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T. Piwowarczyk[1*], M. Korzeniowski[1], P. Kustroń[1], M. Gąbka[2]

[1] *Wrocław University of Technology, Faculty of Mechanical Engineering, Institute of Production Engineering and Automation, Department of Welding, Wrocław, Poland*
* *tomasz.piwowarczyk@pwr.wroc.pl*
[2] *HS Wrocław sp. z o.o.*

PULSED ARC WELDING APPLIED TO ROBOTIZED JOINING OF THIN CAR-BODY STEEL SHEETS

ABSTRACT

The paper presents the potential of robotized welding applied for thin steel sheets using variable parameters of arc (different welding programs: Standard, Pulse, Twin Pulse, and Speed Pulse). Trial welded joints were made for sheets 0.8 to 1.25 mm thick and relevant welding parameters were selected for them during the first stage of examinations. The properties of welded joints were determined with non-destructive and destructive testing. In turn, visual inspection allowed to evaluate the shape and dimensional conformities of joints and to detect superficial imperfections. In order to improve detection accuracy, penetration testing was used for confirmation purposes. Tensile strength testing was also made to determine mechanical properties of the weld and the heat-affected zone. Metallographic examinations were used for sheets of all thickness values and for all welding programs to verify that the structure of joints was correct. All examinations and tests made on trial joints enabled to find how pulsing arc welding affects quality and strength properties of welds as compared with standard method.

Key words: *pulsed arc welding, robotized welding, welding programs*

INTRODUCTION – AUTOMATION AND ROBOTIZATION IN WELDING TECHNOLOGY

Industrial welding processes clearly tend towards automation and robotization in recent years. At present, welding robots are used not only in automotive industry but, to still increasing scale, also in different other branches. Automation brings various benefits; it offers better precision of fabrication and repeatability of operations while depriving the process of human errors resulting from individual worker's predispositions [1]. It shortens the working time, becomes indispensable element for difficult, dangerous and impossible-for-human being operations; it facilitates many works and relieves worker of such activities. At the same time, it connects with demand for qualified workers able to make use of novel solutions.

The most important element we gain with robotizing a welding stand is the effective coefficient of arcing. The effective arcing coefficient is the ratio of arc burning time to the full time necessary to make all welds. It is widely assumed that welding process is thought to be more effective the higher is this coefficient. For manual welding this coefficient is estimated at about 20% while it rises even to 70% when robotized welding stand is used [2]. This difference results from the welding method. In case of manual welding, the weld is made in lengths of several centimetres to up 0.5 m approximately. It is caused by necessary changes in welder position with respect to the welded element and by breaks in work made by welder from time to time. In case of robotized welding, the weld is made incessantly over the full welding length. Repeated movements of the robot reduces the risk of defects due to fatigue, and eliminates the necessity of corrections (weld grinding, chips) when process parameters are selected properly. Robotization also means better control over process parameters. Software used for robots allows for on-line tracking and recording all welding parameters.

PARAMETERS OF PULSED ARC WELDING

The MAG method uses direct current with straight polarity which causes intense melting of welding rod. Current characteristic in time domain is symbolically shown as horizontal straight line; however it is similar to straight line only for sprayed (contactless) transfer of droplets in welding arc, and also at high current levels. In case of droplet arc, current intensity rises when the droplet contacts material, and then returns to fixed value after the droplet comes off.

New generation welding equipment allows controlling many current parameters over wide ranges. In recent several years a clear rise of interest in pulsed arc welding is observed. This method is continuously developed and currently semi-automatic welders are marketed which offer several welding programs like Pulse, Twin Pulse, Speed Pulse or Hybrid Pulse techniques [3-9].

During MIG/MAG welding with pulsed arc, the base current of continuously burning arc is intensified with short-time current pulses which cause acceleration of melting at the end of welding electrode, creating and braking away of metal droplets (Fig, 1) [3, 4]. With pulsed arc, spray transfer of melted metal droplets can be reached at considerably lower current intensity than that of critical current. The finding of comparing MAG welding processes with normal and pulsed arc is that heat carried away by welded parts is 20-30% lower for pulsed arc; hence a lower thermal power is necessary to make a weld of specified volume by pulsed arc than that for the normal arc [6]. Lower heat carried away by welded object causes considerable lower welding stresses and deformations. Superimposed current pulses cause substantial concentration of heat energy in a narrow zone of arc and considerable kinetic energy of droplets transferred by the arc [6]. It causes a deep joint penetration of the material being welded, so enables to weld thick elements without scarfing.

Pulsed arc welding (Single Pulse), both for DC and AC, consists in forced current pulsation, from base current to pulse level (Fig. 2a, b). DC pulsed arc welding enables to control the filler metal droplet transfer in welding arc, so to reduce the spatters (Fig. 2a). AC pulsed arc welding enables, apart from controlling droplet transfer and amount of carried away heat, enables also to reduce the depth of fusion penetration and to improve the efficiency of electrode melting (Fig. 2b). By generating asymmetric rectangular current signal, it is additionally possible to provide continuous adjustment of electrode melting speed (carrying away the melting heat), depth of fusion penetration (reducing the pool temperature by means of fusion heat), welding bead width and pool heating [5].

