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Summaries of the articles

A. Kiszka, T. Pfeifer - Use of anti-spatter substances in welding processes

The article presents the course and results of tests involving the use of anti-spatter substances. The study determined the effect of the anti-spatter substance applied on the surface of workpieces on the quality and properties of welded joints as well as the effect of the anti-spatter substance applied on the welding torch elements on the active life of nozzles and contact tubes used in MIG/MAG welding and plasma cutting processes.

J. Czuchryj, P. Irek - Dye penetrant method of the assessment of the pores size in welded joints made of aluminium and its alloys

The work included the penetrant inspection carried out on AlMg5 aluminium alloy provided with artificial discontinuities, i.e. pores (drilled openings). The tests involved the measurements of indication sizes depending on the time of development and various diameters and depths of openings. The dependences determined enable estimating the depth of pores in welded products made of aluminium and its alloys. The information obtained should enable the decision-making concerning the acceptance of a product for operation or the necessity of repairing it. The tests also included the determination of optimum indication development time for aluminium and its alloys.

M. St. Węglowski, J. Dworak, S. Błacha – Electron beam welding – equipment and accessories

Electron beam welding has been known and used for a long time, yet the recent years have seen increasing advancements in equipment fully utilising this welding method potential. Electron beam welding machines can be both universal and highly specialised, which can translate to significant operating and, first of all, welding costs reduction. Modern electron beam welding devices are provided with control systems and safety features which maximise operator's anti-radiation protection and enable carrying out technological processes in vacuum conditions.

R. Kaczmarek, R. Krawczyk - Analysis of dimensions of test joints in the process of technology qualification according to PN-EN ISO 15614-1 in the aspect of ultrasonic testing according to PN-EN ISO 17640

Quality assurance systems in welding engineering demand that the manufacturers of welded structures and welding equipment should apply qualified welding technologies. The most commonly used mode of welding technology qualification is testing a given welding technology by making test joints and carrying out their examination. This article presents the analysis of test joint dimensions recommended in PN-EN ISO 15614-1 in relation to the possibility of testing the quality of such joints using ultrasonic testing according to recommendations of currently valid related standards. The article contains a proposal how to determine the width of a test joint on the basis of the nomogram developed. The target readers of the article include welding engineers and technologists, other welding coordination personnel involved in the preparation of test joints as well as NDT personnel, due to the extensive analysis concerning the selection of testing methods and ultrasonic examination of test joints.

R. Krawczyk - Welding parameter ranges in relation to metal transfer method in welding arc

The study is concerned with MAG welding. The issues presented are directly related to the transfer of metal in the welding arc depending on power applied. The main objective of the study

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was to present the ranges of welding parameters in relation to the mode of metal transfer in the welding arc. The subject of the study was inspired by the introduction of new standard PN-EN ISO 9606-1 concerning the qualification of welders. This standard features the mode of metal transfer in the welding arc as a new welder qualification variable. As a result, these issues have acquired new significance in terms of this process.

W. Zeman, M. Restecka – Welding industry against economic fluctuations of 2006 – 2012

The article aims to determine the scale of applying welding technologies, the role of welding engineering in production and economy and the impact of economic fluctuations on the dynamics of sales in industries applying welding techniques and on the demand for welding equipment and consumables.

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Agnieszka Kiszka, Tomasz Pfeifer

Use of anti-spatter substances in welding processes

Abstract: The article presents the course and results of tests involving the use of anti-spatter substances. The study determined the effect of the anti-spatter substance applied on the surface of workpieces on the quality and properties of welded joints as well as the effect of the anti-spatter substance applied on the welding torch elements on the active life of nozzles and contact tubes used in MIG/MAG welding and plasma cutting processes.

Keywords: welding, spatter formation, anti-spatter substances, MIG, MAG, plasma cutting

Introduction

The problem of spatter formation during welding works is very common and may be responsible for approximately 5-10% of losses in filler metals. Spatters adhering to welding torch elements necessitate the exchange of contact tubes and cleaning of the nozzles, which in turn decreases the efficiency of welding works. Frequent replacements of welding fixtures increases the costs of welding and cutting. Spatters accompany most welding processes. In MIG/MAG welding spatters are usually caused by the following factors:

- low current in relation to the diameter of electrode wire,
- overly low inductance of a welding circuit during short-circuit metal transfer,
- excessively long, exposed electrode wire,
- type of shielding gas,
- purity of the filler metal (presence of impurities in the form of oxides or other chemical substances) [1].

Spatter-caused impurities settling on welding torch elements can trigger the formation of imperfections such as gas pores, incomplete fusion or lack of penetration in the weld. Spatters accompanying welding processes adhere not only to welding torch elements but also to workpieces, thus deteriorating their aesthetics. This poses a basic technological challenge, e.g. during welding car body sheets. The primary remedy eliminating spatters both from the surface of workpieces as well as from welding torch elements consists in the use of anti-spatter substances. However, if used improperly such substances may contribute to the formation of imperfections in welded joints, e.g. lack of penetration, incomplete fusion and localised porosity. These imperfections are formed during the pre-weld preparation of workpieces as well as while applying the anti-spatter substance on the surface of workpieces when an excessive amount of such a substance enters the area of a weld groove. Classification societies often

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require the presentation of objective test results proving that the use of a given anti-spatter substance does not adversely affect the properties of welded joints.

Scope of tests

The tests involved the use of two types of anti-spatter substances, i.e. aerosol to be applied onto the surface of workpieces and aerosol to be used mainly on welding torch elements. The scope of tests related to the first stage of research was developed on the basis of standard PN-EN ISO 15614-1 [2] and included

- MAG (135) welding of butt joints in 10 mm thick S355J2+N steel,
- MAG welding of T-joints with a filler weld in 10 mm thick S355J2+N steel,
- NDT of all welded joints (visual and radiographic testing of butt joints and visual testing of T-joints),
- destructive testing of welded joints:
    - tensile tests, impact and bend tests as well as macroscopic tests and hardness measurements of butt joints,
    - fracture test of both T-joints as well as macroscopic tests and hardness measurements of a joint with a small amount of anti-spatter substance in the weld groove.

In the case of the anti-spatter substance used on welding torch elements the scope of tests included:

- MAG welding in S355 steel,
- MAG overlay welding in S355 steel,
- MIG welding in 6082, 7075 and 2017A aluminium alloys,
- manual plasma cutting in 12 mm thick S355 steel.

Prior to tests the anti-spatter substance was applied on a welding torch nozzle (both inside and outside) and on a contact tube following the instructions of a related manual. After several seconds the substance dried forming a white ceramic coating on the surface (Fig. 1).

In order to prevent the substance from entering a weld (imperfection risk), the electrode wire was pulled out and its tip covered with the anti-spatter substance was cut off. In doing so, great attention was paid not to damage the anti-spatter coating on the nozzle and on the contact tube. It was observed that the protective coating became hard due to heat emitted at the initial stage of welding. As a result, the durability of the coating increased.

The methodology of testing the anti-spatter substance involved comparing the condition of the welding torch contact tube without the anti-spatter protection and with anti-spatter coating, after MIG/MAG welding, MAG overlay welding and plasma cutting. The tests of the processes enumerated above were carried out for the same time and using the same parameters. The assessment included the amount of spatters and difficulty connected with their removal.

Testing anti-spatter substance applied on workpieces

Welding butt joints with butt weld

In the case of the anti-spatter substance applied on workpieces, joints were made using manual MAG welding. The whole course and range of tests was consistent with requirements related to the qualification of welding technologies presented in standard PN-EN ISO 15614-1. The first butt joint was prepared in accordance with Figure 2. Before welding the workpieces were coated with the anti-spatter substance. The anti-spatter application technique was the same as the one used in practice, i.e. the amount of the substance entering the weld groove was small (Fig. 3). The welding sequence was as presented in Figure 2.

Fig. 1. MAG welding torch tube with anti-spatter substance coating

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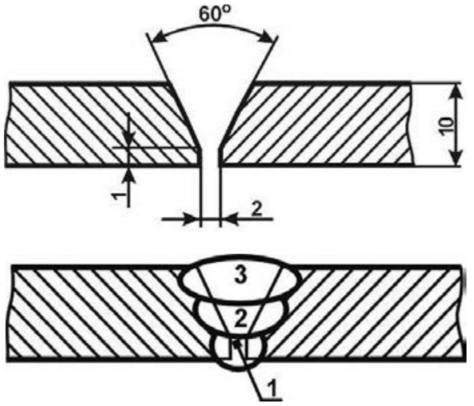

Fig. 2. Preparation of elements for welding and welding sequence

Fig. 3. Weld groove with small amount of anti-spatter substance after making tack welds

The visual testing conducted directly after welding showed that the joint represented the quality level B. The weld surface did not reveal any cracks or porosity. The radiographic tests did not disclose the presence of any welding imperfections. Figure 4 presents the weld radiogram and the macroscopic metallographic photograph of the joint made.

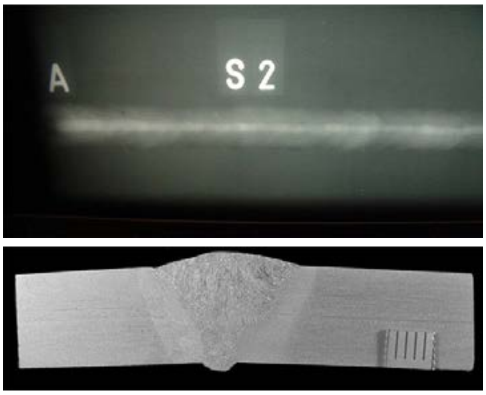

Fig. 4. Radiogram and macrostructure of the weld made with a small amount of the anti-spatter substance in the weld groove, quality level B according to PN-EN ISO 5817

Afterwards, the welded joint was sampled for test pieces for further destructive tests. Tensile tests bend tests, impact tests and hardness measurements were carried out following the requirements of standard PN-EN ISO 15614-1.

The tensile test results of two test pieces sampled from the same joint (549.2 MPa and 547.3 MPa) met the minimum tensile strength criterion (Rm ≥ 470 MPa). The bend tests of 4 test pieces revealed a bend angle of 180° for the bending mandrel diameter of 40 mm. The welds subjected to bending with both weld face and weld root tension contained no scratches or cracks. The impact tests carried out at -20°C revealed an average weld impact strength of 34.7 J and an average HAZ impact strength of 93.3 J. Therefore, the minimum impact strength criterion for S355J2+N steel amounting to 27 J at -20°C was fulfilled. The hardness measurements carried out in two lines of the welded joint section revealed the maximum HAZ hardness at approximately 200 HV, meeting the maximum hardness criterion of ≤380 HV.

Afterwards, a butt welded joint was made, on which the excessive amount of the anti-spatter substance was applied both on the sheet surface and in the weld groove area (Fig. 5). The welding process was conducted using the same parameters as in the case of the previous joint.

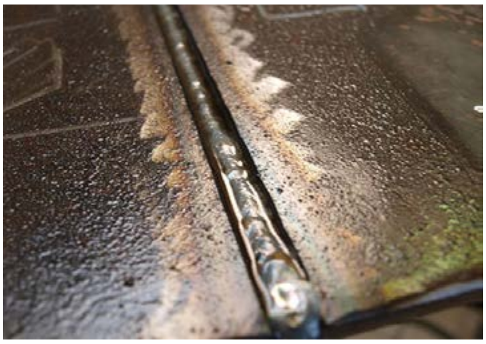

Fig. 5. Weld groove with excessive amount of anti-spatter substance after making a root run

During welding it was observed that even a significant amount of the anti-spatter substance applied did not impede the course of the process, i.e. no excessive spatter was formed and arc burning was stable. The visual tests carried out afterwards did not reveal the presence of pores on the weld surface. The radiographic tests did not reveal the presence of any gas

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Fig. 6. Radiogram of the weld made with the excessive amount of anti-spatter substance in the weld groove, quality level B according to PN-EN ISO 5817

Fig. 7. Workpieces with a small amount of the anti-spatter substance in the interface

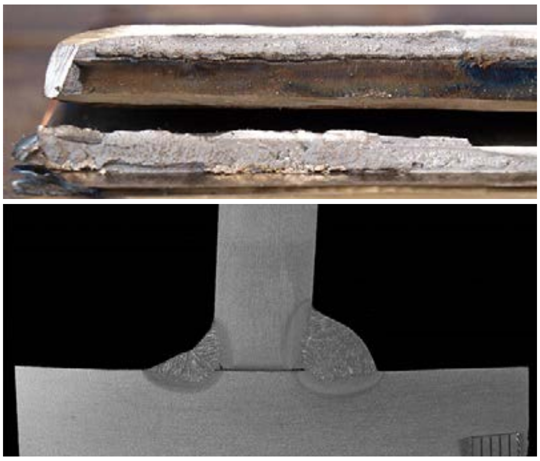

Fig. 8. Weld after the fracture test and the macrostructure of the joint made with the small amount of the anti-spatter substance in the interface

Fig. 9. Elements with the excessive amount of the anti-spatter substance applied in the joint interface

pores in the weld (Fig. 6). The joint represented the quality level B and in terms of quality did not differ from the one made previously.

Welding T-joints using a fillet weld

The testing methodology applied to T-joints with a fillet weld was identical as the one used for butt joints. The first joint was made with the same amount of the anti-spatter substance applied on the surface of elements to be joined as the one used in practice, which means that the amount of the substance entering the weld groove was small (Fig. 7). Before making the main fillet weld a seal weld was made on the other side of the joint. The seal weld presence tightened the restrictions of test conditions as it hindered the release of anti-spatter substance vapours through a gap in the interface. The seal weld was made prior to anti-spatter substance application.

During welding it was possible to observe stable arc burning, proper parent metal wetting and proper fusion into the web and flange material. No excessive spatter could be seen. The visual tests did not reveal any porosity on the weld face surface. The fracture tests and macroscopic metallographic tests revealed proper fusion into both walls of the joint, which represented the quality level B. Figure 8 presents the fracture test result and the joint macrostructure.

The hardness measurements were conducted following the requirements of a related standard concerning the qualification of technologies. The results revealed a HAZ hardness of approximately 350 HV, i.e. meeting the maximum permissible hardness criterion. Afterwards, a T-joint with a fillet weld was made. The excessive amount of the anti-spatter substance was applied both on the surface of sheets and in the interface of the elements (Fig. 9). Welding was carried out using the same parameters as in the case of the previous joint.

During welding with an excessive amount of the anti-spatter substance, it was observed that obtaining proper fusion was very difficult, as

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the anti-spatter substance layer constituted, in a way, a natural barrier preventing proper wetting of the edges to be joined. In order to determine whether the joint was made properly and if fusion into the walls of workpieces was appropriate, it was necessary to conduct a fracture test. The fillet weld was cut along the whole length and next fractured by an impact. The fracture test result and the macroscopic metallographic test result are presented in Figure 10.

The tests conducted confirmed what was observed during welding of a T-joint with a significant amount of the anti-spatter substance applied. Both the fracture test and macroscopic metallographic examination revealed the absence of fusion in the joint. However, the weld did not contain gas pores, which indicates that even such a significant amount of the anti-spatter substance as the one applied in the interface of workpieces can evaporate during welding and does not trigger the formation of gas pores. On the other hand, the absence of fusion disqualified the joint as failing to meet the quality level B requirements according to PN-EN ISO 5817. Proper fusion might have been obtained with greater welding linear energy but it had been assumed previously that joints should be made using similar parameters.

Testing anti-spatter substance applied on welding torch elements

MAG welding

Twelve millimetre thick S355J2 steel sheets were welded using the MAG method, a G3Si1 electrode wire with a diameter of 1.2 mm and CO_2 used as a shielding gas. The conditions of 2-minute and 5-minute long welding were selected in order to generate significant spatter (Fig. 11). The first stage involved testing the MAG welding influence on the condition of a nozzle and on a contact tube not protected with any anti-spatter substance. It was observed that welding torch elements were covered with many spatters difficult, yet possible, to remove (Fig. 12).

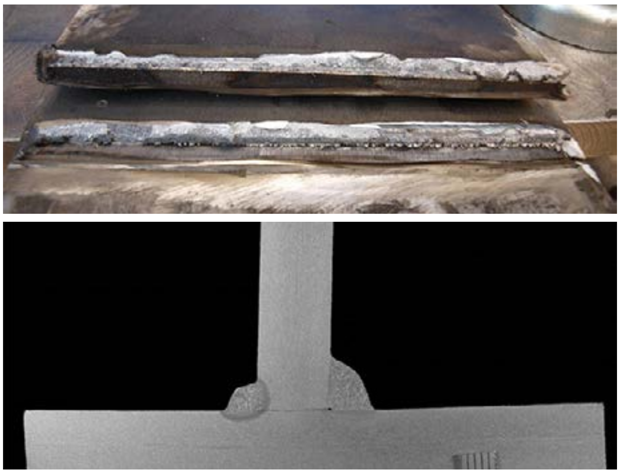

Fig. 10. Weld after the fracture test and the macrostructure of the joint made with the significant amount of the anti-spatter substance in the interface

Fig. 11. MAG welding in steel – visible significant spatter.

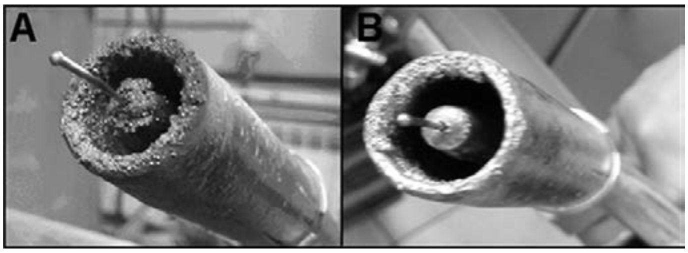

Fig. 12. Nozzle and contact tube without the anti-spatter substance. A- after 5-min long welding, B- after removing most spatters.

Fig. 13. Nozzle and contact tube with the anti-spatter coating after 5-minute long welding.

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Afterwards, the nozzle and the contact tube were coated with the anti-spatter substance following the instructions provided on the anti-spatter substance container. After 2-minutes of welding, the nozzle and the contact tube were still free from spatters, yet 5 minutes of welding led to the appearance of spatters on the nozzle (Fig.13). Hitting the nozzle gently caused the spatters to fall off easily. After removing the spatters it was possible to observe the intact protective coating.

MAG overlay welding

Overlay welding was carried out automatically. The tests involved the use of pipes made of the following materials:

1. R35 steel, 150 mm in diameter; wall thickness of 8 mm,
2. 32HA steel, 150 mm in diameter; wall thickness of 10 mm.

Overlay welding involved the use of a G3Si1 electrode wire with a diameter of 1.2 mm and a shielding gas mixture of 82%Ar+ 18%CO_2 (PN EN ISO 14175 M21-ArC-18). The process lasted approximately 10 minutes and welding current reached as many as 300 A. Overlay welding was accompanied by the formation of significant spatters (Fig. 14).

Fig. 14. MAG overlay welding of pipes

During overlay welding, the nozzle and the contact tube not provided with the protective coating became covered with spatters, the removal of which was difficult (Fig.15). After applying the protective coating the nozzle and the contact tube remained free from spatters (Fig. 16).

