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Effect of Pipe Butting Face Preparation on the Quality of Magnetically Impelled Arc Welded Joints

Abstract: The article presents magnetically impelled arc welding – a technology used when making butt joints mainly of elements having circular cross-sections. In addition, the articles indicates issues related to the preparation of pipe faces and its effect on the quality of welds. The research-related experiment involved the use of selected power transmission elements. The research also included the performance of visual, geometry, metallographic, functional and technological tests of the joints as well as the determination of critical imperfections disqualifying the use of welded joints.

Keywords: surface preparation, Magnetically Impelled Arc Butt welding (MIAB), butt joints, quality of welding processes

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Introduction: Magnetically Impelled Arc Butt Welding

The technology of magnetically impelled arc butt welding (MIAB welding) was developed by E. O. Paton Electric Welding Institute in the 1950-1960s [1-3]. The technology was launched commercially under the name of *Magnetarc* by the KUKA Company [1], the leader, and in some industrial sectors, because of its technological advantage, even a monopolist, in the production of complete welding machines. The 1970s and 1980s saw the most intensive research dedicated to the above named process leading to technological approvals by European and global institutions as well as to the implementation of the MIAB welding technology in the production of many structures of critical importance [3]. When it comes to the automotive industry, particularly often using MIAB welding, typical applications of the technology include the production of drive shafts, axles, fuel tank bleed lines or shock absorbers. Increasing requirements of the automotive industry combined with the progressing optimisation of MIAB welding as well as automation, robotisation and advanced control methods, led to a change in the technology of manufacturing drive transmission elements having walls of thicknesses ≤ 3 mm [4]. In Poland, GKN Driveline was the first company to replace the previously used technique of friction welding with MIAB welding when manufacturing drive

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references (half-shafts and shafts). Before that, research on the MIAB technique was conducted by Instytut Spawalnictwa [3,5-7].

Joint Formation Mechanism

Magnetically impelled arc butt welding is used primarily when making butt joints, usually of thin-walled elements having circular cross-sections. Heat necessary to plasticise butting faces of elements being welded is obtained from electric arc forced to rotate by an external magnetic field (Fig. 1). The magnetic field can be generated by coils (or permanent magnets) controlling the flow of current and enabling the stepless control of welding processes [2]. The rate of electric arc rotation may reach 200 m/s, making it possible to uniformly heat the edges of components being welded [1,3,8].

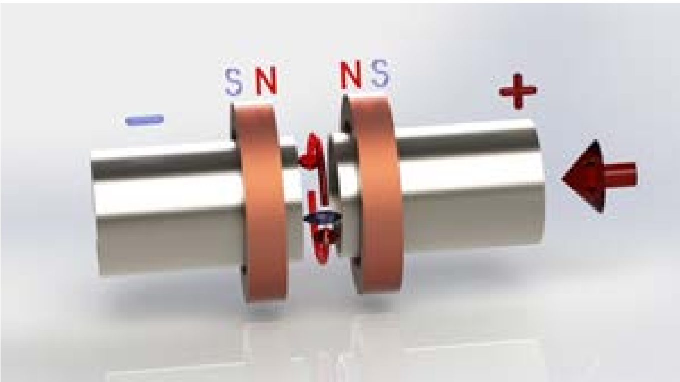

Fig. 1. Concept of making joints using MIAB welding [3,8-10]

The formation of MIAB welded joints is described in publication [8]. The rotation of electric arc is determined by the radial component of the magnetic field. In order to obtain the above named radial component, coils (or permanent magnets) must face each other with the same magnetic pole. The rotation of arc results from the effect of Lorentz force (1) generated through the interaction of arc with the magnetic field.

$$\vec{F} = \overrightarrow{IdL} \times \vec{B} \qquad (1)$$

where
$\vec{F}$ – Lorenz force affecting electric arc,
$\overrightarrow{IdL}$ – current element being the product of the current vector and electric arc length (gap width),
$\vec{B}$ – vector of magnetic induction.

As can be seen from the dependence presented above, the rate of arc rotation (dependent on Lorentz force) is a parameter which can be controlled in a number of manners, e.g. by changing current flowing through coils or by changing welding current or the width of a gap. This enables maintaining an appropriate arc rotation rate in each phase of a cycle, making it possible to minimise the effect of the heating of the material causing the changes of its magnetic and electric properties as well as changes of surface.