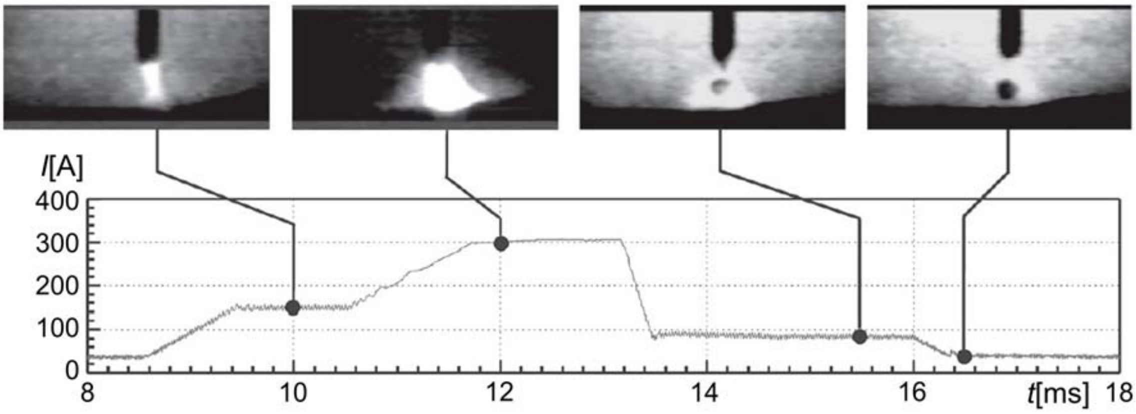

Fig. 1. Pulsed arc welding – Single Pulse [4]

Double-pulsation welding consists in alternate high- and low-frequency pulsation, which causes that the weld is free of tendency to generate cracks, porosity and excessive fusion penetration. For this type of pulsation, due to control over droplet transfer to molten pool, and – in case of AC current – also due to the amount of introduced heat, it is possible to control the pool by melting the substrate, counteracting the weld defects, preventing the overheating and burn-through of material (Fig. 2c, d) [5].

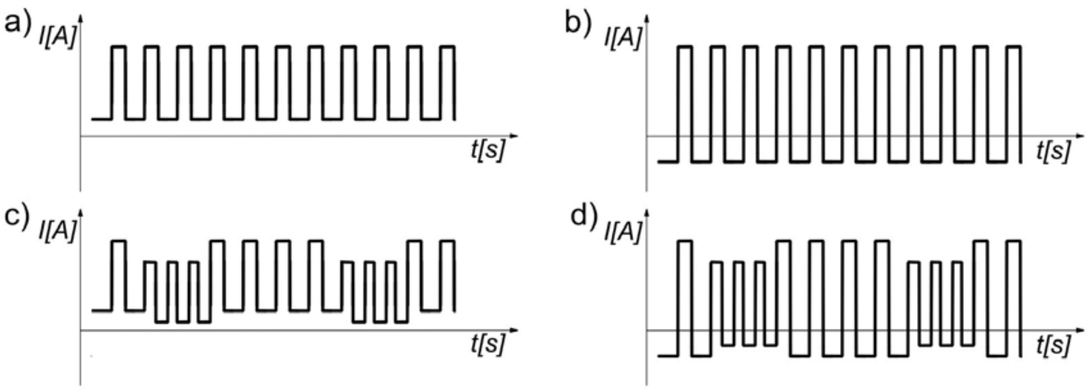

Fig. 2. Arc pulsation depending on current type: Single Pulse (a, b) and Twin Pulse (c, d) [5]

The arc pulsation methods which can be set at selected welding stand are: Pulse (Single), Twin Pulse (double, known also in some studies as Super Pulse) and Speed Pulse. Welding with Speed Pulse method is analogous to pulse welding except that the pulse frequency is increased. Depending on the pulse intensity selected, the Speed Pulse program will make more current pulses than that used in normal pulse mode. This enables to increase the welding speed as compared with Standard Pulse mode as the material droplet is transferred at higher frequency.

ROBOTIZED STAND USED FOR WELDING OPERATIONS

Welded joints on prepared sheet metals were made using Motoman robot supplied from LORCH power source. The Motoman welding robot has 6 controlled axes to ensure fast and efficient access to details being welded. High-quality welding is ensured by stable arc, optimum welding position, optimum bending radius of burner lines – collision free full 360^O turning range of the burner. The robot is controlled from programming panel equipped with 6.5 inch LCD touch screen. The welding power source is the inverter synergic semi-automatic unit which enables welding with the following programs: standard GMA, Pulse, Twin Pulse and Speed Pulse methods. The G3Si1 welding electrode 0.8 mm in diameter was used as an auxiliary material. A mixture of 82% Ar and 18% CO_2 was used as the shielding gas at delivery rate of 12 litres/min.

PREPARING THE TRIAL JOINTS

The DC01 (material number 1.0330) press-forming steel was selected for trial joints. The DC01 steel grade, with chemical constitution shown in Table 1, is suitable for longitudinal stretch drawing, bending and longitudinal roll forming. This material is first and foremost applicable in automotive industry where thin elements need to be joined together.

Table 1. *Chemical constitution of DC01 steel (acc. to manufacturer's certificates)*

Steel grade	Thickness mm	Chemical constitution, wt%										
		C	Si	Mn	P	S	Al	Cr	Ni	V	Ti	Nb
DC01	0,8	0,05	0,02	0,026	0,010	0,011	0,051	0,02	0,02	0	0	0
DC01	1,0	0,05	0,02	0,26	0,012	0,011	0,052	0,02	0,02	0	0	0
DC01	1,25	0,04	0,01	0,25	0,009	0,012	0,051	0,02	0,02	0	0	0

Table 2 provides some selected mechanical properties of DC01 steel. A large elongation of above 40% is the characteristic feature of this sheet metal. An average yield point for this material is 190 MPa at maximum stress of about 315 MPa.