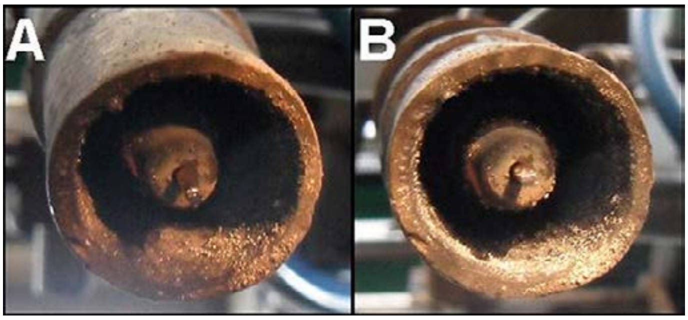

Fig. 15. Nozzle and contact tube after MAG overlay welding, without the anti-spatter coating. A- before cleaning, B- after spatter removal.

Fig. 16. Nozzle and contact tube coated with the anti-spatter substance, after MAG overlay welding (10 min).

MIG welding

MIG welding was carried out on 4 mm thick 6082 aluminium alloy sheets using an AlMg4.5MnCrZr (Al5087) electrode wire with diameters of 1.0 and 1.2 mm and argon as a shielding gas. Similarly to MAG overlay welding, the initial welding tests were carried out without the protective coating applied (Fig. 17).

Fig.17. Nozzle and contact tube after MIG welding (5 min), without the protective coating; visible spatters.

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Afterwards, the anti-spatter substance was applied as in the case of MAG overlay welding (Fig. 18).

The welding process lasted 5 minutes for each type of sheet. The process went on smoothly and no spatters adhering to welding torch elements were observed (Fig. 19). This was due to a relatively low, if compared with steel, aluminium melting point of approximately 660°C.

Fig. 18. Nozzle and contact tube with the anti-spatter substance applied; view before welding

Fig. 19. Nozzle and contact tube with the anti-spatter substance applied, after MIG welding (5 min).

Plasma cutting

During plasma cutting plasma gas blows out molten cut metal, as a result of which significant spatters are formed (Fig. 20). This phenomenon is significantly more intense than in the case of MIG/MAG welding. A material being cut is blown out of a cut gap also in the direction of a welding torch, causing the contamination of the plasma nozzle elements.

The plasma cutting process was carried out for approximately 5 minutes using a manual plasma cutting machine. The tests involved the use of the same materials as in the case of MAG overlay welding, i.e. 12 mm thick S355J2 steel sheets. Initially, the anti-spatter substance was not applied, which led to the formation of spatters permanently adhering to the welding torch elements (Fig. 21).

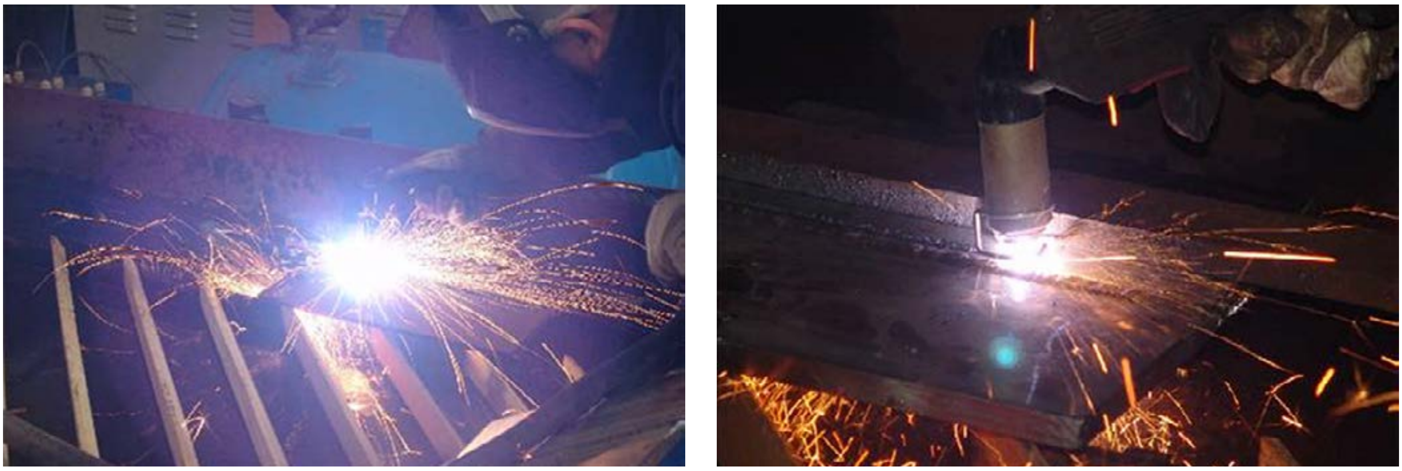

Fig.20. Manual plasma cutting process

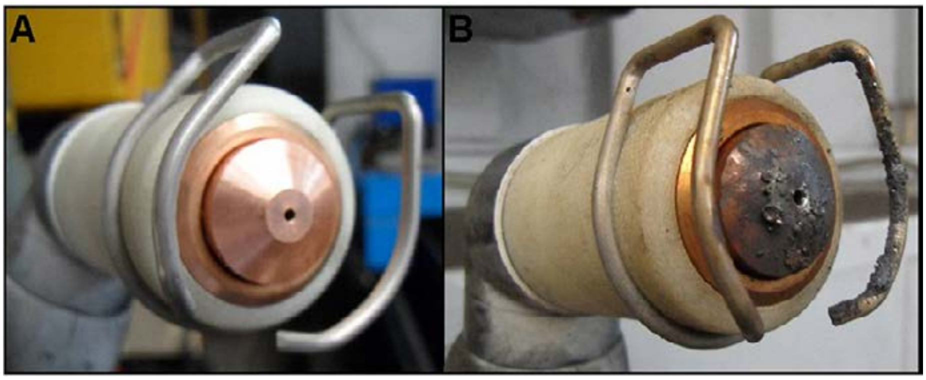

Fig. 21. Plasma nozzle, casing and guide without anti-spatter substance: A- before cutting, B- after cutting.

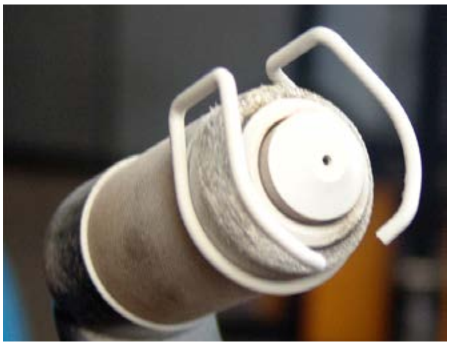

Fig. 22. Plasma nozzle, casing and guide with anti-spatter substance applied; view before plasma cutting

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Next, a new nozzle and casing were provided with the anti-spatter substance as in the previous processes (Fig. 22).

Following plasma cutting, the torch elements were subjected to visual tests revealing the formation of easy-to-remove spatters adhering to the end of the nozzle (Fig. 23).

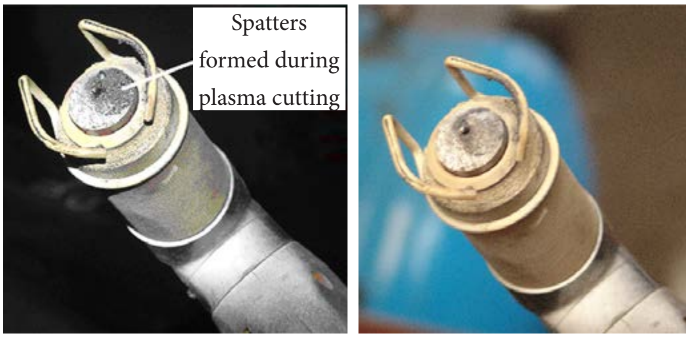

Fig. 23. Plasma nozzle and casing with anti-spatter substance applied; view after plasma cutting: A- nozzle with spatters, B- nozzle after removal of spatters

Summary

Butt joints and T-joints made in 10 mm thick S355J2 steel, protected by the anti-spatter substance applied on manually MAG welded workpieces meet welding technology qualification-related criteria specified in PN-EN ISO 15614-1. The anti-spatter substance can be successfully used for protecting workpieces and welding torch elements against the adhesion of spatters during welding. However, sufficient attention should be paid not to apply the excessive amount of this substance, particularly in the case of T-joints with a fillet weld, as this may impede obtaining proper fusion.

In the case of the anti-spatter substance applied on the welding torch elements it was observed that the substance significantly improved the quality of the aforementioned welding processes. These processes are often accompanied by the formation of spatters adhering to the nozzle and contact tube, destabilising welding works and resulting in the generation of welding imperfections. This necessitates carrying out additional procedures such as cleaning or exchanging nozzles or contact tubes, which increases the time consumption and the cost of works. One-time application of the anti-spatter substance on the welding torch elements provides excellent protection against the adhesion of impurities. The anti-spatter substance is easy to use; the protective coating is resistant to high temperatures and remains for a long time on surfaces where it has been applied.

Concluding remarks

1. The anti-spatter substance applied on workpieces before welding prevents the formation of porosity or gas pores in welds.

2. The butt and T-shaped joints made in 10 mm thick S355J2 steel protected with the anti-spatter substance and welded manually using the MAG method according to WPS meet the criteria related to the qualification of welding technologies referred to in PN-EN ISO 15614-1.

3. The limited but sufficient (spatter formation preventing) amount of anti-spatter substance applied in the weld groove or in the interface between workpieces does not affect the properties of welded joints.

4. If applied excessively in the interface between workpieces, the anti-spatter substance may impede obtaining proper fusion in the case of a T-joint using a fillet weld.

5. The application of the anti-spatter substance on the welding torch elements during such welding works as MAG welding or MAG overlay welding ensures the easy removal of spatters adhering to the nozzle and to the contact tube.

6. The use of the anti-spatter substance to protect the welding torch elements during MIG welding of aluminium alloys entirely protects the nozzle and the contact tube against the adhesion of spatters.

7. Always after applying the anti-spatter substance on the MIG/MAG welding torch elements the end of the electrode wire coated with the anti-spatter substance should be cut off in order to prevent the formation of welding imperfections.

8. The use of the anti-spatter substance on the plasma cutting torch elements provides

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successful protection against the permanent adhesion of spatters.

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Janusz Czuchryj, Paweł Irek

Dye-penetrant method assessment of the size of pores in welded joints made of aluminium and its alloys

Abstract: The work included the penetrant inspection carried out on AlMg5 aluminium alloy provided with artificial discontinuities, i.e. pores (drilled openings). The tests involved the measurements of indication sizes depending on the time of development and various diameters and depths of openings. The dependences determined enable estimating the depth of pores in welded products made of aluminium and its alloys. The information obtained should enable the decision-making concerning the acceptance of a product for operation or the necessity of repairing it. The tests also included the determination of optimum indication development time for aluminium and its alloys.

Keywords: NDT, penetration tests, aluminium, discontinuities, pores

Introduction

In most cases, welded joints are characterised by deviations, i.e. welding imperfections, from the ideal condition. As such imperfections reduce operational properties of joints, their type, number, and size should be the lowest as possible and ensure safe and failure-free operation of a welded product during its entire active life. In order to achieve this goal many various non-destructive tests are used. Among these is the liquid-penetrant inspection method, rated as one of the oldest, and most commonly applied in industry.

Liquid-penetrant inspection makes it possible to discover solely surface discontinuities including, among others, porosity. The depth of pores can be significant and which, as regards the leaktightness and active life of a joint, is highly undesirable. The possibility of estimating the size of pores is of great practical importance as it may facilitate decision-making concerning the acceptance of a tested product for operation or the necessity of repairing it.

The liquid-penetrant method enables the visualisation of discontinuities in the form of a red (most common) or shining indication (Fig. 1) [1].

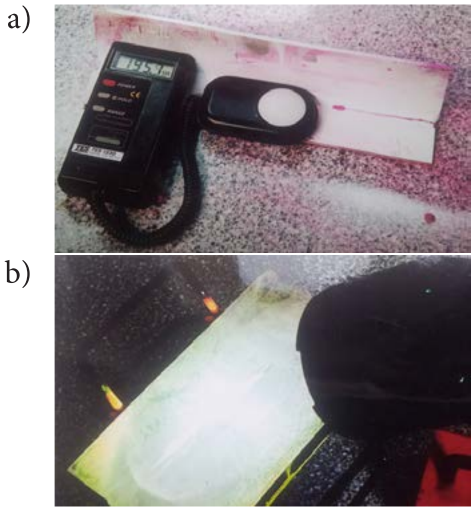

Fig. 1. Indications obtained during liquid-penetrant inspection using: a) dye-penetrant method (observation of surface tested in natural light); b) fluorescent method (observation of surface tested at UV-A radiation).

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The depth of pores can be estimated only on the basis of this indication. Research has been undertaken to define the dependence between the size of an indication and the time of its development and the size of pores [2].

Such information can be useful in the technical diagnostics of a product tested by means of the dye-penetrant method.

The tests described below are the continuation of the research work presented in the publication [3]. The tests involved the use of EN AW-5019 (AlMg5) aluminium alloy, i.e. one of the most popular corrosion resistant parent metals used in welded structures.

Test pieces

In order to determine dependences which enable the assessment of the depth of pores detected by means of dye-penetrant inspection it was necessary to use the simulation of such discontinuities in the form of non-passthrough openings made in aluminium alloy plates. In order to optimise the liquid-penetrant inspection as well as for the sake of the accuracy of indications, only 3 openings were made in each plate. The shape and dimensions of the test plates are presented in Figure 2, whereas the nominal dimensions of the openings are presented in Table 1.

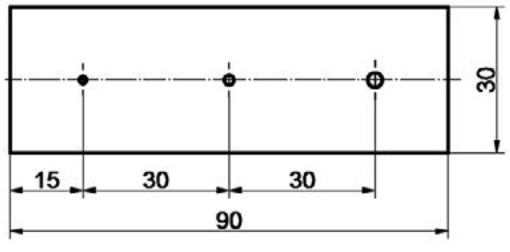

Fig. 2. Shape and dimensions of AlMg5 aluminium alloy plates with openings tested using the dye-penetrant method. Thickness of material: 4 mm

Table 1. Designation and nominal dimensions of openings in aluminium alloy plates tested using the liquid-penetrant method.

No.	Plate designation	Opening designation	Nominal dimensions of openings	
			diameter [mm]	depth [mm][1)]
1	I	1	0.50	0.50
2		2	0.75	
3		3	1.00	
4	II	1	1.25	
5		2	1.50	
6		3	1.75	
7	III	1	0.50	0.75
8		2	0.75	
9		3	1.00	
10	IV	1	1.25	
11		2	1.50	
12		3	1.75	
13	V	1	0.50	1.00
14		2	0.75	
15		3	1.00	
16	VI	1	1.25	
17		2	1.50	
18		3	1.75	
19	VII	1	0.50	1.25
20		2	0.75	
21		3	1.00	
22	VIII	1	1.25	
23		2	1.50	
24		3	1.75	
25	IX	1	0.50	1.50
26		2	0.75	
27		3	1.00	
28	X	1	1.25	
29		2	1.50	
30		3	1.75	
31	XI	1	0.50	1.75
32		2	0.75	
33		3	1.00	
34	XII	1	1.25	
35		2	1.50	
36		3	1.75	

[1)] With reference to discontinuities (welding imperfections) the term ‘height’ should be applied; however, for communication purposes this article uses the term ‘depth’.

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After machining, the plates were thoroughly cleaned, and the remains left by the machining process were removed, and the surface to be tested was degreased in an ultrasonic washer using extraction naphtha and solvent-based remover. Once cleaned, the plates were dried using an air jet under pressure at a temperature of approximately 20°C.

Testing aerosols, equipment and conditions

The liquid-penetrant inspection of the plates with simulated pores involved the use of the set of testing aerosols designated, following the requirements of standard PN-EN ISO 3452-1, as IICe-2, type "Diffu - Therm", manufactured by H. Klumpf Techn. Chemie KG D-45699 Herten (Fig. 3).

Fig. 3. Set of aerosols "Diffu - Therm" used in the liquid-penetrant inspection of plates with simulated pores

The aerosols used in the tests were as follows:

- penetrant – red colour, type BDR-L, lot no.: 20 15, filling date: 09/2012,
- remover – type BRE, lot no.: 22 16, filling date: 02/2013,
- developer – type BEA, lot no.: 23 16, filling date: 06/2013,
- guarantee period – 2 years,
- no chlorine or sulphur compounds in the chemical composition.

The tests involved the use of the following measuring equipment and materials:

- luxmeter – type LX 105 manufactured by the company "LX Lutron";
- thermometer/hygrometer, model 303,
- caliper with measurement accuracy of 0.02 mm;
- workshop magnifying glass (4x);
- non-shredding fabric.

The liquid-penetrant inspections of the plates were conducted in the following conditions:

- temperature of tested surface – 22°C,
- ambient humidity – 23%,
- penetration time – 15 minutes,
- development time – 30 minutes,
- illuminance of tested surface – 584 lx,
- observation distance –10-30 cm,
- observation angle – from 60 to 90°.

Conducted inspections and obtained results

The liquid-penetrant inspections of the samples with simulated pores were carried out using the dye-penetrant method following the requirements of standard PN-EN ISO 3452-1. The measurements of indications were conducted after 2, 5, 10, 15, 20, 25 and 30 minutes. The measurements carried out at the initial stage of the appearance of indications aimed at more accurate determination of the dependence being the subject of this work and the assessment of the dynamics of the formation of the indications. The maximum adopted indication development time met the requirements of standard PN-EN ISO 3452-1, according to which it should be contained within a 10-30 minute range. The samples with developed indications are presented in Figure 4. The test results, in the form of the measurements of the greatest indication values, are presented in Table 2.

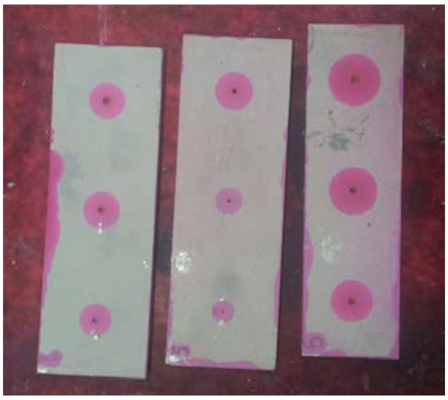

Fig. 4. Samples with developed indications of simulated pores.

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Table2. Results of liquid-penetrant inspections (measurement of indication sizes) for openings with various diameters and various depths in relation to their development time.