Electric arc travels at a constant rate if resultant force amounts to zero (Newton's first law). In practice, electric arc is affected by Lorentz force and resisting force. Assuming that resisting force (F_o) is directly proportional to velocity, current element $\overrightarrow{IdL}$ is perpendicular to the magnetic field and the cross-sectional area of electric arc is constant, it is possible to write:

$$ILB\text{-}F_0=0 \qquad (2)$$

using Ohm's law:

$$\frac{U}{R}LB - av = 0 \qquad (3)$$

and taking into consideration the electromotive force of induction:

$$\frac{U_0 - \varepsilon}{R}LB = av \qquad (4)$$

as well as Faraday's law of electromagnetic induction (relationship between induction electromotive force and arc rotation rate):

$$\frac{U_0 - LBv}{R}LB = av \qquad (5)$$

arc rotation rate in the function of induction and arc length can be calculated using the following dependence:

$$v(B) = \frac{U_0 LB}{Ra + L^2 B^2} \qquad (6)$$

$$v(L) = \frac{U_0 B}{\rho a + LB^2} \qquad (7)$$

where

F_0 – resisting force affecting electric arc,
U – voltage present in electric arc,
U_0 – maximum voltage of the power source,
ε – induction electromotive force,
a – resisting force coefficient,
v – electric arc rotation rate,
ρ – resistance of electric arc per a length unit.

Curves related to the dependence of arc rotation rate in the function of arc length and induction are presented in Figure 2 [8]. An increase in magnetic induction, coming both from supply voltage and current flowing through coils, affected directly two correlated physical quantities present during the process, i.e. Lorentz force and induction electromotive force, the sign of which was contrary to supply voltage. An increase in magnetic induction was accompanied by an increase in arc rotation rate until reaching a maximum where the electromotive force of induction directly related to the rate of rotation became dominant over supply voltage. After reaching its maximum, arc rotation rate decreased, approximately inversely proportional to the square of magnetic induction (Fig. 2a). In turn, an increase in the length of arc was accompanied by a decrease in the rate of rotation. In terms of small gaps, the decrease was relatively steep, as opposed to longer arcs, where changes were not so significant (Fig. 2b).

The process of MIAB welding is usually divided into 4 principal stages (Fig. 3) [1-12]:

a) positioning and fixing of elements in fixtures. At the beginning of the process, butting faces come into contact followed by the flow of coil current.
b) Flow of current through the interface and the formation of a gap between elements in order to ignite electric arc.
c) Rotation of electric arc (2-3 s, depending on the area of cross-section) plasticising the surfaces of elements to be joined.
d) Discontinuation of current flow and the termination of electric arc followed by the exertion of upsetting pressure.

After welding it is possible to perform the heat treatment of the joint (e.g. reheating performed using electric current).

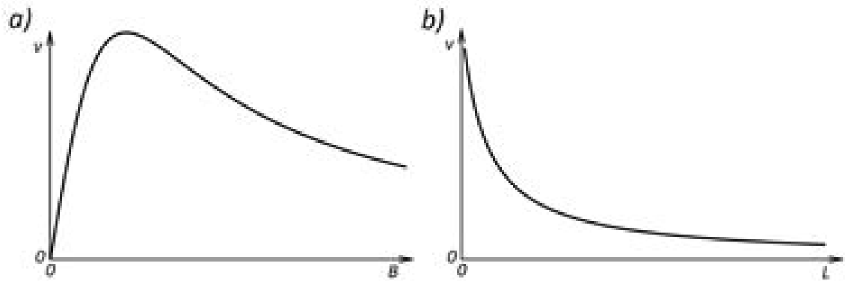

Fig. 2. Dependence of electric arc rotation rate on a) magnetic induction radial component and b) arc length [8]

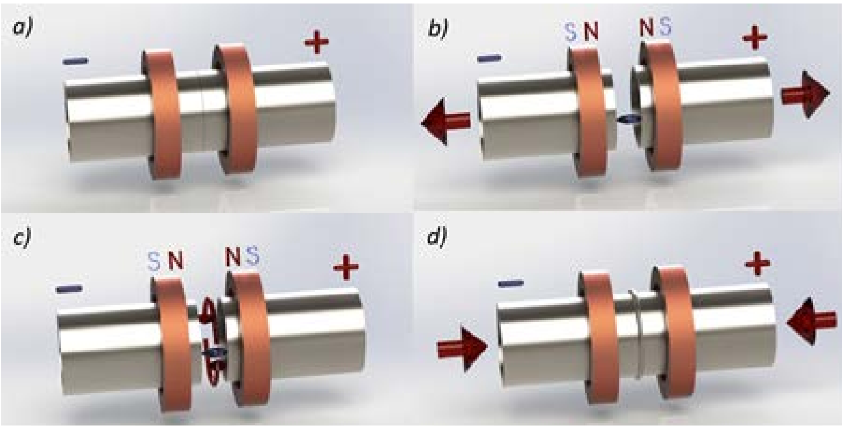

Fig. 3. Stages of Magnetically Impelled Arc Butt Welding [3,4,8]