Table 2. *Mechanical properties of DC01 steel sheets (acc. to manufacturer's certificates)*

Steel grade	Thickness mm	Mechanical properties		
		$R_{p0,2}$ [MPa]	R_m [MPa]	A_{80} [%]
DC01	0,8	185	307	40,9
DC01	1,0	188	312	41,4
DC01	1,25	196	333	42,9

Three sheet metal thickness values of 0.8 mm, 1.0 mm and 1.25 mm were selected for welding. The samples were cut out with hydraulic cutter to the dimensions of 250x100 mm. Twenty sheets of each thickness were prepared, 60 pieces in total. The samples were degreased with a solvent. Three tack welds were made manually to connect two samples of the same thickness. Prepared samples were secured to the positioning table using two welding clamps so as to reduce possible material deformations due to welding stresses to the minimum. The optimum parameters for each sheet metal thickness were selected basing on observations of welding process and visual inspections of the welds.

Trial welds were made with parameters 20% higher and lower than the fixed parameters. The sheets were burnt through for excessive current levels or there were no joint penetrations for insufficient current parameters. One of adjustable variables was the arc length which affects proper and even width of weld face (Fig. 3). The welding current was reduced or increased to get weld penetration or to reduce burn-through of sheets. Adjustments were also made using speed and height of electrode stick-out. These parameters are also affecting proper joint penetration and also proper and even width of the weld.

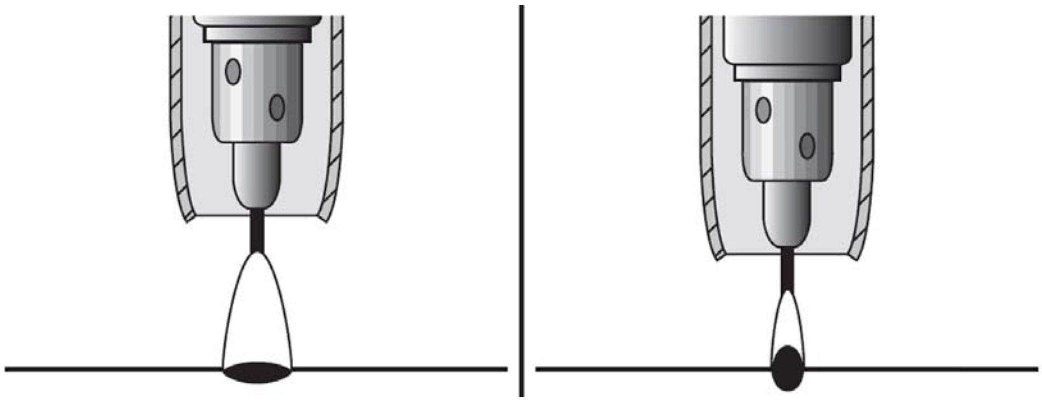

Fig. 3. Arc length correction: long light arc (a), short light arc (b) [4]

While attempts were made to set proper welding parameters, characteristic problems existing during thin sheet welding (Fig. 4) were encountered: too narrow face (a), irregular shape of weld face (b), irregular thickness of weld face (c), sheet burn-through (d), incomplete joint penetration (e), irregular height of weld face (f). Welding stresses caused by temperature were successive problem also encountered. The stresses released during welding and sheet metal subjected to deformation on its ends. This caused arc shortening when it reached the ends of sheet metal. Many times, it resulted in creation of excessively extended root of weld or sheet burn-through. Following visual inspections, these spots were excluded from further examinations and were not taken into account when elaborating the results.

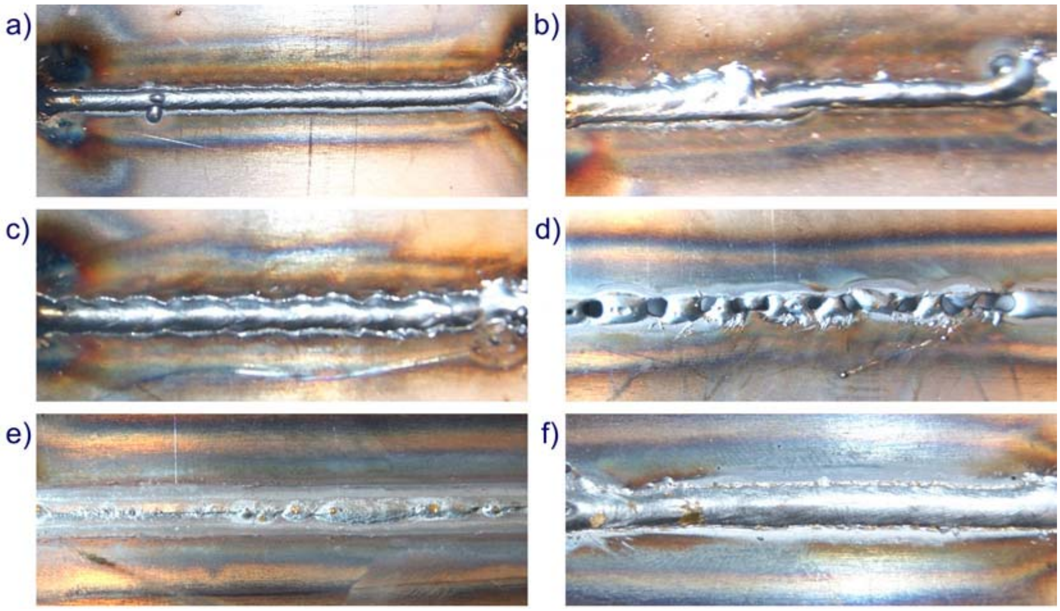

Fig. 4. Imperfections characteristic for thin sheet welding

Upon preparing the trial welds, the best parameters were established and used to weld the sheets. Joints were made for each welding program: Standard Mag, Pulse, Twin Pulse, Speed Pulse, and for each sheet thickness. Selected parameters are shown in Table 3.