No.	Nominal opening diameter [mm]	0.50	0.75	1.00	1.25	1.50	1.75
	Development time [min]	**SIZE OF INDICATION [mm]**					
	h = 0.50 mm$^{1)}$						
1	2	3.42	4.18	4.90	5.22	5.84	5.98
2	5	3.48	4.38	5.14	6.28	6.42	6.96
3	10	3.56	4.4	5.32	6.66	6.72	7.36
4	15	3.56	4.46	5.32	6.66	6.74	7.4
5	20	3.56	4.46	5.32	6.66	6.74	7.4
6	25	3.56	4.46	5.32	6.66	6.74	7.4
7	30	3.56	4.46	5.32	6.66	6.74	7.4
	h = 0.75 mm$^{1)}$						
8	2	3.62	3.92	5.54	4.42	5.15	5.68
9	5	4.26	4.98	6.62	6.38	6.72	7.18
10	10	5.26	5.54	7.72	8.02	8.74	9.08
11	15	5.34	5.56	8.55	8.16	9.58	9.64
12	20	5.34	5.56	8.55	8.34	10.08	10.02
13	25	5.34	5.56	8.55	8.36	10.08	10.02
14	30	5.34	5.56	8.55	8.36	10.08	10.02
	h = 1.00 mm$^{1)}$						
15	2	3.6	4.92	5.56	4.26	5.42	6.08
16	5	4.48	6.04	6.85	6.16	6.94	7.8
17	10	5.64	6.92	8.44	8.22	9.06	10.1
18	15	5.86	7.18	9.72	9.68	10.82	11.74
19	20	5.92	7.22	10.22	10.56	12.04	13.14
20	25	5.92	7.22	10.22	10.9	12.82	13.66
21	30	5.92	7.22	10.22	10.9	13.02	14.08
	h = 1.25 mm$^{1)}$						
22	2	3.56	3.98	5.52	6.54	6.2	6.96
23	5	5.22	5.36	7.32	8.54	8.7	9.28
24	10	5.28	5.88	7.84	9.88	10.14	10.66
25	15	5.3	6.02	8.14	11.18	11.58	11.96
26	20	5.58	6.2	8.22	12.02	12.62	13.18
27	25	5.58	6.2	8.22	12.58	13.84	14.2
28	30	5.58	6.2	8.22	13.52	14.24	15.28
	h = 1.50 mm$^{1)}$						
29	2	2.12	4.02	4.22	5.92	7.06	7.44
30	5	2.2	5.94	6.3	8.32	9.38	9.54
31	10	2.2	7.18	7.68	9.56	10.68	10.82
32	15	2.2	8.18	8.52	11	11.98	12.14
33	20	2.2	9.2	9.24	12.2	12.92	13.34
34	25	2.2	9.68	9.7	12.72	13.94	14.12
35	30	2.2	9.68	9.7	13.06	14.38	14.94

$^{1)}$ h – nominal opening depth.

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Table 2 - continuation

No.	Nominal opening diameter [mm]	0.50	0.75	1.00	1.25	1.50	1.75
	Development time [min]	SIZE OF INDICATION [mm]					
	h = 1.75 mm[1]						
36	2	3.38	3.92	4.12	6.32	7.8	8.26
37	5	4.12	5.1	5.32	7.68	9.24	9.78
38	10	4.46	5.72	6.2	8.38	10.92	11.12
39	15	4.46	6.2	7.16	9.56	11.76	12.4
40	20	4.46	6.2	7.62	10.04	12.2	13.74
41	25	4.46	6.2	7.84	10.72	12.48	14.5
42	30	4.46	6.2	7.84	10.8	12.48	15.22

[1] h – nominal opening depth.

Analysis of inspection results

The values of penetrant indications from simulated pores (Table 2) are presented in the graphic form in Figures 5 – 10.

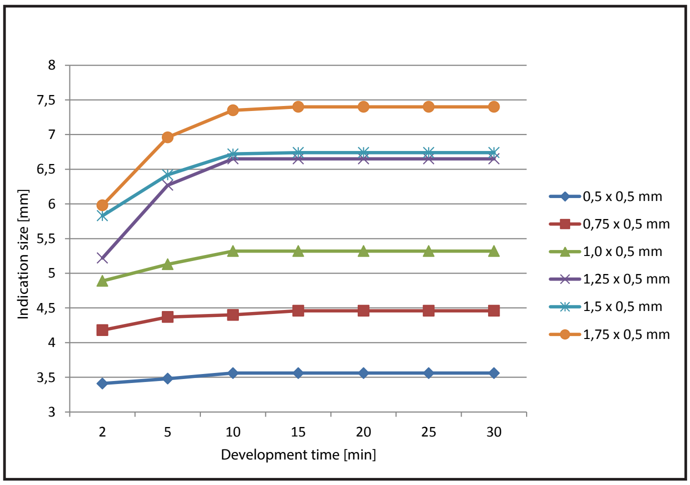

Fig. 5. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 0.50 mm and various diameters.

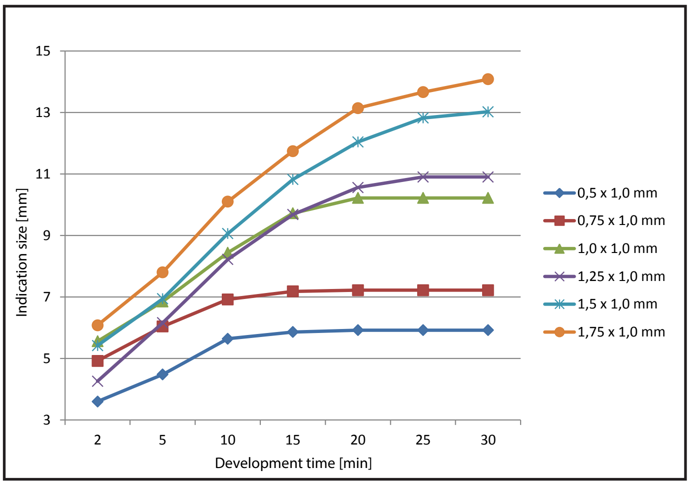

Fig. 7. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.00 mm and various diameters

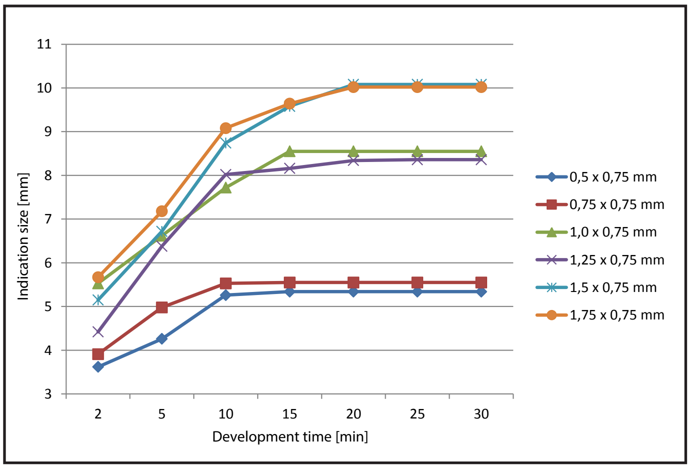

Fig. 6. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 0.75 mm and various diameters.

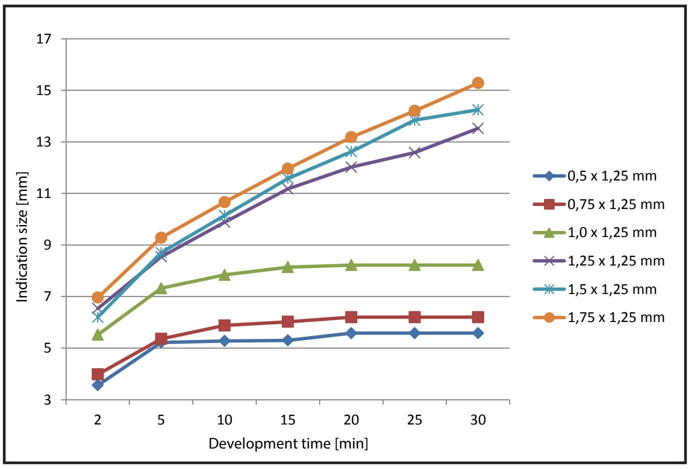

Fig. 8. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.25 mm and various diameters.

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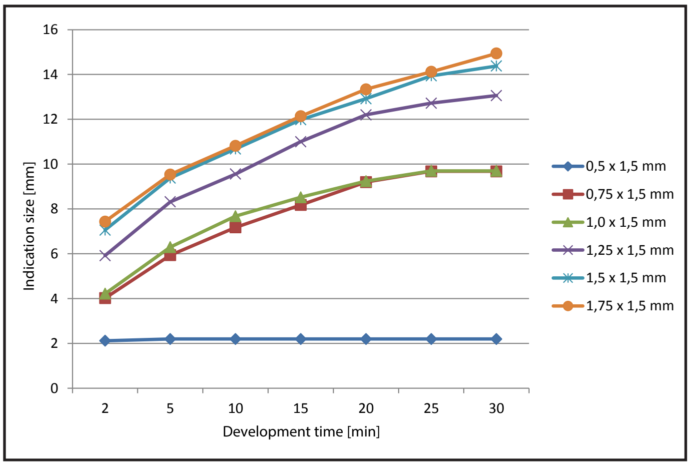

Fig. 9. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.50 mm and various diameters.

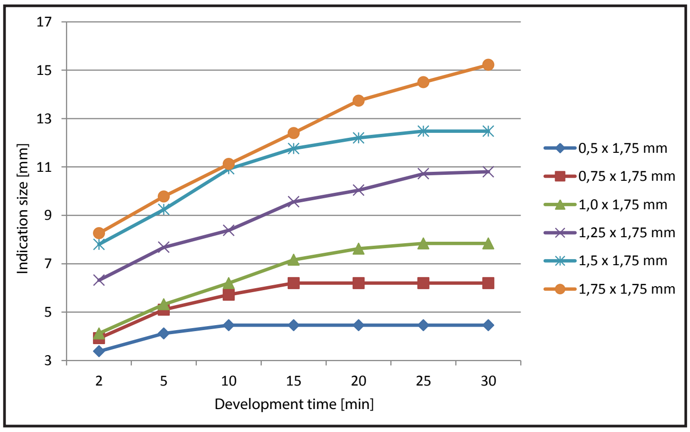

Fig. 10. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.75 mm and various diameters

As can be seen in Figures 5-10, the coordinates of individual measurement points are determined by the measured size of indication and its time of development. Points of various coordinates but related to the same size of a surface pore (pore of the same diameter and depth – imperfection terminology according to PN-EN ISO 6520-1) are connected with sections designating thus a broken line, illustrating the course of the dependence being the subject of this work.

The analysis of the courses of broken lines reveals that an increase in the diameter is, in each case, accompanied by an increase in the maximum size of the indication obtained from this imperfection. Such a result is consistent with expectations. Nevertheless, it is worth mentioning that the courses of individual lines are characterised by certain tendencies. At the initial phase of the generation of indications (a development time from 0 to 5 minutes) the broken lines are characterised by a significant inclination in relation to the axis of the development time. This fact reflects the high dynamics of the increase in indications and concerns almost all the cases. An exception can be observed in the case of the lines representing the pores of the smallest depth (h=0.5 mm) and smallest diameters (ø=0.5 mm, ø=0.75 mm and ø=1.0 mm)(Fig. 5), where the dynamics of indication increase is low. The low dynamics of indication increase is also revealed by the line representing the pores having a small diameter (ø=0,5 mm) and relatively significant depth (h=1.5 mm)(Fig. 9). In the development time range between 5 minutes and 10 minutes the dynamics of indication increase usually decreases. However, in most cases the lines analysed are characterised by the significant stabilisation of indications after the development time of approximately 15-20 minutes. Only the indications of the greatest simulated pores (ø=1.25-1.75 mm and h=1.0-1.75 mm)(Fig. 7-10) tend to be stable after the passage of the normative development time, i.e. after approximately 30 minutes, or even show an increasing tendency. However, such big pores are rarely encountered in welding practice and the information about their course does not play any decisive role in terms of joint diagnostics. Such pores are usually repaired without analysing their possible admission to operation. The above deliberations justify the conclusion that for aluminium and its alloys the indication development time (of pores and, presumably, other surface imperfections) during dye-penetrant inspection can be reduced to approximately 15-20 minutes. In the case of a great number of tests this can bring significant economic effects due to work time savings.

In Figures 6-8 it is also possible to observe the interlacing of some broken lines. For instance, in the area of development time from 2 minutes

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to 15 minutes it is possible to observe the intersection of the lines determining the pores of dimensions: ø1.0×0.75 mm and ø1.25×0.75 mm, ø1.0×0.75 mm and ø1.5×0.75 mm (Fig. 6), ø0.75×1.0 mm and ø1.25×1.0 mm, ø1.0×1.0 mm and ø1.25×1.0 mm (Fig. 7) and ø1.25×1.25 mm and ø1.5×1.25 mm (Fig. 8).

In the first case (Fig. 6), the line representing the pores of the smaller diameter (ø1.0) also shows the maximum indications greater than the line representing the pores of the greater diameter (ø1.25). This observation is inconsistent with expectations. However, it is necessary to take into consideration the fact that the penetrant inspection process is composed of a number of phases to be carried out. Due to the test sensitivity, each of the phases must be conducted with great attention to detail as each, usually unintended, negligence in the course of the process decreases the test sensitivity affecting the final result. In view of the foregoing, it is easy to account for the inaccuracy of the course of some broken lines revealed in the figures.

On the basis of the determined dependence between the size of an indication and its development time, in the function of the size of an imperfection, it has become possible to estimate the depth of pores. A general procedure in this scope includes the following:

- measurement of a pore diameter by means of a caliper or universal weld gauge of accuracy of at least 0.1 mm;
- performance of liquid-penetrant inspection following the requirements of standard PN-EN ISO3452-1;
- providing tested surface observation conditions following the requirements of standard PN-EN ISO 3059;
- measurement of the maximum size of an obtained indication after the passage of the adopted development time;
- determination of a point of the following coordinates: the size of an indication – development time, in such a manner that the point lies on the broken line corresponding to the measured diameter of a pore or as close to this line as possible;
- reading out the estimated depth of a pore, designating the previously determined broken line.

An example of how to determine the estimated depth of pores is presented in Figure 11.

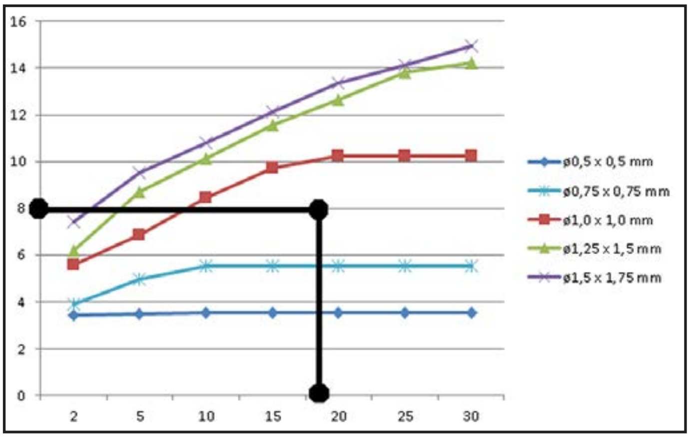

Fig. 11. Example of determination of estimated depth of pores in welded joints made of aluminium and its alloys. Measured values: the size of an indication – 8 mm, development time: 17 minutes, pore diameter – 0.8 mm. As can be seen, the point of the intersection of the coordinates 8 mm and 17 minutes lies slightly below the broken line representing the pore of the dimensions ø1.0 x 1.0 mm. It is therefore possible to conclude that the depth of the pore of the diameter of 0.8 mm amounts to approximately 1.0 mm.

Summary and conclusions

The conducted liquid-penetrant inspections of the samples with openings simulating surface pores revealed that the undertaken target of the research had been reached. The determined dependences make it possible to estimate the depth of pores in welded products made of aluminium and its alloys. Such information should facilitate the decision whether to accept a given product for operation or to repair it. It should also be mentioned that in most cases of determined broken lines they undergo stabilisation after the passage of development time amounting to approximately 15-20 minutes. This fact suggests that during penetrant inspections of joints made of aluminium and its alloys the aforesaid time can be regarded as sufficient for detecting unacceptable internal

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imperfections. The broken lines are only an approximation of real courses, yet they are sufficient for estimate calculations which can be used in welding practice. The research work described above is expected to be continued using other parent metals used in the production of welded structures.

On the basis of the conducted tests it was possible to formulate the following conclusions:

- conducted dye penetrant inspections made it possible to achieve the purpose of the research work consisting in obtaining a possibility of estimating depths of surface porosity present in welded products made of aluminium and its alloys;
- analysis of dye penetrant inspection results indicates that the maximum development time of indications on surfaces of aluminium and its alloys can be limited to approximately 15 – 20 minutes;
- research work should be continued with other parent metals used in the production of welded structures.

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2. Czuchryj J., Sikora S.: Podstawy badań penetracyjnych wyrobów przemysłowych. Wydawnictwo Instytutu Spawalnictwa. Gliwice, 2007.
3. Czuchryj J., Hyc K.: Ocena wielkości nieciągłości powierzchniowych w wyrobach z węglowej stali konstrukcyjnej na podstawie badań penetracyjnych metodą barwną. Biuletyn Instytutu Spawalnictwa, 2012, no. 4.

Reference standards:

- PN-EN ISO 3452-1: Non-destructive testing — Penetrant testing — Part 1: General principles
- PN-EN ISO 3452-2: Non-destructive testing — Penetrant testing — Part 2: Testing of penetrant materials
- PN-EN ISO 3452-3: Non-destructive testing — Penetrant testing — Part 3: Reference test blocks
- PN-EN ISO 3452-4: Non-destructive testing — Penetrant testing — Part 4: Equipment
- PN-ISO 3058: Non-destructive testing — Aids to visual inspection — Selection of low-power magnifiers
- PN-EN ISO 3059: Non-destructive testing — Penetrant testing and magnetic particle testing – Viewing conditions
- PN-EN ISO 12706: Non-destructive testing. Penetrant testing. Vocabulary
- PN-EN ISO 6520-1: Welding and allied processes — Classification of geometric imperfections in metallic materials — Part 1: Fusion welding

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Electron beam welding – equipment and accessories

Abstract: Electron beam welding has been known and used for a long time, yet the recent years have seen increasing advancements in equipment fully utilising this welding method potential. Electron beam welding machines can be both universal and highly specialised, which can translate to significant operating and, first of all, welding costs reduction. Modern electron beam welding devices are provided with control systems and safety features which maximise operator's anti-radiation protection and enable carrying out technological processes in vacuum conditions.

Keywords: electron beam welding, welding machines, equipment, accessories, process control system

Introduction

Electron beam welding is usually carried out in a vacuum, yet there are also non-vacuum welding machines available. The principle of the electron beam welding process itself was presented in the authors' previous work [1]. Modern electron beam welding devices are controlled by PLCs equipped with working tables or numerically controlled welding positioners enabling the automation of welding processes and provided with various control and safety systems aimed to maximise the operator's protection against radiation and carry out technological processes in the vacuum.

Electron beam welding machines – irrespective of their size, intended use and manufacturer – are composed of four basic structural units [2]:
- electron beam generator,
- working unit (working, usually vacuum, chamber and system of manipulators),
- vacuum generation and control system,
- control system.