Preparation of Elements for Magnetically Impelled Arc Butt Welding

The preparation of elements to be joined using MIAB welding does not differ significantly from other butt welding preparation techniques, yet, in the automotive industry, due to thin-walled elements, it should be performed very accurately. This remark concerns not only the butting face, but also the entire joint geometry. It is of great importance that manufactured or delivered components always be characterised by geometry consistent with related technical documentation. This also applies to removing any post-treatment residues (e.g. burrs, grease, coolants etc.). Directly before the process of welding, elements should be subjected to chemical cleaning aimed to remove all impurities. In cases of low quality-related requirements, surfaces to be joined can be prepared using classical, i.e. mechanical or thermal, cutting methods. In cases of more restrictive quality requirements, edges of elements should be previously carefully prepared as any inaccuracies may lead to the formation of welding imperfections in welded joints. Figure 4 schematically presents theoretical assumptions concerning the preparation of elements before welding. In cases of thin-walled elements, the importance of these processes is even greater and requirements very restrictive. Bevelling is necessary when joining elements of highly varied thicknesses, where minimum flash is allowed and in cases of elements having massive cross-sections.

Preparation of Welded Specimens for Tests

Components ordered by Gkn Driveline are delivered in various finishing states. Order-accompanying documentation specifies requirements related to the condition and shapes of elements ordered externally, e.g. the lack of chips, burrs or oil on elements. In order to satisfy the requirements of the ordering party, the supplier can order additional operations enabling the achievement of the required condition of surface and geometry. Unfortunately, such operations may negatively affect the quality of joints, of which sub-suppliers are not often aware. In addition, it is important to properly protect processed components for transportation and storage.

The analysis of the Ishikawa diagram, presenting the problems related to the assurance of the required quality of welded joints, clearly indicates the preparation of components as the potential factor generating errors. In order to assess the effect of the condition of butting faces of components on the quality of welds, elements used in the production were prepared in a manner reflecting actual imperfections generated by sub-suppliers. The analysis involved an entire tubular shaft assembly (tsa) (Fig. 5), composed of a pipe having a 1.5 mm thick wall and two terminals, i.e. a joint and a stubshaft finished with splines. The pipe (steel c22), on the side of the joint (steel uc1), contained simulated critical surface imperfections; in fact, both terminals were made properly, in accordance with the guidelines of the ordering party. Welding parameters for all the joints were the same and consistent with the welding procedure applied. The analysis of actual production-related cases was followed by the selection of the following pipe edge preparation manners (Fig. 6):

- phase on the internal edge of the pipe 1×45° and 0.5×45°,
- phase on the external edge of the pipe 1×45° and 0.5×45°,
- damaged external edge,
- damaged internal edge,
- cuts along the edges,
- oiled surface.

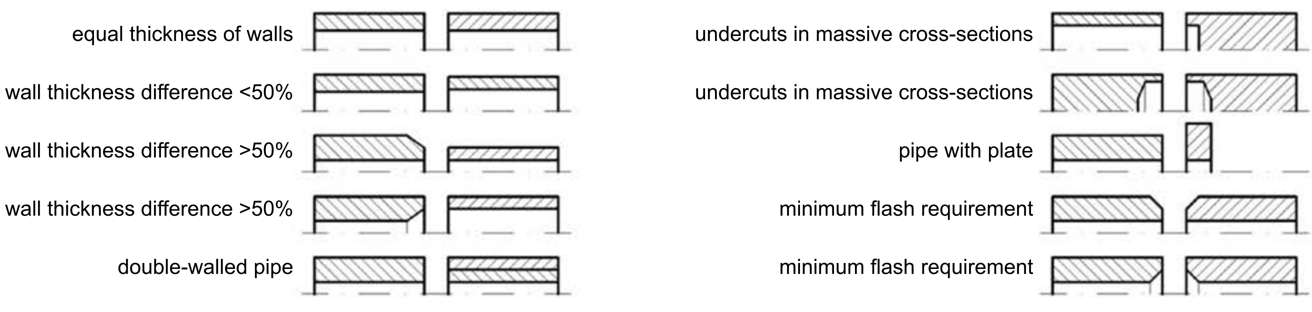

Fig. 4. Possible pre-weld preparation variants [11,12]