Table 3. *Welding parameters selected for trial joints*

Welding program	Current intensity [A]	Voltage [V]	Arc length correction [%]	Welding speed [cm/min]
Sheet thickness 0,8 mm				
Standard MAG	52	16	120	55
Pulse	30	14,7	100	45
Twin Pulse	33	14,8	100	45
Super Pulse	30	14,7	100	45
Sheet thickness 1,0 mm				
Standard MAG	66	16,7	120	55
Pulse	40	15,1	100	45
Twin Pulse	40	15,1	100	45
Super Pulse	40	15,1	100	45
Sheet thickness 1,25 mm				
Standard MAG	75	19	120	55
Pulse	47	15,7	100	45
Twin Pulse	48	15,7	100	45
Super Pulse	47	15,7	100	45

VISUAL INSPECTIONS OF TRIAL JOINTS

All trial joints were visually inspected to determine that the welds are consistent in shape and dimensions and to detect possible superficial imperfections. An analogue weld gauge, type SPA 60, was used to measure geometrical correctness. The provisions of the standard PN-EN ISO 5817:2009, *Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welded excluded).Quality levels for imperfections* were used during measurements of geometrical correctness. The height of weld face shall be equal to h≤1+0.25b (b – weld width), and the weld root shall be h≤1+0,25b (b – root width).

Visual inspection having been carried out did not revealed any superficial imperfections which could affect the quality of welds, independently of sheet metal thickness or welding mode. The heights of weld face and root were correct for all joints inspected. Small spatters (Fig. 5a, b) and uneven heat-affected zone on several samples (Fig. 5c) were found. Local risers and incompletely filled groove of weld face (Fig. 5d) were found in one sample. All aforementioned imperfections would not substantially reduce the strength properties and the quality of the weld.

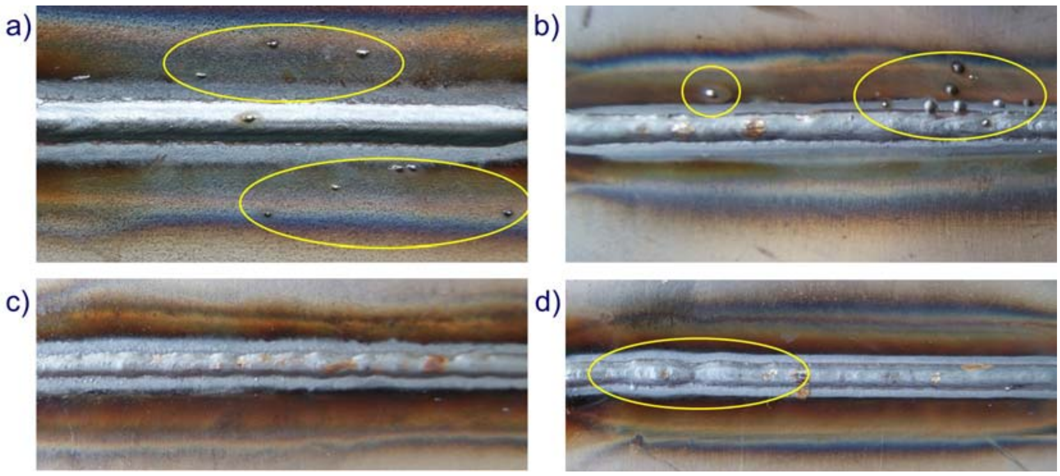

Fig. 5. Imperfections found during visual inspections: local spatters (a, b); uneven heat-affected zone (c); local risers and incompletely filled groove of weld face (d)

LIQUID PENETRANT INSPECTION OF TRIAL JOINTS

Following visual inspections, all welded sheets were inspected with liquid penetrant. These inspections were run to detect superficial imperfections such as: cracks, lack of joint penetration, and surface porosities. Samples were evaluated for meeting the acceptance levels included in the standard PN-EN 571-1:1999, *Non-destructive testing. Liquid-penetrant inspections. General rules* (Table 4).

Table 4. *Acceptance levels for liquid-penetrant inspections acc. to PN-EN 571-1:1999*

Type of indications	*Acceptance level*		
	1	2	3
Linear indications *l* - indications length	*l*≤2	*l*≤4	*l*≤8
nonlinear indications *d* – main axis size	*d*≤4	*d*≤6	d≤8

Samples were cleaned, covered with colour penetrant and left for 30 minutes, in order that it can penetrate into possible joint imperfections (Fig. 6a). Following this time, the samples are thoroughly cleaned and the joints are covered by developer (Fig. 6b). Liquid-penetrant inspections revealed no additional imperfections than those from visual inspections. Small cracks, which fell into the first level of acceptation scale in liquid-penetrant inspections, were found in two samples; however they have no effect on the quality and strength of welds (Fig. 6c, d).

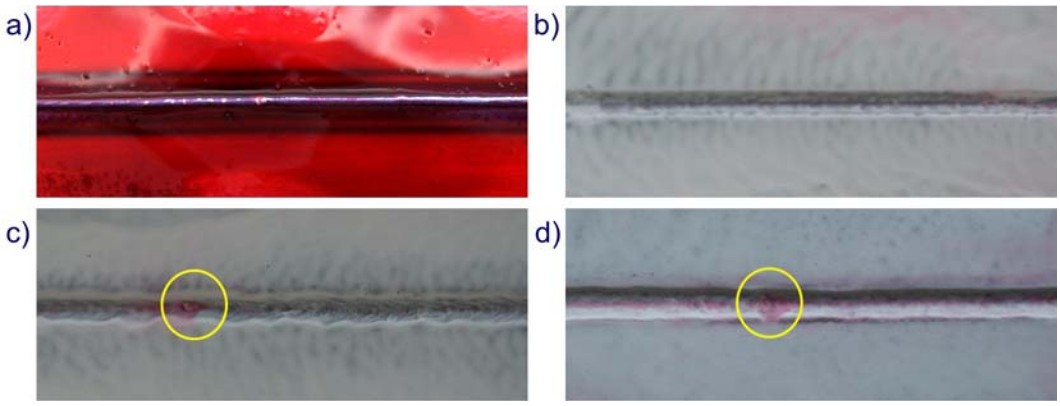

Fig. 6. Stages of liquid-penetrant inspections: penetrant application (a), developer application (b), detection of imperfections (c, d)