Such units can be produced in numerous variants, differ in many technical solutions and be highly customised, with customers' needs usually grouped as follows:
- short-lot production with frequently changing schedules of welding works,
- medium and big-lot production using highly automated welding processes,
- welding large-sized objects.

Depending on their intended use, electron beam generators can work at low (approximately 60 kV) or high voltage (above 60 kV). Low-voltage generators are usually cheaper, whereas high-voltage generators provide a very convenient weld shape coefficient (width-to-depth ratio 1:20) and, at the same time, enable carrying out welding even if the distance between the workpiece and the welding machine electron gun is considerable [2].

The design solution of a working unit depends on the indented use of a given device. The basic type of such a unit is a universal working chamber along with equipment which

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enables welding large-sized workpieces as well as small lots of very diversified and small-sized elements. This solution is usually applied in laboratory devices or in machines used in diversified production.

Another type of an operating unit is the working chamber equipped with an appropriate manipulator, adjusted to the size and shape of workpieces. As a result, it is possible to reduce time necessary for generating the vacuum in the working chamber. Another advantage, in the case of a stroke working table, is the fact that activities connected with loading and unloading individual table pockets do not depend on the welding process and do not extend the total time of a single welding cycle.

Devices for welding large-sized elements can be equipped with working chambers of significant volume, e.g. 600 m3 or chambers with local vacuum. In relation to such elements the process of welding can also be carried out at atmospheric pressure [2].

The vacuum system should ensure possibly short time of vacuum generation in the welding machine working chamber (high pump-out rate) and appropriate working pressure in the welding area and electron gun.

The electron beam welding machine control system is in each case adjusted to a specific device. As a rule, the electron beam welding process control is carried out without the direct participation of the operator, who only sets up welding parameters and decides about welding process commencement [2].

Figure 1 presents an exemplary electron beam welding station with basic components. The working chamber is made of unalloyed steel. Depending on the value of maximum electron gun accelerating voltage additional lead sheet screens of the working chamber can be used. Working chamber internal walls are usually provided with additional screens (easy to disassemble and clean) made of thin austenitic steel sheets aimed to protect the chamber interior against settling vapours of metals generated during welding processes. The electron gun can be positioned horizontally or vertically or be fixed inside the chamber on a dedicated manipulator. The electron beam welding machine working chamber is usually stationary. However, in special cases it is possible to carry out welding processes using a mobile local vacuum chamber fixed on the surface of a big-sized workpiece not performing working motion.

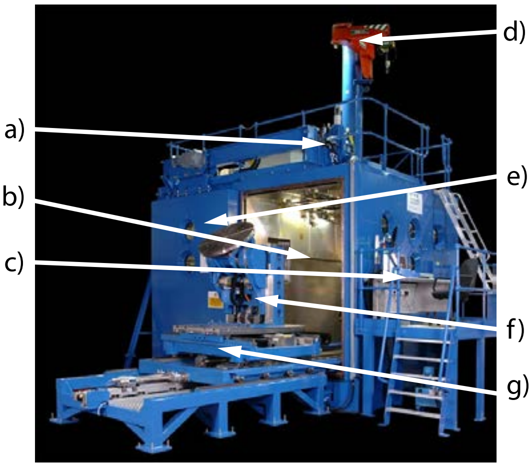

Fig. 1. Example of complete electron beam welding station, a) electron gun, b) vacuum working chamber, c) control system, d) manipulator, e) working chamber sliding door, f) welding positioner, g) CNC table

It should be emphasized that today's devices for welding and surface processing using an electron beam as a welding heat source are additionally equipped with many accessory systems aimed at facilitating operator's work conditions, improving welded joint quality and increasing welding device efficiency.

Division of electron beam welding machines

Depending on intended use the market offer of electron beam welding machines is vast. The selection of a given device is dictated by many factors such as the type of material to be welded, the size, shape and weight of workpieces, expected welding process efficiency and whether the process will be carried out autonomously or as part of a technological line. Taking into consideration all factors makes it possible to design and produce a device in a manner enabling

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the obtainment of the required quality of workpieces and reduction of operating costs. Electron beam welding machines can be universal or specialised, i.e. designed for welding specific types of elements.

Due to technological, production-related and metallurgical requirements electron beam welding solutions include the following machines [3]:

- universal high pressure welding machines, with a gun fixed inside or outside the working chamber. After appropriate tooling modification such devices enable welding a vast range of products and elements;
- special high pressure welding machines, intended for welding specific elements such as, for instance band saws, toothed wheels, turbo-compressor rotors;
- reduced pressure electron beam welding machines (RPEB) with local chambers fixed on a structure being welded. The electron gun is located outside a local chamber of small volume, covering only a section of a flat or girth joint being welded, e.g. of storage tanks. The vacuum is only maintained in the small chamber. Such a solution minimises the time needed to generate the vacuum;
- non-vacuum electron beam welding machines (NVEBW). The electron beam is generated in high vacuum and at high accelerating voltage of 150-220 kV. The beam is moved towards the workpiece by the system of vacuum passes, i.e. the system of nozzles gradually reducing vacuum to atmospheric pressure. Welding at atmospheric pressure almost entirely eliminates problems related to the size of a structure being welded. The NVEBW machines are provided with high-efficient pumps and special electron beam discharge orifices to ensure the highest vacuum decrease gradient between the electron gun and atmosphere.

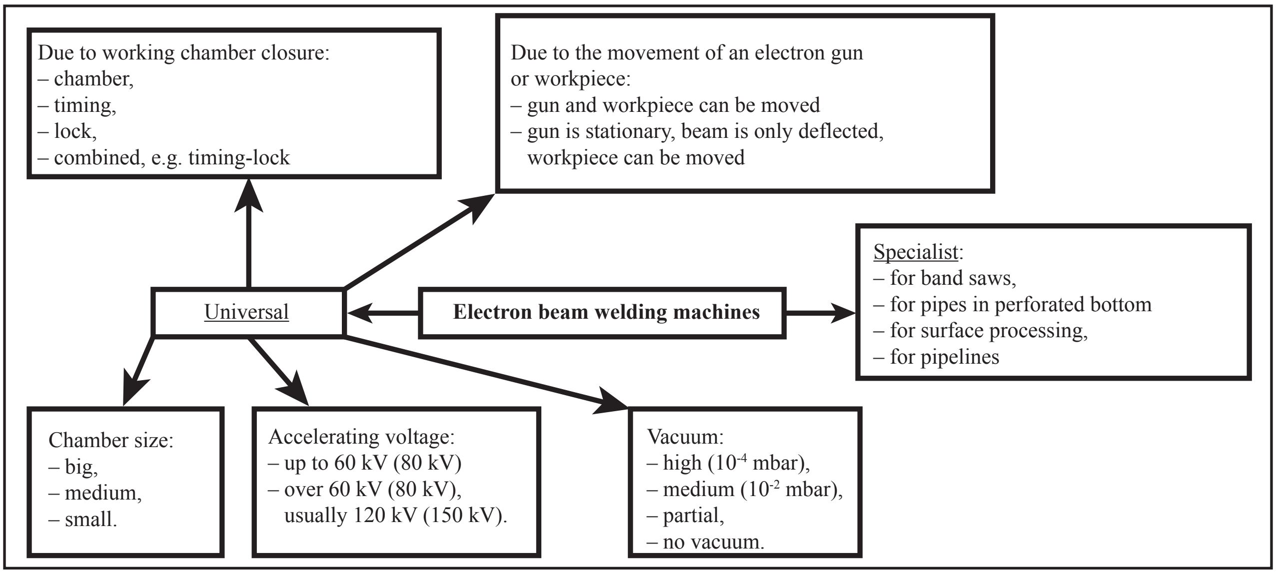

Fig. 2. Division of electron beam welding machines

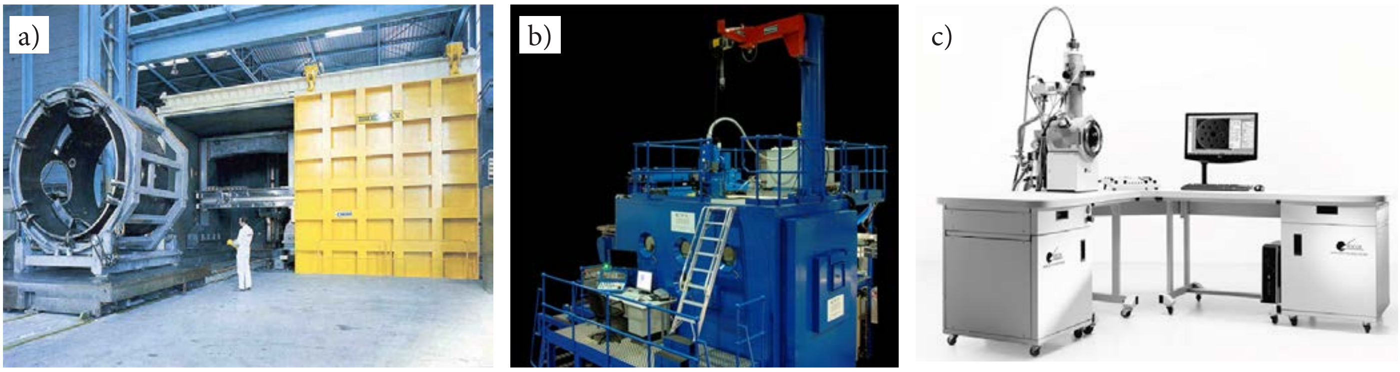

Fig. 3. Examples of working chambers a) big, b) medium and c) small [4, 5]

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Figure 2 presents the division of electron beam welding machines. Examples of electron beam welding machines based on various working chambers are presented in Figure 3. Figure 4 presents the schemes of equipment design in relation to welding process pressure. In turn, Figure 5 presents the types of devices due to working chamber design. In most solutions the electron gun is motionless in relation to the workpiece. However, in special cases it is possible to use a device with a moving gun fixed on a manipulator (Fig. 6). As was described above, it is also possible to use welding machines with a local vacuum working chamber (Fig. 7) or non-vacuum machines (Fig. 8). The market offer also includes special design or customised welding devices such as, for instance, a subsea pipeline welding machine developed within an international research programme (Fig. 9).

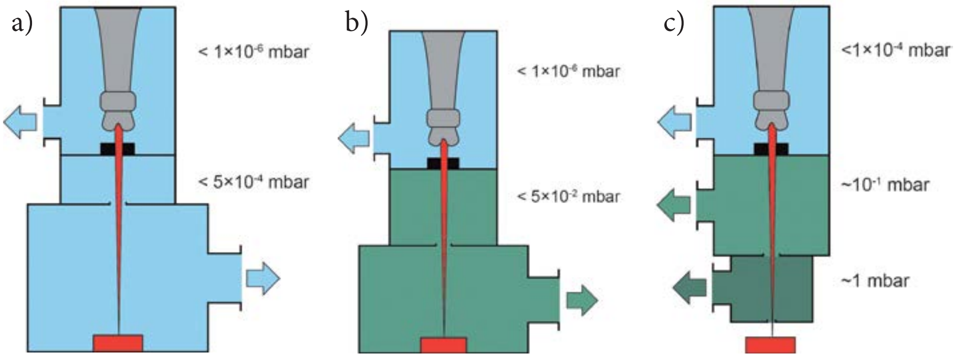

Fig. 4. Schemes of electron beam welding machines due to working chamber vacuum a) high vacuum, b) medium vacuum c) welding under atmospheric pressure [6]

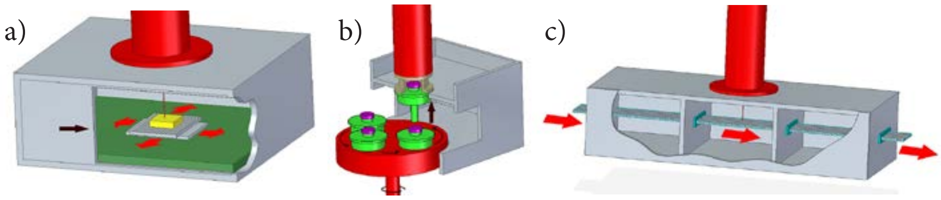

Fig. 5. Types of electron beam welding machines due to working chamber design a) universal welding machine with a big volume chamber, b) stroke welding machine, c) continuous operation welding machine (lock) [6]

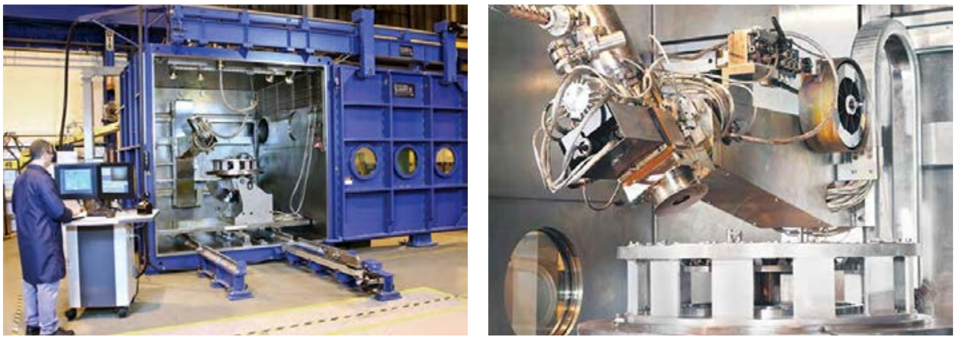

Fig. 6. Example of a Sciaky-manufactured electron beam welding machine with a moving electron gun [7]

Fig. 7. Example of an electron beam welding machine with a local chamber [8]

Fig. 8. Non-vacuum electron beam welding machine, P=24.5 kW, U=175kV [9]

Fig. 9. Example of a specialist electron beam welding machine for welding subsea pipelines [10]

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Additional equipment of electron beam welding devices

As regards increasing the welding process efficiency, ensuring the best quality of welded joints and facilitating operators' work, electron beam welding equipment manufacturers offer many additional systems, including the following [11]:

- automatic beam correction system,
- CCD camera-based welding area monitoring system,
- welding area monitoring system using back-scattered electrons,
- automatic joint axis tracking system,
- automatic process control system,
- automatic joint quality control system.

Automatic beam correction system

One of the most important preventive measures enabling the obtainment of the highest quality welded joints is the proper electron beam correction. Growing demands for joint quality are accompanied by similar requirements as regards the quality of electron beam. The primary issue is focusing a beam on the surface of a welded workpiece using the smallest possible diameter and the highest available power density. In order to minimise the movement of a beam having the highest power density along with the change of focus, the electron beam must be centred in the optical axis of lenses. Electron guns, particularly those of high power, are additionally provided with a system enabling the elimination of possible electron beam astigmatism and obtain an axially symmetrical beam. After conducting all correction stages, the electron beam power density distribution should correspond to the Gaussian curve, which guarantees the obtainment of best quality joints. Ensuring the proper beam shape is particularly important in industrial-scale electron beam applications. If an electron beam welding device is just one element of a technological line, the process-operating personnel usually do not have sufficient knowledge and have not had adequate practice in terms of proper electron beam calibration. The result obtained in such a case may significantly differ from the optimum solution, which, as a result, fails to guarantee the repeatability of welding process. In addition, in practice, often even experienced equipment operators are unable to properly conduct electron beam correction. The comparison of results achieved by inexperienced and experienced operators and those obtained using the automatic system is presented in Figure 10.

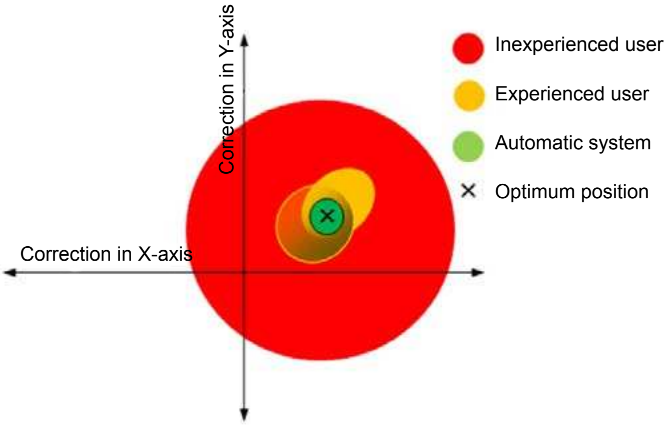

Fig. 10. Centring and removing astigmatism has two basic parameters, i.e. calibration in X and Y axes. An error in both axes generates the area of an improperly positioned beam [11]

Welding area monitoring

The monitoring of a welding area in the vacuum working chamber can be conducted using either of the two techniques:

- optical method,
- electron-optical method (EO).

The first method utilises a CCD camera for observation. The disadvantage of the method is its sensitivity to the reflection of light against "mirror" surfaces. The second method utilises back-scattered electrons, similarly as in a scanning microscope (SEM). An electron beam scans the surface of a welded or processed workpiece and back-scattered electrons generated from each point of the electrode are recorded by sensors. The contrast of images obtained is 1:15000. The EO-based system advantage relies on its insensitivity to light reflections, high detail detectability (Fig. 11) and the possibility of

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differentiating between various materials. Figure 12 presents the comparison of two images of the same element recorded with both methods.

Fig. 11. Example of an image recorded using back-scattered electrons [4]

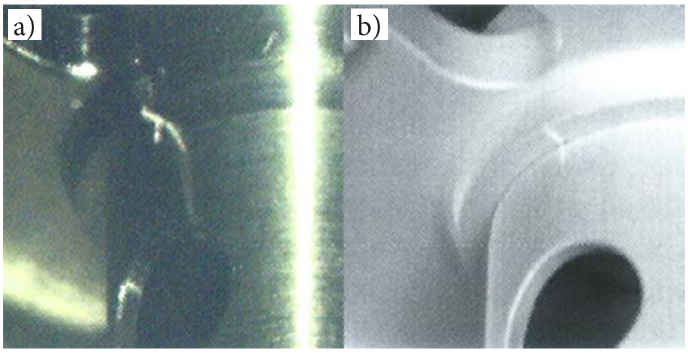

Fig. 12. Comparison of the same surface image recorded using a CCD camera (a) using back-scattered electrons (b) [11]

Automatic joint axis tracking system

In industrial practice electron beam welding is usually used for making girth welds. A particular feature of the joint axis tracking system is, in this particular case, the possibility of observing a weld on a plane, which facilitates process monitoring and detection of potential imperfections. An example of using the system for welding pressure sensors is presented in Figure 13.

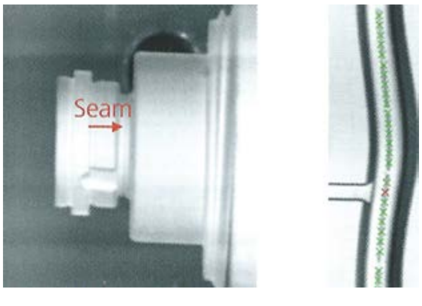

Fig. 13. Example of a joint axis tracking system using back-scattered electrons during welding a pressure sensor [11]

Joint axis tracking systems utilising the electron-optical method are also used for geometrical measurements, which enables setting corrections during welding. The system can monitor a joint several metres in length with the accuracy of 0.1 mm. Such monitoring is used, e.g. during the production of radiator elements [11].