Fig. 5. TSA subjected to analysis

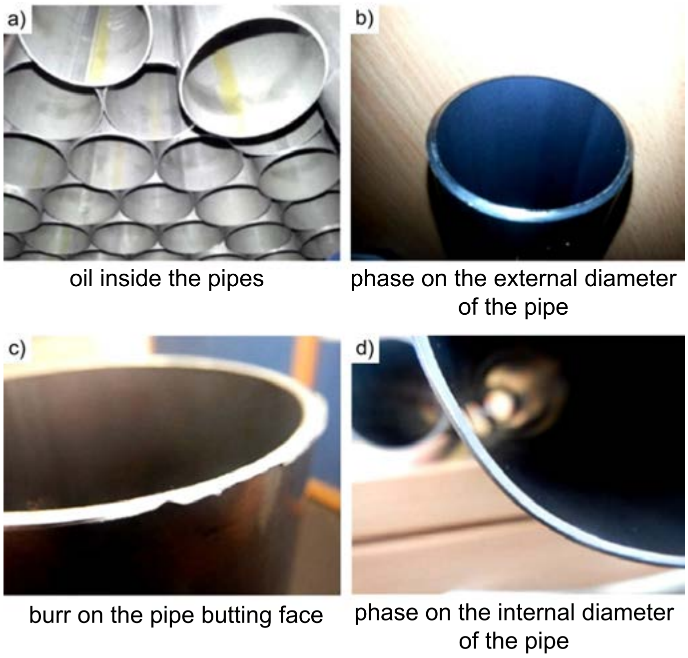

Fig. 6. Exemplary imperfections simulated on pipe butting surface

Visual Tests

Visual tests involved both the internal and external sides of the welds, after previously cutting them out of the element. Because of the fact that no other welding imperfections were detected, the analysis was only concerned with the shape of flash, unremoved after the process of welding. A proper weld is presented in Figure 7a. Most of the joints had a characteristically shaped flash, the so-called "fish-mouth", on fragments of the weld circumference (Fig. 7b). This was the effect of upsetting and in most cases did not turn into a crack. The "fish-mouth" was formed in the central part of the weld, at the edge of the flash, yet in some cases the shift in the direction of one of the parts was observed. The bevelling on the external side caused the formation of an irregular and narrower flash (Fig. 7c). In turn, internal necks resulted in the formation of wide and uneven flash with numerous areas where greater amounts of the material were ejected (Fig. 7d). The width of the flash was directly proportional to bevelling dimensions. Necks, regardless of their location and size, additionally contributed to the formation of spatters (Fig. 7e). The simulated damage to the pipe caused significant deviations of the weld plane (Fig. 7f) and local imperfections (Fig. 7g). It should be noted that in the company practice, irregular flash is not the basis for the withdrawal of an element from the cycle of production as long as the excessive dimensions of the flash do not create problems related to the fixing of a finished component or its combined operation with other elements.

