boundaries. In the HAZ of steel HCT 600 one could observe martensite with a slight amount of bainite. The structures obtained during the welding of high-strength low-alloy steels with protective coatings are typical of GMA welding.

T a b l e 3. Results of microscopic metallographic tests of selected joints of steel HCT 600 X ZF 100 RBO (2.0 mm thick), HX 420 LAD 100 MBO (3.0 mm thick) and CPW 800 (1.5 mm thick)

Steel grade	Structure of base metal	Structure of HAZ	Structure of weld
HCT 600X th. 2 mm	 Ferrite + martensite	 Martensite + slight amounts of bainite + slight amounts of granular ferrite	 Bainite + coarse-grained ferrite on former austenite grain boundaries
HX 420 LAD 100 th. 3 mm	 Fine-gained ferrite + very small amounts of pearlite	 Bainite + granular ferrite + lamellar ferrite (Widmanstatten pattern)	 Bainite + coarse-grained ferrite on former austenite grain boundaries
CPW 800 th. 1.5 mm	 Martensite + slight amounts of bainite	 Bainite + very small amounts of ferrite	 Martensite + ferrite + bainite in strip arrangement
NOTE: etchant Nital, magnification x 200			

T a b l e 4. Results of static tensile tests of butt joints

Steel grade	Thickness (mm)	R_m (MPa)	Min. R_m (MPa) acc. to: PN-EN 10346, PN-EN 10 152
HCT600X ZF 100 RBO	1.0	628.2 596.7	600
HCT 600X ZF 100 RBO	2.0	642.1 613.5	600
HX 420 LAD 100 MBO	3.0	511.2 514.0	470
CPW 800 Z100 MBO	1.5	807.2 804.4	800

In the tensile tests all the test pieces underwent rupture in the base metal. The results obtained in the tests meet the minimum tensile strength requirements of each of the steels under test. One may conclude that the application of the device DW300 and variable polarity AC makes it possible to obtain joints of adequate strength, meeting the requirements set out for individual base metals.

The hardness measurement results revealed that the values of weld hardness are usually comparable with the hardness of the base metal. In case of HAZ one could observe an increase in hardness. In the joints made of steel CPW 800, the hardness of HAZ reached approx. 400 HV. In the remaining cases, hardness did not exceed 350 HV. The aforesaid values are acceptable acc. to PN-EN ISO 15614-1:2008. The increase in hardness observed in the cases presented above indicates that the welding process was carried out prop-

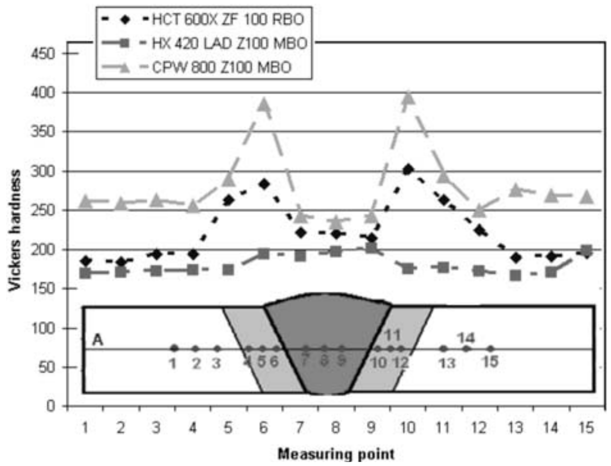


Fig. 4. Results of hardness measurements of selected butt joints.

erly. The results also show that the structural changes caused in the HAZ during welding will not adversely affect the operating properties of joints.

4. Conclusions

1. Modern, innovative variants of welding with variable polarity AC enable welding of thin steel plates (0.8 mm and thicker) and ensure good quality, aesthetic appearance and high mechanical and plastic properties of joints.

2. The basic parameter influencing the course of the process, the quality of a joint and the depth of penetration is, apart from technological parameters, the electrode negative ratio in the course of current. From the process stability and the appearance of joints point of view, the most advantageous setting is that amounting to 0. Increasing the electrode negative ratio enables welding of thin plates and misfit joints, whereas the application of electrode positive ratio increases heat input and penetration depth.

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