Welding process control system

Similarly as in the case of welding area monitoring system also the welding process control can be carried out using two methods, i.e. optical and electron-optical. Such a system is used for detecting spatters during welding as well as for monitoring a weld key-hole and metal melting process. The EO-based systems are not sensitive to reflections from the workpiece surface and also make it possible to detect some welding imperfections as they emerge [11].

Joint quality control system

Joint quality control methods are many and varied. One of them is monitoring beam parameters. Another solution is based on back-scattered electrons enabling the workpiece surface quality control and detection of excess penetration, lack of penetration, undercut or spatter. Additionally, after welding it is possible to use X-radiation for detecting internal joint imperfections, e.g. gas pores [11].

Working chamber equipment

In order to fully utilise the potential of electron beam welding or surface processing it is necessary to use additional tooling, particularly if a welding machine is equipped with a stationary electron gun (electron beam movement is then possible only by means of coils deflecting in a very limited range). The basic tooling includes:

- X-Y CNC table (Fig. 1),
- disc or roller welding positioner (Fig. 1, 14),
- manipulator,
- electrode wire feeding system (Fig. 15),
- positioners and clamps,
- beam control systems.

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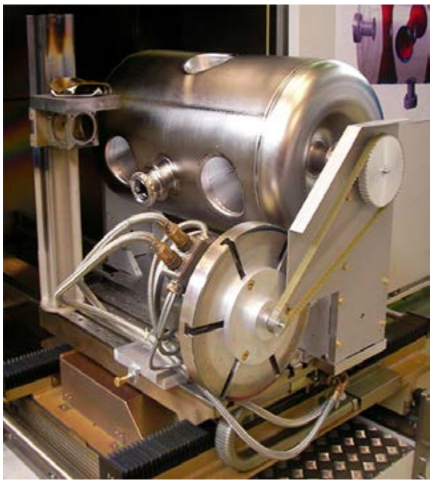

Fig. 14. Example of using a welding positioner during electron beam welding of a girth weld in a container made of 4 mm thick RR300 niobium alloy [12]

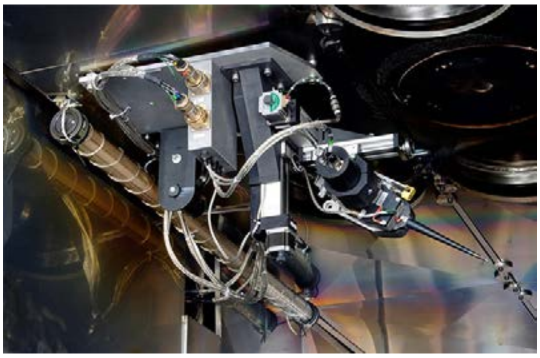

Fig. 15. Electron beam welding electrode wire feeding system [4]

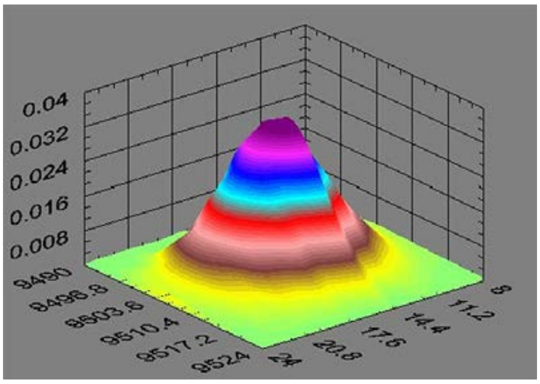

Fig. 16. Electron beam power density distribution

Fig. 17. Electron beam quality control device diaBEAM by Aixact [14]

Beam control systems

In the case of an electron beam it is essential to maintain the proper symmetry of power density distribution. Even slight differences can generate imperfections in welded joints. Figure 16 presents electron beam power density distribution composed of a high-density core and a rim characterised by lower power density. Beams of the same diameter can thus provide entirely different welded joint quality. An excessively wide rim of excessively high power density can generate an excessively wide heat affected zone or an improper weld shape [13].

Although, as standard, electron beam welding devices are equipped with beam quality control systems, in many cases it appears necessary to verify whether a given beam is characterised by proper parameters [14, 15]. Such a necessity usually follows the replacement of a cathode or the failure of a device. Also, the electron beam profile can change due to the following reasons [13]:

- changes in workpiece position in relation to the beam,
- power supply system instability,
- tooling damage.

Beam parameters which can be defined using external control systems include, among others, the following:

Fig. 18. Electron beam quality control device Probe Beam by CVE [13]

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- beam diameters,
- FWHM (Full Width at Half Maximum), beam width at 50% power,
- FWe2, (Full Width at $1/e^2$) beam width at 13.5% power,
- beam density distribution,
- beam symmetricalness.

The systems are composed of a sensor and a system for collecting and archiving data. Specialist software enables the presentation and analysis of collected data. An example of a beam control device is a diaBEAM system (Fig. 17) developed by Aixact or Probe BEAM (Fig. 18) manufactured by CVE.

Manufacturers also offer devices which monitor welding processes in real time or facilitate controlling the quality of electron beam itself. Such equipment is usually operated via a "user-friendly" control panel enabling setting required welding process technological parameters and informing about the present status of individual components indicating exceedings of permissible limits. In addition, modern devices enable the on-line diagnostics of device operation, which significantly facilitates communication with the manufacturer's service department and quickens the removing of failures.

Summary

The versatility of the market offer makes electron beam welding, despite available laser beam welding solutions, increasingly popular for joining thick elements or materials impossible to weld using other welding technologies. Manufacturers in conjunction with research establishments such as Instytut Spawalnictwa can offer a welding device along with related technology. An important factor is the possibility of customising devices, optimising the shape and size of working chambers, selection of pumps and, most importantly, making precise electron guns. Electron beam welding machine designs enable carrying out processes using a local chamber or at atmospheric pressure. Such devices can be provided with various welding positioners, CNC tables and electrode wire or flux feeding systems. During electron beam welding the electron gun can be operated vertically or horizontally. It is also possible to make joints in restricted positions. Presently used electron beam welding machine designs maximise personnel protection against X-radiation. Even devices with accelerating voltage of 150 kV pose no threat to operators. In addition, electron beam welding machines are equipped with a number of systems facilitating work and significantly improving the quality of joints, e.g. welding area visualisation using back-scattered electrons.

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Rafał Kaczmarek, Ryszard Krawczyk

Analysis of dimensions of test joints in the process of technology qualification according to PN-EN ISO 15614-1 in the aspect of ultrasonic testing according to PN-EN ISO 17640

Abstract: Quality assurance systems in welding engineering demand that the manufacturers of welded structures and welding equipment should apply qualified welding technologies. The most commonly used mode of welding technology qualification is testing a given welding technology by making test joints and carrying out their examination. This article presents the analysis of test joint dimensions recommended in PN-EN ISO 15614-1 in relation to the possibility of testing the quality of such joints using ultrasonic testing according to recommendations of currently valid related standards. The article contains a proposal how to determine the width of a test joint on the basis of the nomogram developed. The target readers of the article include welding engineers and technologists, other welding coordination personnel involved in the preparation of test joints as well as NDT personnel, due to the extensive analysis concerning the selection of testing methods and ultrasonic examination of test joints.

Keywords: test joints dimensions, ultrasonic testing, PN-EN ISO 15614-1, PN-EN ISO 17640

Introduction

The concept of quality assurance according to PN-EN ISO 3834 assumes that in production processes, non-destructive testing (NDT) plays an important role not only at the phase of finished product quality control but also at the stage of production preparation. NDT is used for controlling the quality of test joints in the most common welding technology qualification mode, i.e. one based on testing a given technology in accordance with PN-EN ISO 15614-1 [1]. The type and range of tests used is presented in Table 1 of the standard referred to above [4]. Both butt joints and T-joints as well as pipe branches with butt welds should undergo radiographic or ultrasonic testing in the test range covering 100% of the weld length. In order to select an NDT method, as well as due to the correlation between the required quality level B and acceptance levels for individual NDT methods standard PN-EN ISO 15614-1 refers to EN 12062 replaced in 2010 by PN-EN ISO 17635. Table 3 of this standard [7] contains recommendations concerning the selection of a volumetric testing method depending on the material thickness t; for joints having thicknesses t>40mm it is also recommended to carry out ultrasonic examination, whereas conducting

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radiographic examination is not recommended. At the same time, PN-EN ISO 15614-1 requires that in the case of the ultrasonic method, related tests should be carried out in accordance with PN-EN 1714 (the standard replaced by PN-EN ISO 17640). For this reason it is important that test joints, particularly those of great thicknesses, have a sufficient width enabling the performance of UT in accordance with PN-EN ISO 17640.

Test joint dimensions

In the case of butt joints of plates and pipes as well as for T-joints PN-EN ISO 15614-1 specifies only the minimum values of individual test joint dimensions. These dimensions for butt joints being the basis for further analysis are presented in Figure 1. The minimum value a = 150 mm is constant and does not depend on thickness. At the same time the standard contains an instruction that test joint dimensions should be sufficient for carrying out all required tests. A person preparing a test joint is obliged, among others, to ensure that the joint width (dimension a) is sufficient for carrying out ultrasonic examination. In most cases it is difficult or impossible due to the lack of necessary information related to UT resulting from the specific character of this testing method and requirements of related standards, in particular PN-EN ISO 17640. For this reason, in practice it is often necessary to use recommendations contained in appropriate reference publications such as those, among others, which can be found in "Poradnik inżyniera Spawalnictwo" (Engineer's Guide; Welding Engineering) [2], based on withdrawn standard PN-EN 288-3. In 2005 standard PN-EN 288-3 [6] was replaced by PN-EN ISO 15614-1. In addition to providing information about the minimum dimensions of test joints identical with the recommendations of the current standard [4], standard PN-EN 288-3 also contained formulas for joint dimensions in relation to material thicknesses. In the case of test plates the dependence defining the half-width of plates has the form a = 3t; minimum 150 mm. The analysis conducted has revealed that in the case of very thick joints, this width also is not sufficient for ensuring the minimum head travel zone during ultrasonic examination according to normative regulations concerning UT and, as a result, fails to satisfy the requirements of PN-EN ISO 15614-1. These circumstances lie at the heart of the attempt to determine the range of material thicknesses for which it would be possible to carry out UT in accordance with PN-EN ISO 17640 using available heads having various angles of beam insertion.

UT standard requirements

As it was mentioned above, standard PN-EN ISO 15614-1 assumes that test joints should meet the requirements specified for quality level B (with some minor exceptions negligible for UT). In turn, PN-EN ISO 17635 in Table A.7.1 assigns for the quality level B the following levels in UT involving the echo technique:

- acceptance level 2 according to PN-EN ISO 11666,
- test level at least B according to PN-EN ISO 17640.

In UT from test level A to test level C increased detectability is obtained by the increased coverage of the test area by, e.g. the number of searches (using several types of heads, carrying out additional searches for transverse indications) or by surface treatments (grinding of weld faces and roots) [5]. Standard PN-EN ISO 17640 in Table A.1 contains recommendations concerning the number of angles for inserting a beam and head travel zone width along with head positions depending on the test level and joint thickness. In the case of a butt joint, required quality level B and a thickness exceeding 15 mm it is necessary to use two angles for inserting a beam. If the frequency of a head used is below 3 MHz, it is possible to carry out the test using only one angle for inserting a beam, yet only for a joint thickness lower or amounting to 25 mm. This justifies the conclusion that for test joint thicknesses above 25 mm the width of such joints must

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enable carrying out ultrasonic examination with two angles for inserting a beam, between which – in accordance with PN-EN ISO 17640 recommendations – it is necessary to maintain at least 10° difference. The standard also assumes that tests should allow the use of heads having angles for beam insertion between 35° and 70°. Therefore, for available ultrasonic heads it is possible to use the following beam insertion angles: $\alpha = 35°$, 45°, 60° and 70°. The standard also requires that the width of head travel zone should be not less than $b_{min} = 1.25\,p$, where p – head pitch. Such a width along with the angle of a head used determines the minimum test joint dimension a which must amount to at least bmin increased by the half-length of the housing of an ultrasonic head used, i.e. usually approximately 13 mm (it was taken into account that the insertion of an ultrasonic beam takes place at the half-length of the head housing).

Analysis of test joint dimensions in relation to UT requirements

The analysis took into consideration the dimensions of test joints specified in PN-EN ISO 15614-1. Due to the previously mentioned fact that the determination of test joint widths for great thicknesses very often requires the use of reference publication recommendations [8], the analysis of test joint widths incorporated the use of instructions contained in the previous standard, i.e. PN-EN 288-3.

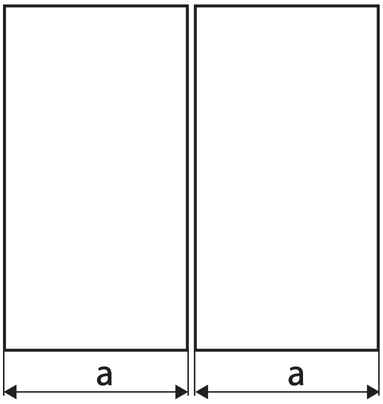

Fig. 1. Test plate dimension a according to PN-EN ISO 15614-1 [4]; a – minimum value 150 mm

Standard PN-EN ISO 15614-1 imposes only the minimum test joint dimension a amounting to 150 mm. In turn, following PN-EN 288-3 the width of one test plate part a is the triple material thickness, yet it cannot be less than 150 mm (Fig. 1). This means that for a material thickness $t = 50$ mm the width of a test plate is always 150 mm, and that above 50 mm the width is the function of material thickness and amounts to $a = 3t$.

In turn, standard PN-EN ISO 17640 specifies that the minimum test area width b for the UT method should amount to $b_{min} = 1.25\,p$, where p – head pitch. The head pitch p (Fig. 2) is the function of beam insertion angle α and test material thickness t and amounts to: $p = 2t \cdot tg\,\alpha$

Bearing in mind the assumptions mentioned above it was necessary to carry out calculations aimed at verifying whether for test plate dimensions required by PN-EN ISO 15614-1 and PN-EN 288-3 there is a sufficient test area width which would enable conducting ultrasonic examination in accordance with the requirements of PN-EN ISO 17640. The calculations were carried out for all conventional ultrasonic heads available on the market, i.e. those having beam insertion angles $\alpha = 35°$, 45°, 60° and 70°. The head $\alpha = 80°$ was not included on purpose as it is used solely for testing very thin elements rarely examined using UT methods. The calculations also took into consideration the test area width recommended from the practical point of view, i.e.:

$$b = 1.5 \cdot p,$$

where p – head pitch, at which, during a search, an ultrasonic wave strikes the root of a weld two times. Such an approach is justified due to very dangerous imperfections often present in this part of a weld and being of critical importance to the strength of a joint.

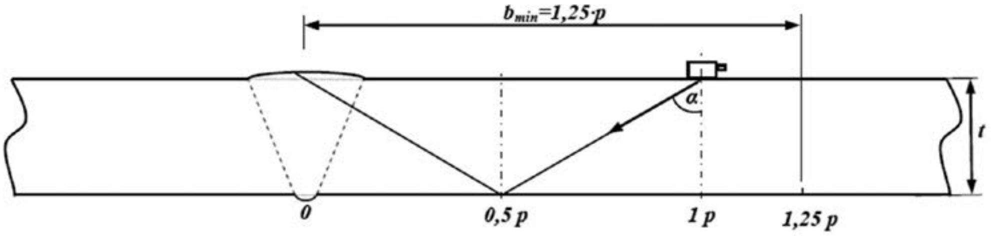

Fig. 2. Search zone width b according to PN-EN ISO 17640 [5]

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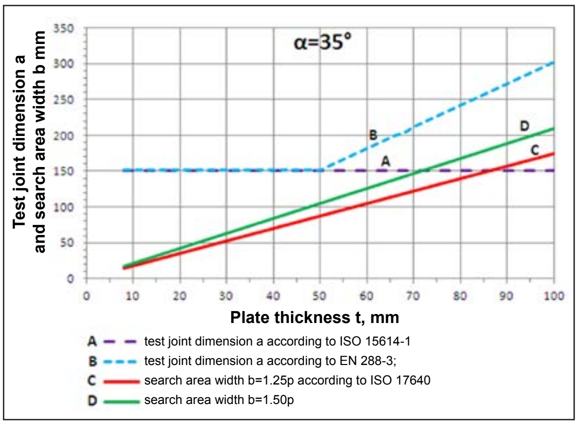

Fig. 3. Test plate width and search area width for the head having the beam insertion angle α=35°[3]

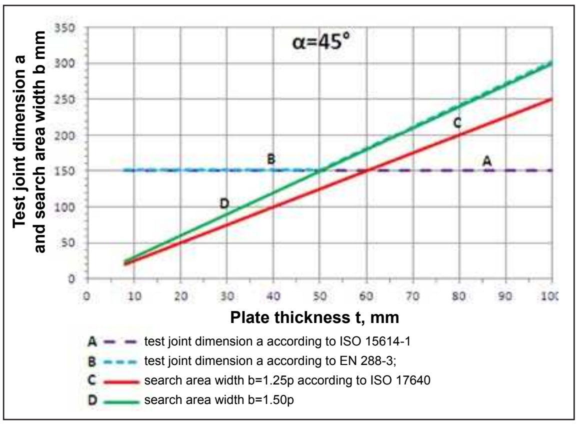

Fig. 4. Test plate width and search area width for the head having the beam insertion angle α=45°[3]

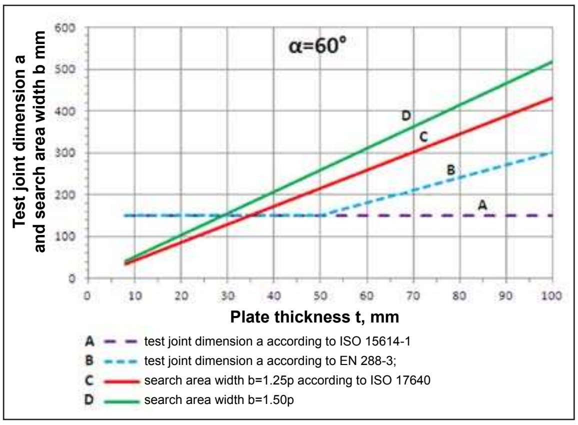

Fig. 5. Test plate width and search area width for the head having the beam insertion angle α=60°[3]

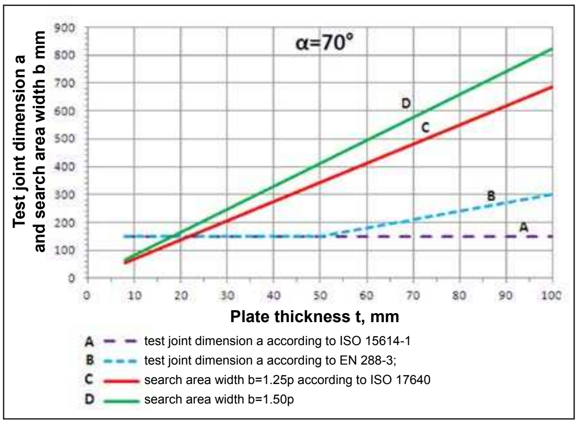

Fig. 6. Test plate width and search area width for the head having the beam insertion angle α=70°[3]

The calculation results are presented in the form of four diagrams (Fig. 3÷6), at which the axis of abscissae represents the parent metal thickness t and the axis of ordinates represents the test plate width a (corresponding to the above-mentioned thickness) in accordance with PN-EN ISO 15614-1 and PN-EN 288-3 as well as the search area width $b_{min}=1.25\cdot p$ (recommended by PN-EN ISO 17640) and $b = 1.5\cdot p$. The diagrams contain four curves:

- curve A (violet, dashed) – test plate width according to PN-EN ISO 15614-1 (a = 150mm),
- curve B (blue, dashed) - test plate width according to PN-EN 288-3 (a = 3·t, min. 150 mm),
- curve C (red, full) – test area width b depending on the full head pitch p according to PN-EN ISO 17640, bmin = 1.25·p,
- curve D (green, full) – recommended test area width enabling the double passage of a beam through the root of a weld, $b = 1.5\cdot p$.