TENSILE STRENGTH TESTING OF TRIAL JOINTS

Trial welded joints were tested for tensile strength. A single breaking force is determined for welded joints due to metallurgical and structural heterogeneity (weld – heat-affected zone – parent metal). The INSTRON testing machine, Model 3369, was used at beam feed speed V_b = *0.2 cm/min*. Specimens were secured with self-locking clamps.

Welded sheets were preliminary cut to specimens 24 mm wide. Two kinds of specimens were prepared for strength testing as it turned out during preliminary tests that in case of classic flat samples (Fig. 7a) each time the rupture occurred in parent metal. Hence, the specimens milled at the weld were also prepared to direct the point of rupture (Fig. 7b). After milling, the width at the weld was 12 mm. The accurate width used to calculate the tensile strength was measured and recorded prior to starting with tensioning process.

Fig. 7. Specimens prepared for tensile strength testing

The MAG and Speed Pulse welding programs were selected for strength testing of flat specimens (Fig. 7a). Since, as expected, each time the rupture occurred in parent material, the results were compared with figures given by sheet metal manufacturers (Fig. 8). The results having been obtained were very similar to theoretical properties of the DC01 material as shown in Table 3 (the max. difference is 10%). The value of R_m was 280-330 MPa, depending on sheet thickness. These results were confirmed by the remaining welding programs (Pulse and Twin Pulse), which were used for verifying one specimen per each program.

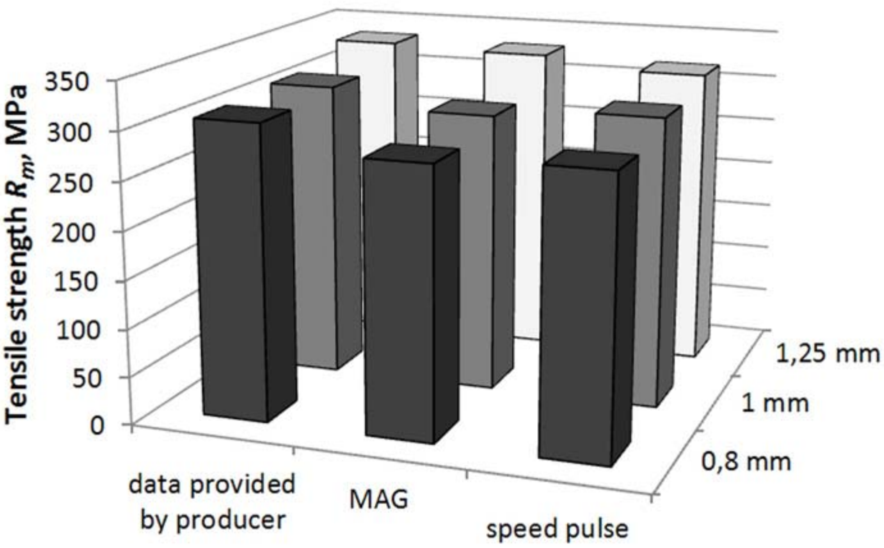

Fig. 8. Tensile strength of flat specimens (without milling)

Three specimens (Fig. 7b) were used for each sheet thickness and for each welding program in tensile test to determine tensile strength of the weld/heat-affected zone. Specimens were prepared so as their smallest cross-section area was at the weld. In such case, material rupture would occur just at the weld, so tensile strength properties were tested for the weld or possibly for the heat-affected zone. Figure 9 illustrates exemplary results for joint made for sheets 0.8 mm thick. As can be seen, diagrams are similar for all process variables; hence the three specimens were sufficient. As the diagrams for the remaining thickness values were analogous and had stable waveforms, all results were summarized in Table 5 and shown in common in the diagram of Fig. 10.