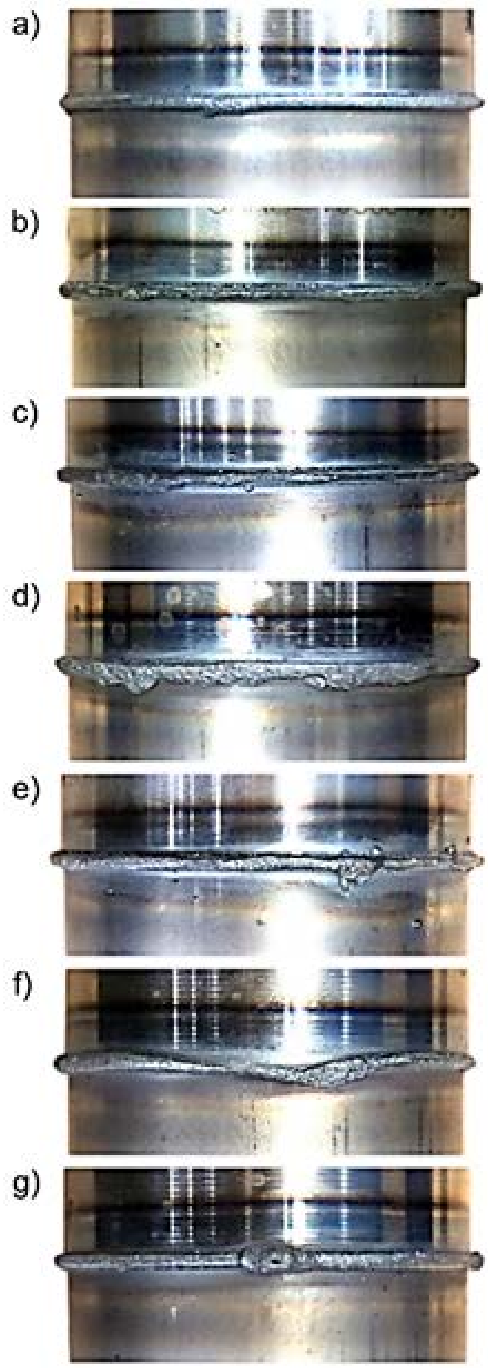

Fig. 7. Effect of pipe butting face preparation on the shape of flash

The oiling of the butting face led to the formation of tarnish resulting from the combustion of lubricant/coolant. Even if the operating parameters of joints are appropriate, the tarnish causes the elimination of a given element from further production (Fig. 8).

The analysis of the internal flashes revealed numerous shape irregularities and areas of potential welding imperfections (Fig. 9), i.e. spatters and the so-called "fish-mouth", often irregular and having variable widths. The internal side was less regular and homogenous than the external side, where existing deviations were rather local in nature. The test consisting in the making of longitudinal cuts, starting on the pipe butting face, due to the heating of the pipe, precluded the obtainment of a proper joint. This confirmed the necessity of using closed sections when performing magnetically impelled arc butt welding.

Macroscopic Tests

In order to perform the macroscopic tests, it was necessary to cut the rings embracing the joints and heat affected zones into 4 parts, using the criterion of cutting the plane of the greatest run-out (base plane) and the planes oriented in relation to the base plane by the n-tuple of 90°. In the case of the analysis of the elements with the damaged edge, the base plane was the area of damage.

Figure 10 presents selected microscopic photographs. All of the structures contained the "fish-mouth" formation. In some cases, indentations were clearly visible and sharp, resembling the area of a potential notch (Fig. 10a). Functional tests [4] performed by GKN Driveline did not confirm this hypothesis, as even in cases of critical stresses, the rupture took place outside the joint. Figure 10b presents the possibly significant size of flash in relation to the entire joint. Figures 10c and d present improper joints caused by the deformation of the pipe. This is the effect of the simulated damage to the internal (c) and external (d) edges of the element.