Tables 1 and 2 contain the ranges of test plate thicknesses for which it is possible to carry out UT in accordance with the recommendations of PN-EN ISO 17640 using the heads referred to above. On this basis it is easily possible to observe which of the heads ensure conducting UT in accordance with guidelines for a given test plate thickness t.

The ranges were determined for the widths (dimension a) of test joints according to PN-EN ISO 15614-1 (Table 1) and PN-EN 288-3

Table 1. Ranges of test joint thicknesses which enable conducting UT in accordance with the requirements of PN-EN ISO 17640. The test joint dimension a adopted for all plate thicknesses is the minimum dimension required by PN-EN ISO 15640-1, i.e. a = 150 mm [3]

Criterion of search area width b in relation to full head pitch p	Range of plate thicknesses possible to test in accordance with adopted criterion (mm)			
	35°	45°	60°	70°
b = 1.25 · p according to PN-EN ISO 17640	8-84	8-60	8-34	8-20
b = 1.5 · p	8-70	8-50	8-28	8-18

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Table 2. Ranges of test joint thicknesses which enable conducting UT in accordance with the requirements of PN-EN ISO 17640. The adopted test joint dimension is the minimum dimension required by PN-EN ISO 288-3, i.e. a = 3t, min. 150 mm [3]

Criterion of search area width *b* in relation to full head pitch *p*	Range of plate thicknesses possible to test in accordance with adopted criterion (mm)			
	35°	45°	60°	70°
b = 1.25·p according to PN-EN ISO 17640	8-without limits	8-without limits	8-34	8-20
b = 1.5·p	8-without limits	8-without limits	8-28	8-18

(Table 2). The bottom range limit always amounts to 8 mm as standard PN-EN ISO 17640 is concerned with UT of joints having thicknesses equal to or exceeding 8 mm.

Results of test joint width analysis - discussion

The analysis of the diagrams (Fig. 3÷6) and Tables (1 and 2) leads to the conclusion that for the minimum test plate thickness according to ISO 15614-1 (*a* = 150 mm) none of the available ultrasonic heads ensures testing the complete range of thicknesses (Table 1). The 35°, 45° and 60° heads provide the proper head travel width *b* only for the thickness values of 84 mm, 60 mm and 34 mm respectively. This means that in the case of thick elements $t > 40$ mm, for which the standards [7] recommend carrying out UT and do not recommend conducting alternative RT, a test joint should have the dimension a greater than the minimum value of 150 mm recommended in PN-EN ISO 15614-1. Such a situation is assumed in the standard itself, containing the instruction that the dimensions of test joints should be sufficient for carrying out all required tests.

The case when the test joint was prepared on the basis of reference publication recommendations [2] contained in withdrawn standard PN-EN 288-3 is presented in Table 2. As can be seen, the width of test joints in this case enables testing the whole range of thicknesses using the 35° and 45° heads. The 60° head enables carrying out tests for thicknesses not exceeding 34 mm. However, as it was mentioned before, quite often for joints of thicknesses from the 15-25 mm range (i.e. for the frequency of a head amounting to 4MHz) and always for thicknesses exceeding 25 mm (irrespective of frequency) it is necessary to use two beam insertion angles [5]. Tables 1 and 2 reveal that for thicknesses above 34 mm and test joint dimensions as specified in PN-EN ISO 15614-1 and PN-EN 288-3 it is possible to use 60° and 45° heads. In turn, above this thickness, in order to ensure the search area width required by ISO 17640 it would be necessary to use the angle of 35° as the second angle of the head. However, such a head configuration (45° and 35°) for thicknesses above 34 mm entirely fails to meet another requirement of the standard stating that the beam insertion angle of at least one head used should make it possible for the ultrasonic beam to strike the fusion line at an angle close to 90°. Such an approach aims to increase the detectability of edge incomplete fusions oriented in relation to the ultrasonic beam as the groove wall. For the most commonly used bevelling angles restricted within a range between 22.5° and 30° [2] such an assumption is best fulfilled by the 60° head. If the assumption mentioned above is not fulfilled, in the echo method the beam emitted at an inconvenient angle may strike even a significant incomplete fusion and be reflected in another direction failing to return to the head and signal such a discontinuity on a defectoscope [8]. As a result, it is possible to omit even the whole series of edge incomplete fusions as each of them tends to be oriented in the same way. Such an error could dramatically affect the whole WPS-based production approved on the basis of improperly conducted tests having lower detectability. Although while qualifying a welding technology NDT is accompanied by

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destructive tests which can detect incomplete fusions, yet they are carried out on test pieces sampled from small weld fragments, whereas NDT, in this case UT, covers 100% of the joint length.

For this reason, in order to increase detectability it is necessary to ensure a test joint width which enables carrying out UT using a 60° head. Although such a solution entails greater test-related labour due to significantly greater search area than in the case of a 35° head, yet, in return, it ensures the detection of incomplete fusions and satisfaction of related standard requirements.

The foregoing justifies the conclusion that also the width of the test plate made assuming $a = 3t$, min. 150 mm (according to PN-EN 288-3) is not sufficient for the proper performance of test joint ultrasonic examination; the reason being the overly low dimension a for joint thicknesses exceeding 34 mm. In order to properly carry out examination following all the requirements of related standards as regards large thicknesses t of test joints their dimension should be adequate for carrying out tests using 60° and 45° heads within the whole thickness range.

In order to facilitate the determination of the proper dimension a in relation to the angle α of the head used and the joint thickness t, Figure 7 presents the nomogram developed on the basis of the analysis conducted. The nomogram shows the minimum test joint dimension a for ultrasonic examination. In addition to the minimum width of the head travel the nomogram takes into consideration the half-length of the head housing (13 mm) valid for commonly used miniature heads (e.g. AM2R-8X9-60, MWB60-2). If tests involve the use of heads with 20x22mm transducers (e.g. AM2R-20X22-60, WB60-2), it is necessary to add 14 mm to the value read out of the nomogram; this is due to the greater housing length of such heads.

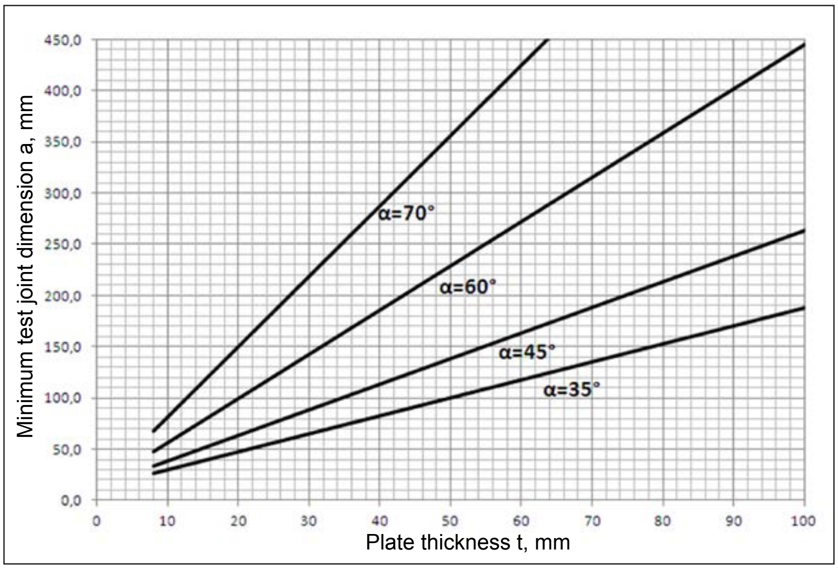

Fig. 7. Nomogram for determining the minimum dimension a of test joints in relation to the angle α of an ultrasonic head used for testing the thickness t of plates

Summary

In order to properly carry out the qualification of welding technologies for great thicknesses it is necessary to take into consideration the minimum dimensions of test joints necessary for conducting all required destructive and non-destructive tests. The minimum dimension a provided in PN-EN ISO 15614-1 for the thickness $t > 34$ mm is not sufficient for carrying out ultrasonic examination recommended in this thickness range. For this reason it is recommended that test joint widths a should be selected on the basis of the nomogram (Fig. 7) using the assumption that examination with the 60° head must be possible to carry out within the whole thickness range. Such an assumption will make it possible to satisfy all the requirements set for ultrasonic examination in PN-EN ISO 17640 as well as will ensure the proper detectability and assessment accuracy of potential indications.

Using greater widths of test joints for great thicknesses is necessary not only due to ultrasonic examination requirements. It is known that a test joint having a thickness of 100 mm and a minimum width of 150 mm has different key welding process

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conditions (heating, heat distribution, cooling rate, stresses etc.) than a structural element having the same thickness, but – usually – significantly greater width. Such a test joint fails to fulfil its primary task, i.e. the simulation of conditions possibly the closest to those present during making joints in a given structure. Adopting such an approach is necessary in order to initially eliminate the possibility of using a welding technology which will lead to the production of faulty joints failing to provide proper load capacity.

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Ryszard Krawczyk

Welding parameter ranges in relation to metal transfer method in welding arc

Abstract: The study is concerned with MAG welding. The issues presented are directly related to the transfer of metal in the welding arc depending on power applied. The main objective of the study was to present the ranges of welding parameters in relation to the mode of metal transfer in the welding arc. The subject of the study was inspired by the introduction of new standard PN-EN ISO 9606-1 concerning the qualification of welders. This standard features the mode of metal transfer in the welding arc as a new welder qualification variable. As a result, these issues have acquired new significance in terms of this process.

Keywords: metal transfer methods, welding arc, welding parameters, MAG, PN-EN ISO 9606-1

Introduction

Welding processes used in the production of various structures are rated among special processes. This fact results from the complexity of welding processes characterised by numerous variables which are often difficult to define and sometimes even impossible to predict. In order to ensure the proper course of welding processes, it is necessary to extensively qualify welding technologies and personnel participating in their execution. This requirement concerns personnel directly involved in welding processes (welders and welding station operators), surveillance personnel (welding engineers and junior personnel) and inspection personnel (welding inspectors and NDT personnel). The primary objective of qualification is to ensure the most convenient conditions for the proper course of welding processes at various stages of their execution. This special task includes welder qualification. The new PN-EN ISO 9606-1 standard concerning the qualification of welders, includes a new welder qualification variable taking into consideration also the mode of metal transfer in the welding arc. This concerns the MAG 135, MAG 138 and MIG 131 welding processes. The revision requires good knowledge of the operation of a heat source used in these processes, i.e. an electric arc as well as the application of welding parameter ranges in relation to the mode of metal transfer in the welding arc. The objective of this study is to introduce these issues in the scope contained in PN-EN ISO 9606-1.

Welding arc characteristics

The welding arc can be simply defined as a "**discharge in the inter-electrode area**". The arc used in welding engineering is characterised by many variables depending on the type of a welding process. The basic welding arc variables include the following:

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1. Type of power supply forming the character of a discharge:
    - type and polarity of current,
    - static and dynamic characteristics of the welding power source,
    - control conditions and power supply parameter values,
    - disturbance in the supply circuit.
2. Type of electrodes:
    - character of fusibility,
    - thermal and electric properties,
    - diameter or thickness,
    - introducing and maintaining stability,
    - purity.
3. Formation of inter-electrode area:
    - type and efficiency of a gas shield,
    - inter-electrode distance and its stability,
    - **changes taking place as a result of material transport in the arc area.**

The basic types of arc welding processes commonly used in production include the following methods:

- **MMA (111)** – *Manual Metal Arc*,
- **MAG (135 and 138)** – *Metal Active Gas* (with solid wire electrode – 135 and metal cored electrode – 138),
- **MIG (131)** – *Metal Inert Gas*,
- **TIG (141)** – *Tungsten Inert Gas*,
- **SAW (121)** – *Submerged Arc Welding*.

The most convenient conditions affecting arc burning stability are present in TIG welding and include, among others, the following:

- solid non-consumable electrode,
- constant distance between the electrode and the material,
- stable (steep) arc supply characteristics,
- noble gas shield,
- absence of disturbance caused by the transfer of a metal drop in the arc area.

In turn, the most inconvenient conditions affecting arc burning stability are present in MMA welding and include, among others, the following:

- consumable electrode,
- changeable distance between the electrode and the material,
- non-uniform gas shield,
- disturbance caused by the transfer of a metal drop in the arc area.

Significant differences characterise TIG and MMA despite using electric arc power supply sources having the same features, i.e. steeply drooping characteristics. The measure of these features is the significant difference present in the conventional voltage waveform for both processes, illustrated in the diagram (Fig. 1).

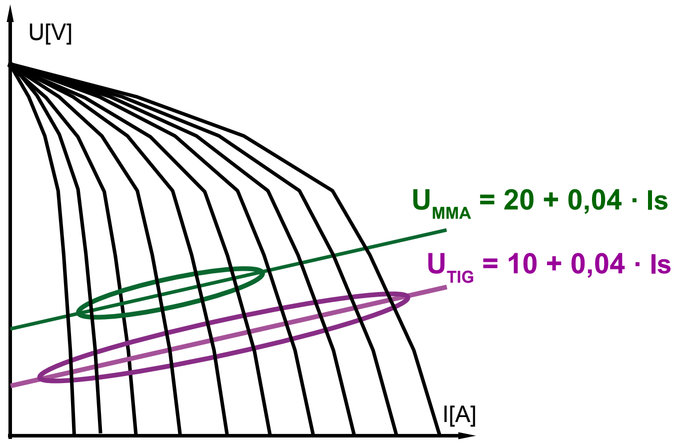

Fig. 1. Voltage static characteristics and welding arc conventional characteristics in MMA and TIG

Modes of Metal Transfer in Welding Arc

The transfer of metal in the welding arc is directly connected with consumable electrodes and is related to most arc welding processes, e.g. 111, 135, 138, 131 and 121, as well as their varieties.

The most interesting form of metal transfer in the welding arc is present in MAG and MIG welding processes and is directly connected with significant current density, the rate of current density changes and the wide range of welding arc power. These features result mainly from small diameters of electrode wires fed within a wide range of feeding rates and from supplying the arc with flat characteristics power sources within a wide power range, which enables significant freedom of melting rate changes. As a result, depending on welding arc power applied the welding methods mentioned above are characterised by widely diversified modes of metal transfer in the arc. The basic modes of metal transfer in the arc are the following:

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1. **short-circuit** (fine droplet),
2. **globular** (coarse droplet, mixed),
3. **spray** (stream),
4. **rotating** (eddy),
5. **pulsed** (in pulsed arc).

The first four modes of metal transfer in the welding arc (short-circuit, globular, spray and rotating) are present in a natural process usually referred to as standard, as distinct from the pulsed arc process developed in the 1990s. The basis of the pulsed arc process is the uniform pulsed mode of metal transfer in the arc. The pulsed metal transfer has all the features of the spray transfer, yet it takes place within the whole range of applied welding arc power. Figure 2 illustrates the static characteristics and conventional arc voltage dependence in the MAG standard process taking into consideration various modes of metal transfer in the arc zone in the current range up to 400 A.

The dependences of conventional arc voltage presented in Figure 2 concern Ar82CO$_2$18 gas-shielded welding of group 1 steels using a G3Si1 electrode wire with a diameter of 1.2 mm and at the same time are concerned with current ranges related to various modes of metal transfer in the welding arc in the MAG standard method. The analogous illustration of static power supply characteristics and dependence of conventional arc voltage in the MAG pulse method is presented in Figure 3.

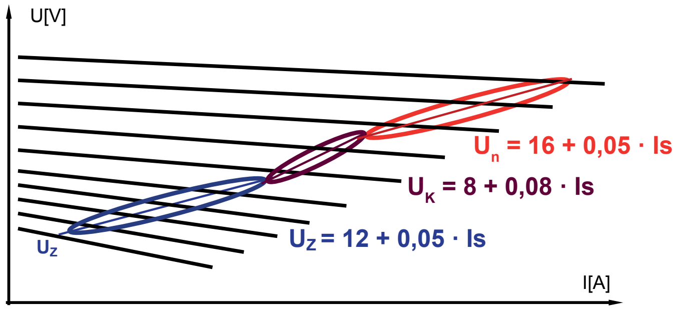

Fig. 2. Static power supply characteristics and conventional arc voltage characteristics in the MAG standard method with various modes of metal transfer in the arc zone

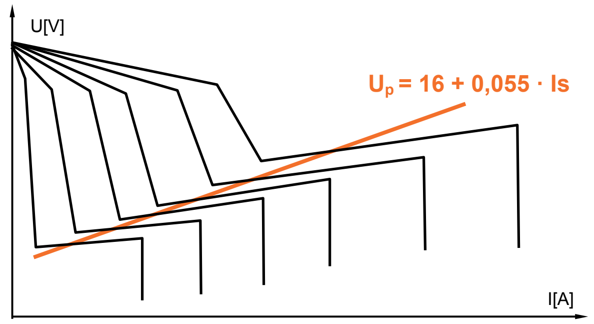

Fig. 3. Static power supply characteristics and conventional arc voltage characteristics in the MAG pulse method in the entire current range up to 400A

The dependence of conventional pulsed arc voltage concerns Ar82CO$_2$18 gas-shielded welding of group 1 steels using a G3Si1 electrode wire having a diameter of 1.2 mm in a current range up to 400 A.

Characteristics of basic dependences and welding parameter ranges for unalloyed steels in relation to mode of metal transfer in welding arc in MAG-135 method

Complete characteristics of the changes of the basic (voltage-current) dependences for M21 (Ar82CO$_2$18) gas-shielded MAG welding of S235 unalloyed steels with G3Si1 electrode wires having diameters of 1.2; 1.0 and 0.8 mm, using the standard arc and various modes of metal transfer in the welding arc and with a pulsed arc are presented in Figures 4, 5 and 6. Tables 1, 2 and 3 contain detailed information concerning basic arc control parameter ranges (v, U and I) in relation to the modes of metal transfer in the arc (short-circuit, globular, spray and pulsed).