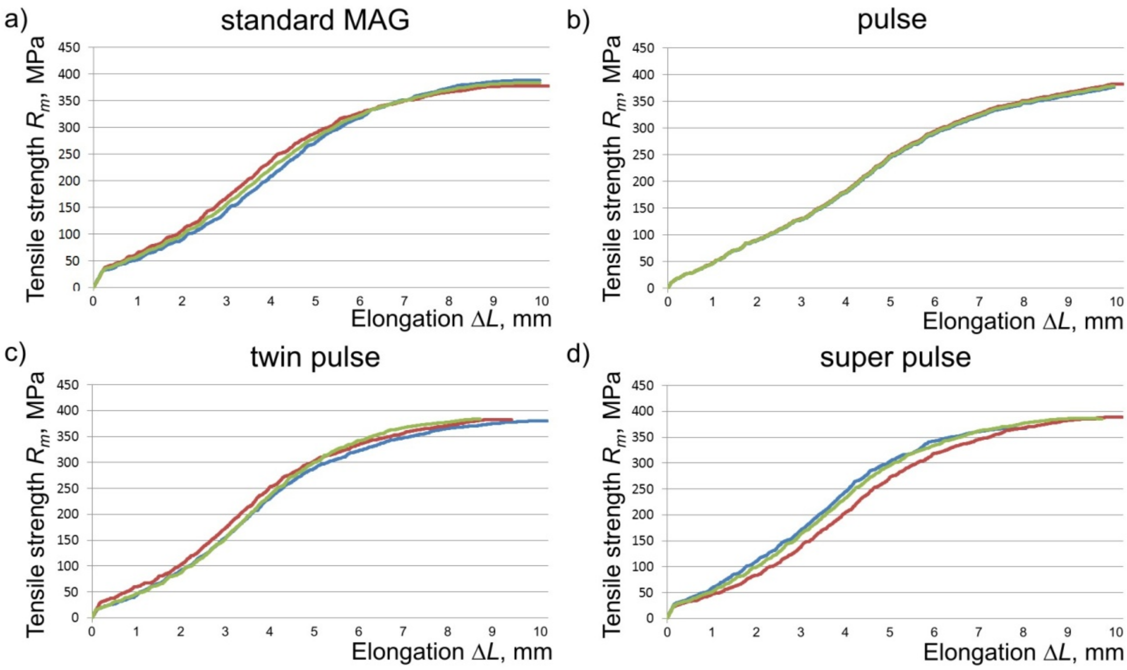

Fig. 9. Diagrams of tensile tests for sheets 0.8 mm thick versus various welding programs

Table 5. *Strength test results for milled specimens*

Welding program	Sheet thickness [mm]	Tensile strength R_m [MPa]
standard MAG	0,8	383
pulse		387
twin pulse		382
speed pulse		384
standard MAG	1	389
pulse		385
twin pulse		392
speed pulse		385
standard MAG	1,25	397
pulse		403
twin pulse		410
speed pulse		402

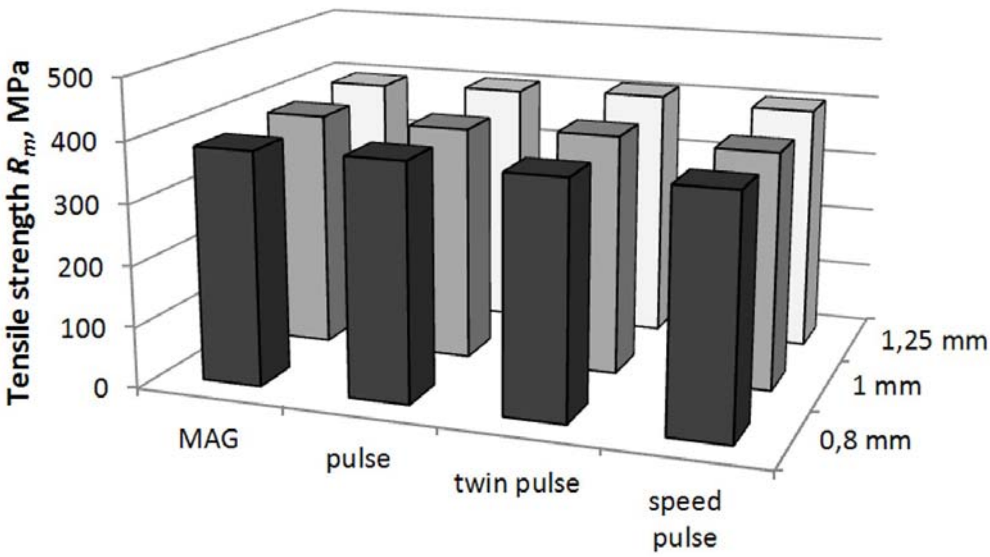

Fig. 10. Tensile strength of sheets, 0.8 mm, 1 mm and 1.25 mm for four welding programs: standard MAG, Pulse, Twin Pulse and Speed Pulse

Tests of all specimens were run under the same external conditions, using the same testing machine and using uniform, constant load applied to the material. Each time the material was broken within the heat-affected zone (Fig. 11). The results acquired explicitly point out that the welding program applied has a slight effect on joint strength for thin sheet metals. The discrepancies in tensile strength values are up to 20 MPa, i.e. about 5% of their levels. The highest strength was found for sheet 1.25 mm thick welded with Twin Pulse program, and the lowest value was observed for sheet 0.8 mm thick made with standard MAG program. When analysing welding programs, the best strength parameters were for the Twin Pulse mode. An exception is when this program was used for sheet 0.8 mm thick; however also in this case the value of 384 MPa is very close to the highest level of 386 MPa attained with the Pulse program. The worst strength parameters were found for sheet welded with standard program.

Fig. 11. Exemplary specimen after completing the tensile test

MACROSCOPIC EXAMINATIONS OF TRIAL JOINTS

A set of 12 samples representing three sheet thicknesses and four welding programs was prepared. Specimens, properly cut out, were mounted in a resin and then ground and polished. Abrasive papers, grades 200 through 2500, were used for this purpose. Then, Adler's reagent was used (crystalline cupric chloride 5g, distilled water 25g, hydrochloric acid 50 ml, and anhydrous ferric chloride) to etch the welds under testing.

Two-stage analysis of welds was used. At first, metallographic specimens were observed immediately after etching when material imperfections like porosity and cracks were better revealed. Then, the surface of microsections was covered with oil which causes that the weld and heat-affected zone were clearly visible. Figure 12 illustrates exemplary macrostructure of welded joint made with standard MAG program for 0.8 mm thick sheet.