Fig. 8. Effect of the welding of oiled butting faces of elements

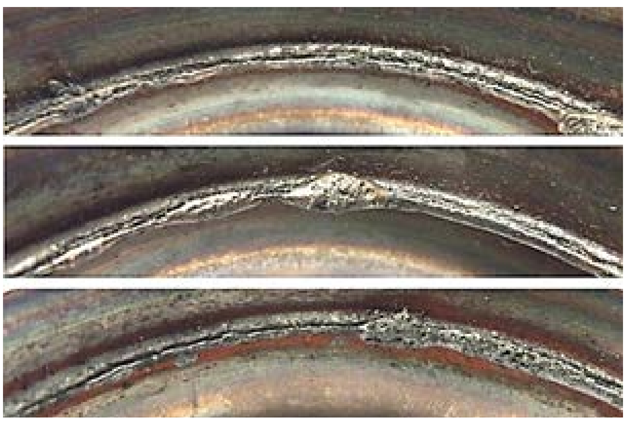

Fig. 9. Outside view of selected joints

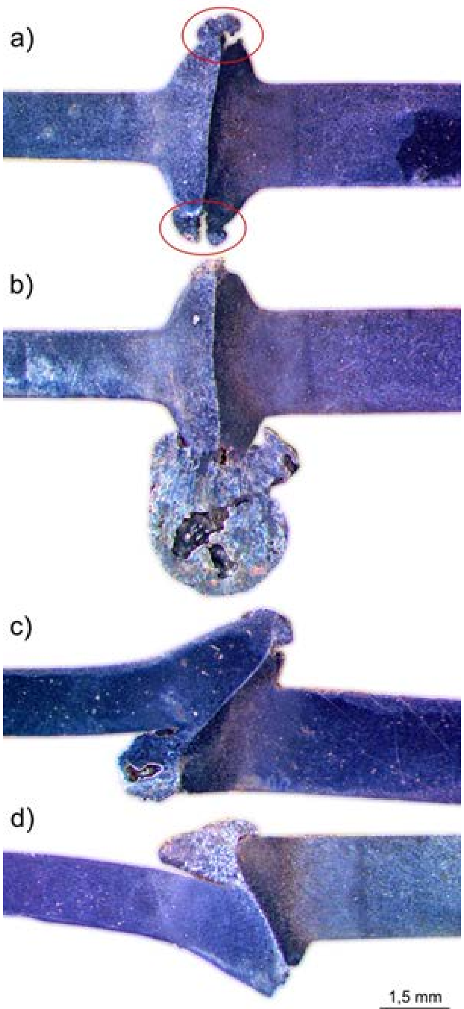

Fig. 10. Selected macroscopic photographs of the welded joints

The photographs were not taken in the area of the imperfection but in the planes perpendicular to the imperfection area. The macroscopic tests did not reveal any other imperfections apart from shape-related errors.

Measurements of Weld and Flash Angles

Macroscopic photographs were used for measuring angles of the weld. The weld angle is the measure of the perpendicularity of the weld line in relation to the axis of symmetry of elements being welded (pipe and terminal components) [4]. The improper angle measure, directly related to the length of the weld may result in the presence of metal oxides, which in properly made joints would be pushed outside. For this reason, it is desirable for the angle of the weld line to be as close to 90° as possible. In addition, it is necessary to measure the angle of flash, which, due to the possibility of mechanical notch formation, should be obtuse [4]. Each specimen was subjected to weld and flash angle measurements, from the internal and external side, in four cross-sections (Fig. 11).

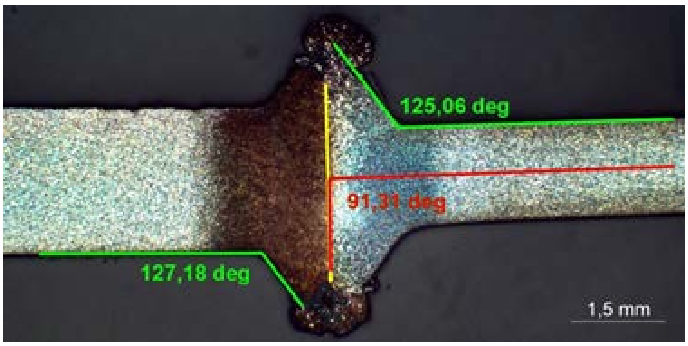

Fig. 11. Measured weld and flash angles

All of the simulated defects translated negatively into angle measurement results. Significant circumferential irregularities and the scatter of values for individual planes oriented every 90° were observed. An increase in the phase size was accompanied by an increase in the scatter of results (e.g. for the angle of flash as many as 30°). The damage to the pipe edges changed the geometry of the welds so significantly that it was often difficult or impossible to perform measurements. The greatest deviations of symmetry were not present in the area of damage, which indicated the negative effect of the improper preparation of the butting faces of the elements on the quality of the welds around the entire circumference. The lack of joint symmetry indicated the potential error of the geometry of the element. The results of weld angle measurements were reflected in additionally performed measurements concerning post-weld lengths of the elements. The value of flash angle was inversely proportional to the length of the element.

Microscopic Tests

The microscopic tests did not reveal any significant structural differences in relation to various manners of pipe butting face preparation. The HAZ microstructure on the pipe side was transformed if compared with that of the base material and was composed primarily of ferrite and pearlite. The fusion zone contained hardening lath martensite with a structure having features of Widmanstätten ferrite. The line connecting the joint and the pipe was clearly visible (Fig. 12). The HAZ on the joint side was slightly wider than the HAZ of the pipe and contained several characteristic zones. The structure closest to the fusion line was composed of martensite of diversified morphology. Behind the above named structure there was a zone consisting of sorbite and hardening troostite with precipitates of granular ferrite. The areas closer to the base material revealed the growing