Welding parameter ranges for unalloyed steels in relation to mode of metal transfer in welding arc in MAG-138 Method

Detailed information related to the ranges of basic arc control parameters (v, U and I) in the MAG-138 method in relation to the modes of metal transfer in the arc (short-circuit, globular, spray and pulsed) is presented in Tables 4 and 5. The data refer to M21 active gas-shielded welding of S235 low-carbon steels using metallic flux-cored wire having the diameters of 1.6 and 1.2 mm. As regards the materials mentioned above, manufacturers do not recommend using

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Data for the electrode wire with the diameter of 1.2 mm

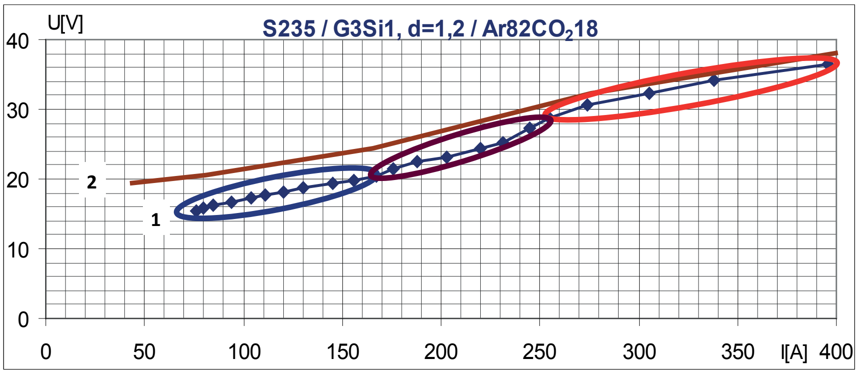

Fig. 4. Arc voltage dependences in the function of welding current in arc control in the MAG standard method with various modes of metal transfer in the arc zone (curve 1) and MAG pulse (curve 2)

Table 1. Ranges of the basic arc control parameters (v, U, and I) depending on the modes of metal transfer in the arc

Parameter type	Parameter ranges due to metal transfer mode in arc			
	short-circuit	globular	spray	pulsed
v [m/min]	1.5–4.0	4.2–7.5	8.0–14.0	1.2–14.0
U [V]	15.5–20.0	20.5–28.0	29.0–36.5	19.0–39.0
I[A]	75–160	165–250	260–400	40–400

Data for the electrode wire with the diameter of 1.0 mm

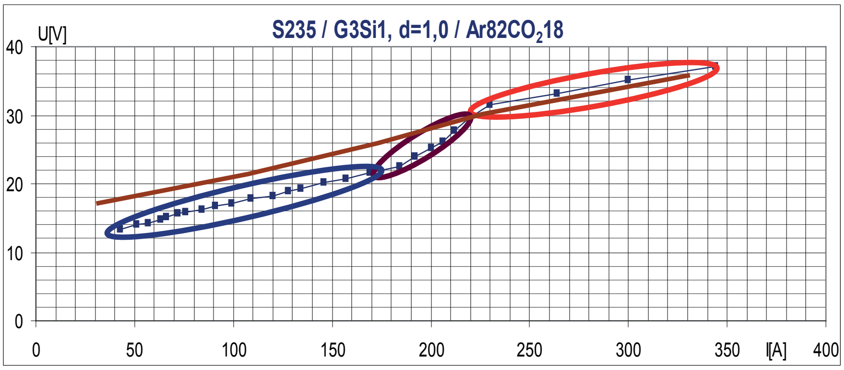

Fig. 5. Arc voltage dependences in the function of welding current in arc control in the MAG standard method with various modes of metal transfer in the arc zone (curve 1) and MAG pulse (curve 2)

Table 2. Ranges of the basic arc control parameters (v, U, and I) depending on the modes of metal transfer in the arc

Parameter type	Parameter ranges due to metal transfer mode in arc			
	short-circuit	globular	spray	pulsed
v [m/min]	1.5 – 7.0	8.0 – 10.5	11.0 – 19.0	1.4 – 21.0
U [V]	13.5 – 21.5	22.0 – 28.0	29.0 – 37.5	17.0 – 35.5
I[A]	45 - 170	180 – 215	220 - 350	30 - 335

Data for the electrode wire with the diameter of 0.8 mm

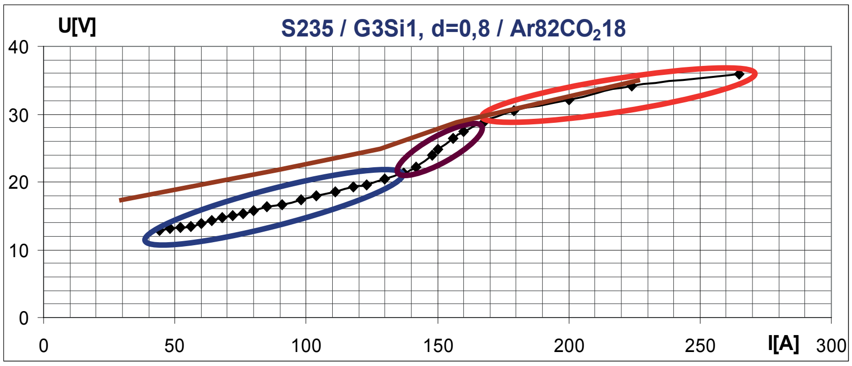

Fig. 6. Arc voltage dependences in the function of welding current in arc control in the MAG standard method with various modes of metal transfer in the arc zone (curve 1) and MAG pulse (curve 2)

Table 3. Ranges of the basic arc control parameters (v, U, and I) depending on the modes of metal transfer in the arc

Parameter type	Parameter ranges due to metal transfer mode in arc			
	short-circuit	globular	spray	pulsed
v [m/min]	2.0 – 8.5	9.0 – 11.5	12.0 – 25.0	2.0 – 23.5
U [V]	13.0 – 20.5	21.0 – 27.5	28.0 – 36.0	18.0 – 35.0
I[A]	45 - 130	135 – 160	165 - 265	30 - 225

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welding parameters in the range of globular metal transfer (coarse droplet, mixed) in the arc.

MAG-135 welding parameter ranges for CrNi alloy steels in relation to the mode of metal transfer in a welding arc in the MAG-135 method

Further data presented in Tables 6, 7 and 8 concern using the MAG-135 method in M11 active gas-shielded welding of CrNi type alloy steels with wires having diameters of 1.2; 1.0 and 0.8 mm. The detailed information refers to the ranges of basic arc control parameters (v, U and I) in the MAG-135 method in relation to the modes of metal transfer in the arc (short-circuit, globular, spray and pulsed)

Conclusions

1. The transition from one mode of metal transfer in the welding arc to another takes place within the narrow range of current change referred to as critical. In this area, the transfer of metal in the arc takes on a mixed form.

2. The boundaries of the ranges of transition from one mode of metal transfer in the welding arc to another, i.e. the values of current in the critical area depend on the types of materials, diameters of electrode wires, types of shielding gases, exposed lengths of electrode wires, as well as on the static and dynamic properties

Table 4. Ranges of the basic arc control parameters (v, U, and I) depending on the modes of metal transfer in the arc for flux-cored wire with the diameter of 1.6 mm for M21 gas-shielded welding (Ar82C0218)

Parameter type	Parameter ranges due to metal transfer mode in arc			
	short-circuit	globular	spray	pulsed
v [m/min]	1.7 – 3.5	–	3.5 – 9.0	1.5 – 12.0
U [V]	14.5 – 20.0	–	25.5 – 36.5	18.0 – 36.0
I[A]	130 - 215	–	235 - 400	100 - 450

Table 5. Ranges of the basic arc control parameters (v, U, and I) depending on the modes of metal transfer in the arc for flux-cored wire with the diameter of 1.2 mm for M21 gas-shielded welding (Ar82C0218)

Parameter type	Parameter ranges due to metal transfer mode in arc			
	short-circuit	globular	spray	pulsed
v [m/min]	1.7 – 3.5	–	3.5 – 9.0	1.5 – 12.0
U [V]	14.5 – 20.0	–	25.5 – 36.5	18.0 – 36.0
I[A]	130 - 215	–	235 - 400	100 - 450

Table 6. Ranges of the basic arc control parameters (v, U, and I) depending on the modes of metal transfer in the arc for electrode wire 316LSi/d =1.2 mm for M11 gas-shielded welding (Ar98C022)

Parameter type	Parameter ranges due to metal transfer mode in arc			
	short-circuit	globular	spray	pulsed
v [m/min]	1.5-5.0	5.5-8.5	9.0-22.0	1.2-14.0
U [V]	14.0-20.0	20.5-26.0	27.0-36.0	15.0-31.0
I[A]	60-165	170-230	240-410	40-330

Table 7. Ranges of the basic arc control parameters (v, U, and I) depending on the modes of metal transfer in the arc for electrode wire 316LSi/d = 1.0 mm for M11 gas-shielded welding (Ar98C022)

Parameter type	Parameter ranges due to metal transfer mode in arc			
	short-circuit	globular	spray	pulsed
v [m/min]	1.5-7.0	7.5-8.5	9.0-24.0	1.5-20.0
U [V]	14.0-22.5	23.0-25.0	25.5-32.5	15.5-32.0
I[A]	45 - 145	150-160	170-320	35-285

Table 8. Ranges of the basic arc control parameters (v, U, and I) depending on the modes of metal transfer in the arc for electrode wire 316LSi/d=0.8 mm for M11 gas-shielded welding (Ar98C022)

Parameter type	Parameter ranges due to metal transfer mode in arc			
	short-circuit	globular	spray	pulsed
v [m/min]	2.5-8.0	8.5-14.5	15.0-25.0	2.2-23.0
U [V]	13.5-19.0	19.5-25.0	25.5-31.0	16.0-30.0
I[A]	45-110	115-160	170-250	30-210

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of the welding arc power source.

3. Deteriorating conditions in the welding process are responsible for the decrease in the boundary of transition from the short-circuit arc to the globular arc and for the increase in the boundary of transition from the globular arc to the spray arc. In such conditions the area of the globular arc (coarse droplet, mixed) becomes extended.

4. The most convenient welding process conditions are obtained in the welding arc with short-circuit and spray metal transfer, as well as pulsed transfer while using the pulsed arc.

5. The most inconvenient welding process conditions are present in the arc with the globular metal transfer (coarse droplet, mixed).

6. The application of arc with various metal transfer modes is the following:

- short-circuit – welding of thin elements in various positions and thicker elements in restricted positions,
- globular – welding of thicker elements in flat and horizontal positions,
- spray – welding of thick elements in flat and horizontal positions,
- pulsed – welding elements of various thicknesses in flat and horizontal positions.

7. The qualification of welders according to PN-EN ISO 9606-1 has adopted preference conditions for welding processes 131, 135 and 138 with the short-circuit arc following the instruction: **“Welder qualification for short-circuit arc welding (short arc) (processes 131, 135 and 138) qualifies for other metal transfer modes, but not vice versa”**.

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Wanda Zeman, Monika Restecka

Welding industry against economic fluctuations of 2006-2012

Abstract: The article aims to determine the scale of applying welding technologies, the role of welding engineering in production and economy and the impact of economic fluctuations on the dynamics of sales in industries applying welding techniques and on the demand for welding equipment and consumables.

Keywords: welding industry analysis, production, employment, technology

Following the adopted terminology, the notion of "industry" is usually reserved for the production of one type of goods. In the case of welding engineering, the potential of industry results from the presence of joining technologies in manufacturing processes of most products and structures made of steel, non-ferrous metals and their alloys, as well as products made of plastics, composites, ceramics, multimaterials and even of wood. Such products, in the form of bridges, power systems and boilers, pipelines, vehicles, building structures, household equipment etc., are manufactured in over 100 various industries of Poland's economy.

The term of joining usually refers to three basic technologies, i.e. fusion welding, pressure welding and brazing/soldering. However, this very general division does not reflect the scale, potential and role of these technologies in production processes and economy. According to the standard PN-EN ISO 4063:2011E *Welding and Allied Processes – Nomenclature of Processes and Reference Numbers* within the three primary technologies, i.e. fusion welding, pressure welding and brazing/soldering as well as cutting and gouging as allied processes it is possible to enumerate 46 various methods and approximately 100 variants of these methods used for joining various structural materials.

Application of joining technologies and allied techniques

In spite of increasing consumption of aluminium and plastics, steel continues to remain the primary structural material, therefore the consumption of steel was adopted as the basis for the analysis of the welding industry situation. It is estimated that approximately 65% of rolled steel products (i.e. in Poland, depending on the market situation between 3.5 and 5 m tons) is used for welded structures and products made by means of, among others, welding techniques (Fig. 1).

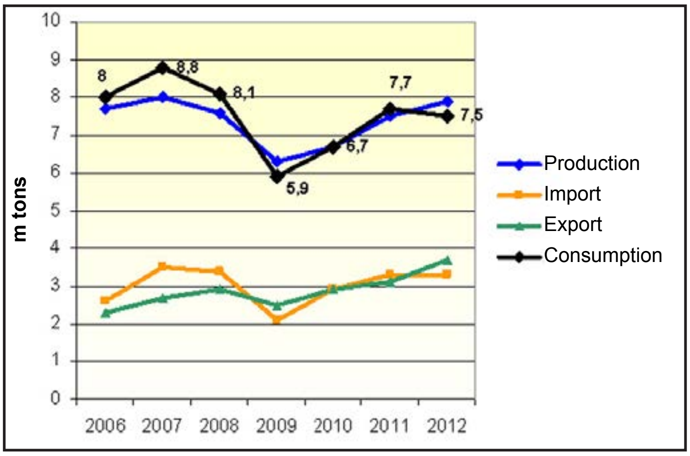

Fig. 1. Consumption of hot rolled products in Poland in 2006-2012

Figure 1 presents the impact of market fluctuations on the consumption of hot rolled products. In 2009, in comparison with the

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prosperity time of 2007, the consumption of such products dropped by 2.9 m tons, i.e. by over 36%. The period of economic revival of 2010-2011 was reflected by an increase in the consumption of the aforementioned products by approximately 1.8 m tons. The economic downturn of 2012 was not as severe as that of 2009. In comparison with the previous year the consumption fell by a mere 0.2 m tons. However, by 2012 the consumption of hot rolled products had not reached the level of 2006, i.e. the year preceding the greatest economic boom in the last decade. These changes influenced the economic situation in the welding industry.

Among 22 industrial processing sectors, 6 (being the main users of welding techniques, i.e. the production of metals, metal products, equipment and machinery, cars, trailers and semitrailers, other vehicles and electronic equipment) consume approximately 95% of rolled products (Fig. 2).

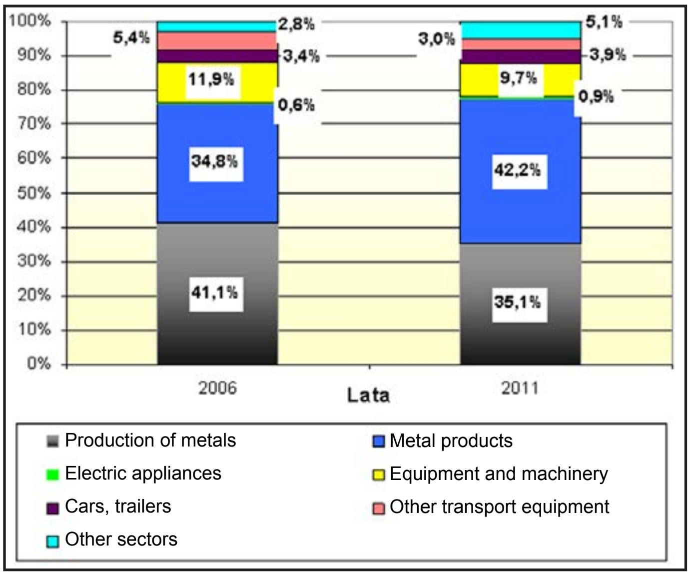

Fig. 2. Structure of hot rolled product consumption according to sectors of economy and industry in 2006 and 2011

The structure of rolled product consumption reveals that the years 2006-2011 saw a consumption increase in such sectors as metal products (by 7.4%), cars, trailers and semitrailers (by 0.5%) as well as electric appliances (by 0.3%) and a decrease in the production of metals (by 6%), equipment and machinery (by 2.2%) and of other transport equipment (2.4%). As regards the use of welding technologies, the manufacture of metal products is the most important sector of industry (Fig. 2).

The scale of welding technologies application is affected, among others, by changes in employment and number of enterprises (referred to as business entities in statistics terminology) taking place in industry sectors using welding techniques. In the years 2006-2012 the number of business entities in the sectors mentioned above rose from 7574 to 7774, i.e. by mere 200 companies. As regards employment numbers the structure of companies practically did not change. Small and medium enterprises (SME), i.e. those employing up to 250 workers make up 93% of the total number of enterprises. Only 7% of businesses are companies employing above 250 workers, i.e. companies rated as big (Fig. 3).

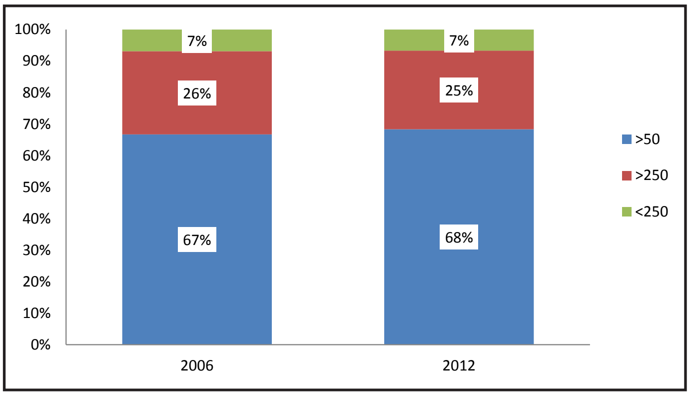

Fig. 3. Structure of business entities in welding engineering-related industry sectors according to the number of employed workers

Table 1 presents that in 2012 7774 companies were involved in the manufacture of metals, metal products, electric appliances, equipment and machinery, vehicles and transport equipment, i.e. goods requiring the use of joining technologies. This constitutes approximately ¼ of all the companies in the industrial processing sector, employing 697.5 thousand workers, i.e. 34% of the total number of workers employed in the processing industry. The manufacture of metal products is the greatest user of welding processes both in terms of the number of business entities (4426) and the scale of employment (234 thousand workers).

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Table 1. Number of business entities and employment in industry sectors using welding technologies in 2012

Description	Number of entities*	Share %	Av. employment in thous.	Share %
Industrial processing in total	29 333	100	2052	100
including the manufacture in sectors using welding techniques	7774	25.5	697.5	34
• metals	metals	1.5	61.0	3.0
• metal products	metal products	15.0	234.5	11.4
• electric appliances	electric appliances	2.2	90.8	4.4
• equipment and machinery	equipment and machinery	4.9	116.5	5.7
• cars	cars	2.0	153.4	7.5
• other transport equipment	other transport equipment	0.9	41.3	2.0
Building engineering in total	236 361	100	612.8	100
• including civil engineering objects	including civil engineering objects	6.3	157.8	25.7

*Data refer to enterprises employing over 9 workers

It is problematic to estimate the number of companies using welding technologies in building industry as some companies manufacture building materials and perform building processes without using welding technologies. According to American data the share of welding in the total labour cost in building sector amounts to approximately 13% (Fig. 4).