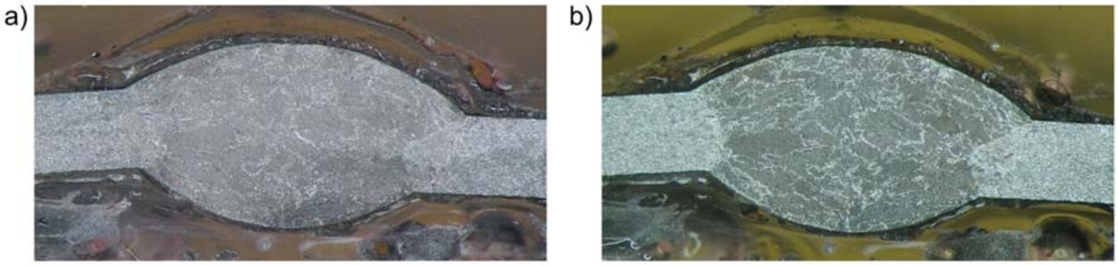

Fig. 12. Macrostructure of trial joint made for 0.8 mm thick sheet welded with standard MAG program: after etching (a), and after oil application (b)

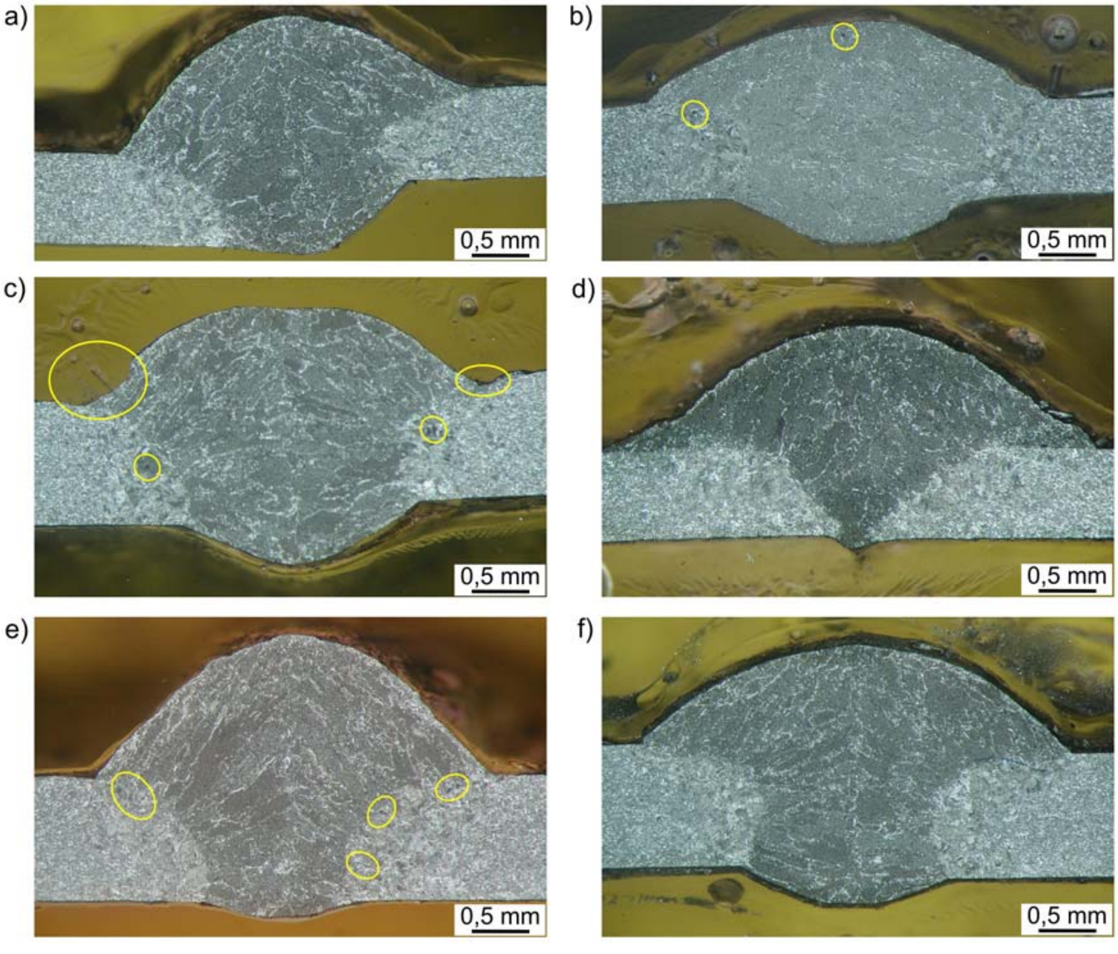

Fig. 13. Welding imperfections and lack of shape/dimensional correctness detected during macroscopic examinations

Microscopic examinations revealed correct joint penetration, no cracks, incomplete fusions, porosity or inclusions for most joints. The expansion degree of face and root weld was correct. Generally, the welds were made correctly and meet the quality criteria as concerns their structure. However, several joints demonstrated welding imperfections and lack of shape/dimensional correctness. Figure 13 illustrates characteristic imperfections revealed during macroscopic examinations: considerable shift of welded sheets each other – this defect should be eliminated at the stage of sheet positioning and clamping (a), occasional porosity (b), undercuts and blisters (c), excessively extended face and too small root of weld (d), very extended face and blisters (e), incomplete joint penetration (f).

HARDNESS MEASUREMENTS

Vickers hardness test and the load of 500 g were used. A series of indentations were made for each sheet metal (method R acc. to PN-EN ISO 9015-1:2011) in 0.25 mm intervals, hence the condition of observing the distance equal to triple diagonal between adjoining indentations was met. Measurements were made from the weld axis towards parent metal. According to literature information, the DC01 steel demonstrates hardness level of 105 HV.