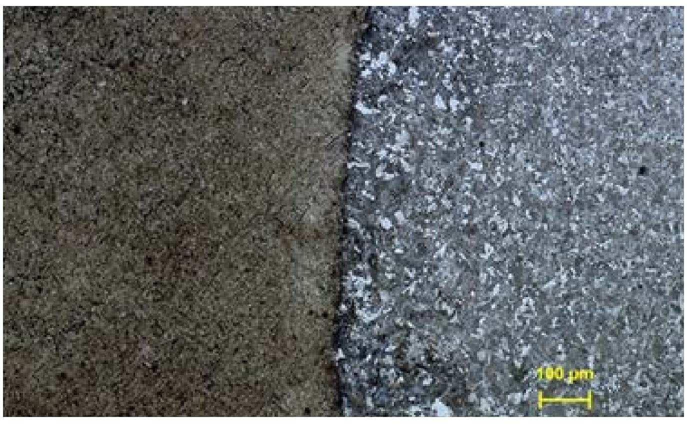

Fig. 12. Microstructure of the joint-pipe welding line

content of ferrite and the decreasing content of martensite. The area closer to the joint material contained fine-dispersive granular pearlite and ferrite, having smaller-sized grains if compared with those of the base material.

Hardness Tests

Hardness measurements were performed using the Vickers hardness test, in accordance with the company practice, under a load of 1 kg. The first measurements were performed 0.1 mm away from the weld line, whereas the subsequent measurements were made every 0.2 mm, in the direction of the base material. Similar to the microstructural analysis, no hardness changes in relation to various manners of pipe butting face preparation were observed. The hardness of the pipe material amounted to approximately 230 HV1, yet approximately 1.5 mm from the weld line (the beginning of HAZ), because of a lower carbon content, amounted to 170 HV1. Near the weld line, the hardness reached >200 HV1. On the other side of the interface of the materials, i.e. in the HAZ on the joint side, hardness significantly rose above 600 HV1. Further measurements in the direction of the joint revealed decreasing hardness, reaching stability 1.5÷2.5 mm away from the weld line, i.e. where the HAZ of the joint finished and the base material started. Only in the case of simulated damage to the surface of the pipes, slightly higher HV1 values in the HAZ near the weld line were observed, probably caused by the different distribution of heat during welding (Fig. 13).

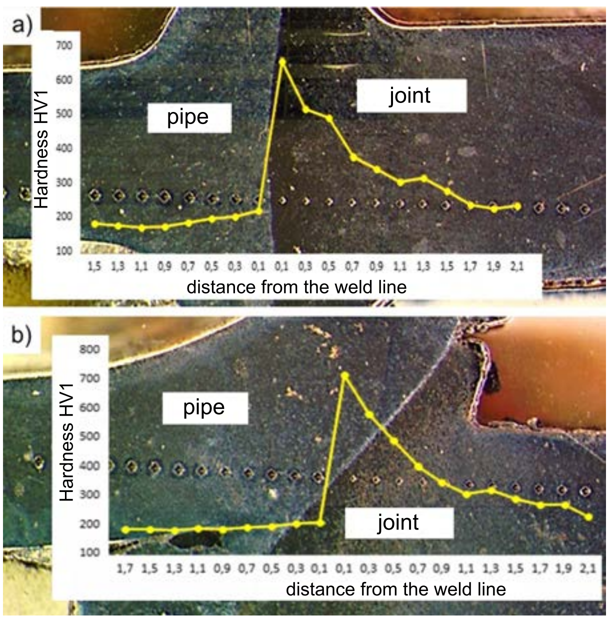

Fig. 13. HV 1 hardness measurement results: joint with internal phase 0.5×45° (a), joint with damaged external edge (b)

Summary

The analysis aimed at assessing the effect of the improper preparation of the butting face of elements to be welded (in this case, pipes) on the quality of welded joints. The welds were subjected to tests performed in accordance with the company procedures of GKN Driveline [4] performing geometrical measurements (of the length and run-out), metallographic examinations (macro and microscopic tests), measurements of angles of welds/flashes and hardness measurements. The extensive scope of the tests made it possible to determine the effect of pipe edge condition on shape-dimension dependences and on the properties of the welds obtained. The test results led to the identification of the critical values of tested quantities consulted with component suppliers. Elements, which were not eliminated from further tests on the basis of the above-presented analyses, were subjected to functional and technological tests (bend and torsion tests). Each time, the test results were proper, which indicated the dependence of the geometry and structure of the joints on their operating parameters.

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PBS Program Badań Stosowanych

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