In the building engineering sector civil engineering objects (railway tracks, bridges, railway bridges, and pipelines) are examples of building structures requiring the use of welding technologies. This production process involves over 15 thousand companies employing over 150 thousand workers, which makes up more than 25% of the total number of workers employed in the building sector. Industrial buildings, warehouses and office buildings are other structures made using welding techniques. Also broadly defined service industry offering various types of repairs, tests and training utilising welding technologies affects the potential of welding engineering sector.

It is estimated that, depending on the economic situation, welding sector directly or indirectly employs between 120 and 180 thousand workers. This number includes welders (the largest group), welding coordination and quality control workers, personnel dealing with the production, distribution and service of welding equipment and consumables, workers involved in training of welding personnel as well as welding research specialists.

Role of welding industry in production and economy

The role of welding industry in the Polish economy is indicated by many factors such as, among others, the number of enterprises involved in the production of welded goods and structures as well as the share of industry sectors using welding technologies in the production sold and in the generation of gross added value (Tables 2 and 3).

Table 2. Examples of industries using joining technologies and their share in the production sold in 2005 and 2012

Description	2005		2012	
	BN PLN	share %	BN PLN	share %
Industrial processing in total	571.6	100	985.3	100
including metal products	38.2	6.7	78.4	7.9
Building and assembling in total	82.5	100	170.6	100
including civil engineering objects	15.4	18.7	46.9	27.5

According to the data presented in Table 2, in spite of the economic downturn, in the total industrial production sold the share of industry sectors closely related to welding engineering, i.e. the manufacture of metal products and civil engineering objects, increased from 6.7 to 7.9% and from 15.4 to 27.5% respectively.

The manufacture of metal products had the greatest share in the generation of gross added value, i.e. 7.8% and 7. 7% in 2006 and 2012 respectively (Table 3).

Table 3. Share of industry sectors utilising welding technologies in the generation of gross added value

Description	Share %	
	2006	2012
Industry in total	100	100
including industrial processing, including the manufacture of:	76.3	70.1
• metals	3.8	1.9
• metal products	7.8	7.7
• electric appliances	3.1	2.9
• equipment and machinery	6.0	3.7
• cars	5.2	5.7
• other transport equipment	1.8	1.5

The contribution of welding engineering in the generation of added value is diversified in individual sectors. Until today there has been no research performed relating to this issue. In spite of individual classification for given countries it is possible to use results from other countries as such data depict to what extent individual sectors of economy are related to welding engineering. According to Figure 4, in the US economy sectors, the highest share of welding engineering in the total labour costs is in heavy industry (15.97%) and in building engineering (13%).

In the case of aviation industry, electronics and automotive industry this share amounted to from 0.63 to 2.63% respectively. However, it should be emphasized that these sectors utilise the most advanced welding technologies and that progress made in structural materials and welding technologies can change such statistics. [1]

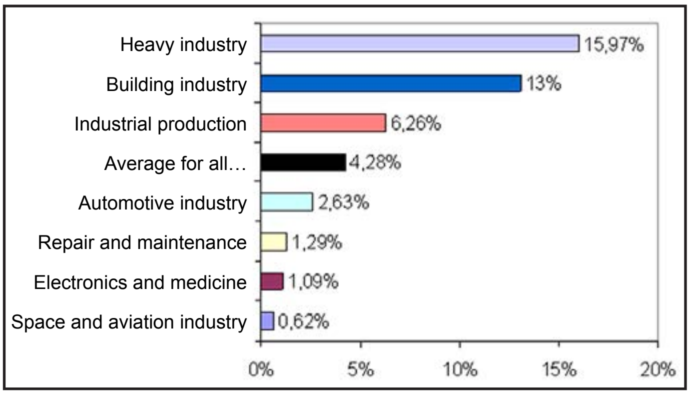

Fig. 4. Share of welding engineering in total labour costs in US economy [1]

According to research conducted in Germany, the share of welding technologies in the added value generated by “vehicle production” was 7.1%, that generated by metal structures amounted to 4.5%, and that generated by production of machinery was 1.8%. Without risking any major error such data can be referred to Polish conditions. It is estimated that, on average, 5% of gross added value generated by welding engineering-related sectors is contributed by welding technologies.[2]

Analysing the dynamics of production sold in 6 industry sectors using welding techniques leads to the conclusion that the economic downturn most significantly affected the sector named as “other transport equipment” (i.e. ships, railway and tram rolling stock etc.). Although, in comparison with 2009, this sector saw an increase in production in the years which followed, by 2012 the manufactures of equipment and machinery had failed to reach the sales volume of the base year of 2006. The sectors referred to as “manufacture of metal products” and “electric appliances”, relatively slightly affected by the 2009 crisis, were in a comparatively good condition. (Fig. 5).

As opposed to other sectors of economy, if compared with 2008 in the crisis year of 2009 the production of steel structures decreased by 30 thousand tons only, i.e. less than in the next period of economic downturn of 2012, when year-to-year decrease amounted to approximately 50 thousand tons. Although the export of steel structures has not reached the most

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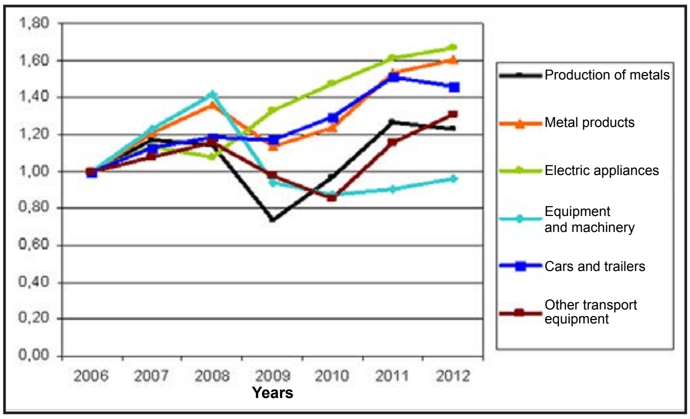

Fig. 5. Dynamics of production sold in 6 industry sectors utilising welding technologies. Year 2006 = 1

prosperous level of 2008, it is possible to observe that the sector is regaining its position in the market by successive production increase and positive price ratio of exported and imported structures in 2012. This observation is confirmed by data related to the production and export of steel structures, within which civil engineering structures, bridges, towers, masts, prefabricated steel buildings etc. are made of rolled products joined, among others, by means of welding technologies (Fig. 6 and 7).

The data presented in Figures 1, 5, 6 and 7 indicate that economic fluctuations are reflected in all sectors analysed, with differences relating to their intensity and time. Quite frequently a decrease in one sector is compensated by a growth in another. For instance, the crisis which affected the production of transport equipment in 2010 was, to some extent, remedied by an increase in the sales of metal products, cars, trailers and semitrailers and of electric appliances. It is also necessary to emphasise the relatively high dynamics of the "metal products" sector, i.e. of the greatest user of welding technologies.

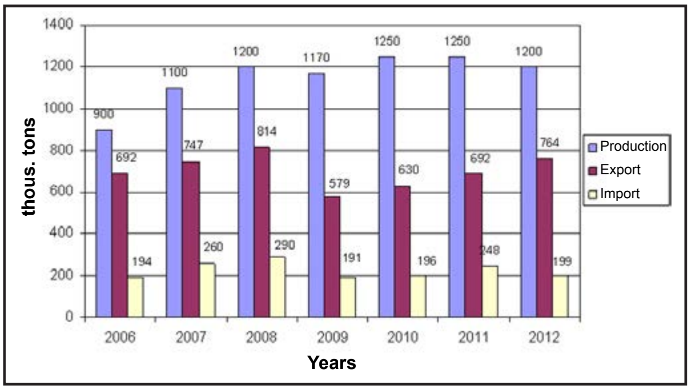

Fig.6. Production, export and import of steel structures in 2006-2012

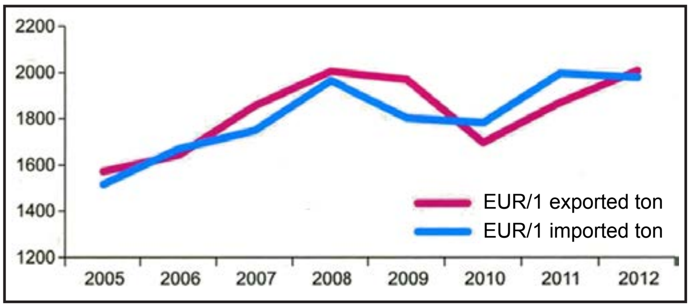

Fig. 7. Prices of exported and imported steel structures [3]

Relationships between the number of business entities and the value of production sold

Special attention should be paid to the relationships between the structure of companies as regards their number and the structure of production sold as such relationships indicate which companies generate the greatest value of sales. While analysing the 6 sectors as the whole, it is possible to notice, to some extent, the correctness of the Pareto principle, according to which the greatest volume of sales is generated by the smallest number of companies, where such companies are big. The value of production sold by 68% of companies employing up to 50 workers (the related data do not include companies employing up to 9 workers) makes up only 9% of the total sales of companies analysed. In turn, 7% of companies sell products, the value of which in the sales structure amounts to 70%. The value of production sold by 25% of companies employing between

Table 4. Structure of business entities in 6 sectors of industry using welding techniques according to the number of employed and to the value of production sold in 2012

Employment	Number of entities		Production sold	
	2006	2012	2006	2012
below 50*	67%	68%	9%	9%
from 51 to 250	26%	25%	21%	21%
above 250	7%	7%	70%	70%
	100%	100%	100%	100%

*Data refer to enterprises employing over 9 workers

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51 and 250 workers amounts to 21%. As can be seen, the economic changes in the years 2006 – 2012 had no impact on the structure of companies in terms of employment and production sold (Table 4).

Detailed analysis of individual industry sectors related to welding engineering indicates that as regards the manufacture of metal products it is small and medium enterprises and not big companies that play a leading role as far as the value of production sold is concerned. In 2006 and 2012 the share of such companies in the volume of sales amounted to 66 and 64% respectively. In the years analysed an increase in the sales share for big companies from 34 to 36% and a decrease in the share related to the number of companies from 4 to 3% indicates a slight increase in production concentration in big companies (Table 5).

Table 5. Structure of production sold and the number of business entities in individual industry sectors related to welding engineering

Sector		SME		Big companies	
		Share %			
		2006	2012	2006	2012
Production of metals	Production sold	14	20	86	80
	Number of entities	85	89	15	11
Manufacture of metal products	Production sold	66	64	34	36
	Number of entities	96	97	4	3
Production of equipment and machinery	Production sold	42	49	58	51
	Number of entities	94	94	6	6
Production of electric appliances	Production sold	30	22	70	78
	Number of entities	89	88	11	12
Production of cars	Production sold	12	9	88	91
	Number of entities	86	77	14	23
Production of other transport equipment	Production sold	22	26	78	74
	Number of entities	85	85	15	15

The sector referred to as “the manufacture of metal products” is one of the greatest users of welding technologies as well as of welding equipment, consumables and all types of services related to the production of welded structures and products (e.g. NDT, examination etc.).

Impact of economic fluctuations on the market of welding equipment and consumables

The fluctuations in economy were reflected in the production, export, import and demand for welding equipment and consumables. The economic downturn of 2009 affected mostly the national manufacturers of welding equipment and components, the production sold of which in 2009 fell in comparison with 2007-2008 by approximately 50%. A smaller, approximately 30% decrease affected the so-called market of welding equipment and components (production – export + import) as companies purchased both domestic and imported equipment (Fig. 8).

While comparing data presented in Figures 5 and 8 it is possible to notice that the sales dynamics in the sectors of industry utilising welding techniques does not directly translate to the dynamics of demand for welding equipment. As opposed to the slump of 2009, indicated by a significant decrease in demand, the economic upturn was not reflected in the dynamics of equipment purchase.

In fear of sales fall companies in the years which followed did not invest in new welding equipment. Consequently, the equipment market value of 2012 was lower by approximately 28% than that of 2006. For domestic manufacturers, a smaller demand for welding equipment was compensated by an

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increase in export, which in 2012 exceeded that of 2006 two times. In the years 2006 – 2012 the import of welding equipment remained stable, with fluctuations not exceeding 18% (Fig. 8).

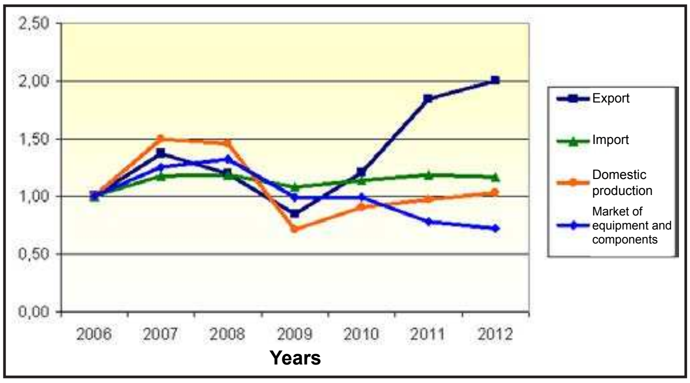

Fig. 8. Dynamics of production, import, export and market of welding equipment (market = production + export - import). Year 2006 = 1

The dynamics of electrode market shows that after 2010 the production and export of covered electrodes suffered from a decline. An increase in import did not compensate for such falls. As a result, the consumption of electrodes in 2012 was approximately 50% lower than that of 2006. The decrease in electrode consumption results from the number and types of welded structures (less welding on assembly due to investment reductions) as well as from the general tendency to replace MMA welding with welding utilising solid wire electrodes or flux-cored wires (Fig. 9).

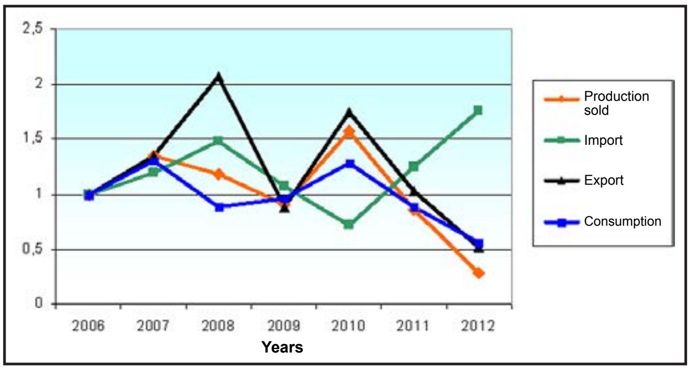

Fig. 9. Dynamics of covered electrode market according to mass. Year 2006 = 1

The market of flux-cored wires reacted to economic downturn both in 2009 and 2012. However, the increase in production and export as well as the growing tendency of flux-cored wire consumption in the years 2009 –2012 should be viewed with optimism (Fig. 10).

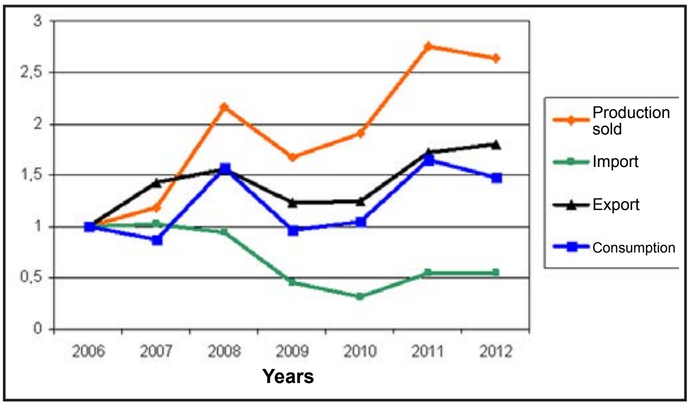

Fig. 10. Dynamics of flux-cored wire market according to mass. Year 2006 = 1

The diagrams presenting the data related to the market of covered electrodes and flux-cored wires indicate that in the period of economic fluctuations entrepreneurs respond to demand for welding consumables otherwise than they do in terms of welding equipment. An economic downturn-triggered decrease in demand for welding consumables was not as deep as that related to welding equipment. Enterprises do not need to invest in new equipment, yet they have to purchase wires and electrodes to joint elements making a commissioned and designed structure.

In the future the use of welding consumables may not indicate the scale of welding technologies application as modern methods such as laser welding, electron beam welding etc. enable joining elements without using welding consumables.

Summary

Welding engineering, due to its scale, significantly affects the national economy. More than 40 various welding methods and approximately 100 variants of these methods find applications in the production of welded structures and in the manufacture of welded products in over 100 industries of the Polish economy. Industrial processing includes 24 industry sectors out of which 6 (i.e. the manufacture of metals,

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metal products, equipment and machinery, cars, trailers and semitrailers, other transport equipment and electric appliances) consume approximately 95% of rolled products. These products are processed into finished goods using, among others, welding technologies in approximately 8 thousand companies representing industry and building engineering. It is estimated that, depending on the economic situation, welding sector employs between 120 and 180 thousand workers.

Conclusions

1. The market fluctuations of 2006-2012 were reflected in the welding industry; their indicators being, among others, changes in the consumption of rolled products, number and structure of companies using welding techniques, value of production sold and that of production added as well as demand for welding equipment and consumables.

2. In the crisis year of 2009 the consumption of rolled products processed into finished goods by means of, among others, welding techniques fell by 36% in comparison with 2007. In spite of the economic revival of 2010-2011 the consumption did not reach the base level of 2006. The reason for this was another economic downturn of 2012.

3. In the years 2006-2012 the consumption of rolled products rose in 3 out of 6 economic sectors, i.e. in the manufacture of metal products from 34.8% to 42,2%, in the production of cars from 3.4% to 3.9% and in the production of electric appliances from 0.6% to 0.9%. These sectors are characterised by greater resistance to economic fluctuations and by high sales growth dynamics.

4. The manufacture of metal products and the production cars, trailers and semitrailers have the greatest, among 6 sectors analysed, share in the gross added value generation structure. In 2012 this share amounted to 7.7% and 5.7% respectively.

5. In 2006-2012 the number of business entities in 6 industry sectors grew by 200. In terms of employment the structure of companies did not change. Small and medium enterprises (employing up to 250 workers) made up 93%, whereas big companies (with employment exceeding 250 workers) constituted 7% of the total number of companies.

6. As regards the manufacture of metal products (as opposed to other sectors analysed), it is SMEs, and not the big companies, that played the leading role in the size of production sold. The share of SMEs in the sales structure amounted to 66 and 64% in 2006 and 2012 respectively.

7. The periods of economic downturn particularly severely affected the demand for welding equipment. As regards welding engineering the sales dynamics increase in 6 most important industry sectors did not translate to growing demand for welding equipment. In 2012 the value of welding equipment market did not reach the level of 2006.

8. The dynamics of flux-cored wire consumption is on the increase. The consumption of covered electrodes is fluctuating, yet a falling tendency can be observed.

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