Hardness values measured for 0.8 mm sheet was summarized on the diagram in Figure 14. The values of HV0.5 for the remaining thicknesses of parent metal were similar; differences concerned only the widths of individual zones (weld, heat-affected zone). Waveforms of particular welding programs do not differ significantly each other. The highest hardness in the weld (average of 227 HV0.5) was observed for standard MAG welding. This can be explained by lower speed of carrying away of heat as compared with the remaining welding programs which linear energy is at lower level. Individual diagrams show clear zone of various structures with different hardness values: weld, overheated zone, normalized/partly normalized zone, and zone with predominating parent material.

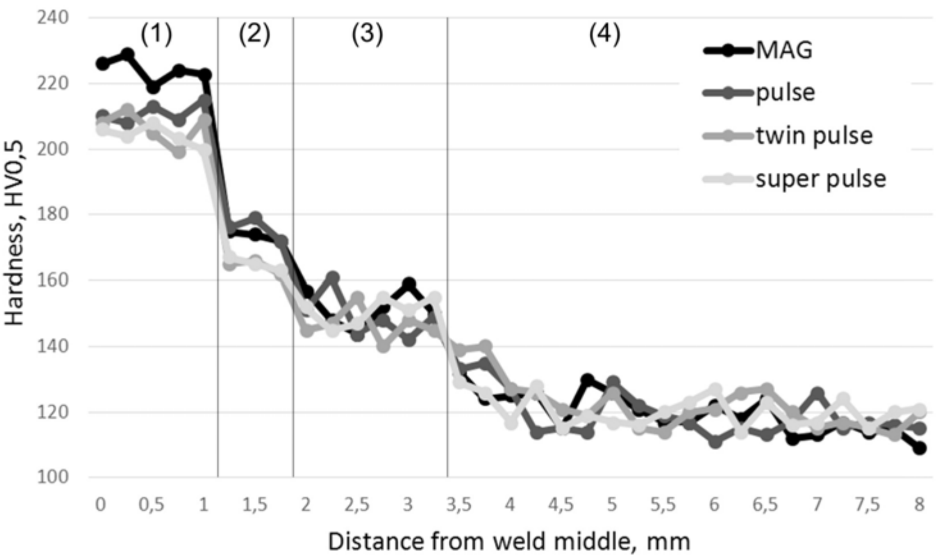

Fig. 14. Distribution of hardness for welds made with 4 welding programs, 0.8 mm sheet

CONCLUSIONS

The examinations having been run allow expressing the following conclusions:

- Welding the thin steel elements often is a debatable task which can lead to joints with characteristic welding imperfections. A serious problem which should be eliminated at the stage of positioning the elements are the welding stresses which may cause substantial deformations of thin sheets during welding. This causes a change of arc length, hence automatic change of linear energy causing, for instance, generation of excessively extended root of weld or sheet burn-through.
- Visual inspections found no superficial imperfections which could affect the quality of welds, however minor spatters, non-uniform heat-affected zone or local risers and underwashings in weld face were detected. All aforementioned imperfections do not substantially reduce strength properties and quality of the weld.
- Liquid penetrant examinations, apart from two samples where small cracks were found (level 1), did not revealed any additional imperfections as compared with visual inspections.
- Tensile strength tests proved that there is no strong correlation between welding program applied and mechanical strength of joints. Discrepancy between results is not higher than 5% and joints were always broken within the heat-affected zone.
- Macroscopic examinations did not revealed major welding imperfections. Only several single blisters and undercuts in one weld were found. A greater problem was with improper shape and geometry of welds. Non-aligned positioning of sheets and excessively extended face/root of weld were pointed out.
- Characteristics of hardness distribution in joints welded with various programs did not manifest any substantial differences. Only the hardness of weld made with standard MAG program was about 20 HV higher than those of remaining programs which featured lower heat load of welds. These relations occurred for all thicknesses of sheets.
- Welding of thin sheets made of readily welded materials using advanced welding programs (Pulse, Twin Pulse, Super Pulse) demonstrated no distinct benefits as compared with standard MAG mode. Due to great share of parent metal in the weld, speed of heat carrying away, and first and foremost, due to the lack of tendency to sheet hardening, welded joints made with particular method did not differ substantially. In case of readily welded steel grades, the only discernible difference is the sheet deformation which is the greatest for conventional MAD method and respectively lower for the Pulse, Twin Pulse and Super Pulse programs.

REFERENCES

1. Kruczyński M.: Robotized welding process, Mechanical engineering and design, no 1-2/2011, (in polish).
2. Kruczyński M.: Kawasaki, Friendly robotic, friendly welding, Welding of construction materials, no 3/2009, (in polish).
3. Pilarczyk J.: Handbook of Welding Technology, vo.l II, WNT, Warszawa 2005, (in polish)
4. User guide S SpeedPulse, LORCH Schweißtechnik GmbH, 2008, (in polish).

5. Jastrzębski A., Tasak E., Influence of pulsation of the MIG arc on the structure of aluminium alloys welds, Welding Technology Review, no. 7-8, 2009, (in polish).
6. Lange A.: MIG/MAG welding, educational materials of the project "Improving the competitiveness of the automotive industry through staff training", Wrocław 2008, (in polish).
7. Mizerski J.: MAG and MiG Gas-shielded welding methods, Handbook for welders and welding supervision personnel, REA, Warszawa 2005, (in polish).
8. Kiszka A., Technological properties of low-energy welding methods ColdArc, CMT, AC Pulse and Cold Process, Welding Departments and Institutes symposium "Modern Applications of welding technology", Byczyna 2012, (in polish).
9. Klimpel A., Janicki D., Cyroń M., Pulse arc GTA automatic welding process of thin austenitic AISI 321 steel, Welding Technology Review, no. 2-3, 2006, (in polish).