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# INVESTIGATIONS OF THE QUALITY OF WELDED JOINTS OF PIPES FROM STEEL OF ASTM A106/API 5L GRADE, USING MAGNETICALLY IMPELLED ARC BUTT WELDING

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**ABSTRACT**

Magnetically impelled arc butt welding (MIAB) is a welding process applied for joining pipes with an external magnetic field, which influences the arc displacement in a narrow gap between the pipe ends. This welding process consists of a complex interaction between the electric arc, external magnetic field and upset value. In this work, investigations were performed on MIAB welding of seamless pipes from carbon steel of ASTM A106/API 5L grade, which is used in electric power plants, boilers, petrochemical plants, petroleum processing plants and ships, where the pipeline should transport fluids and gases under high pressure and temperature. The experimental procedure includes a range of tests for development and assessment of the knowledge base on MIAB welding of seamless pipes. Then mechanical testing of MIAB welded joints of ASTM A106/API 5L sample was performed to assess its strength and weld integrity in keeping with API 1104 standard. In addition to investigations, a conceptual specification of MIAB welding procedure and protocol of welding procedure qualification for welding pipes and their further application were developed and presented. The experimental results emphasized that the MIAB welded joints demonstrate the high strength and good integrity of the weld on the level of the pipe base metal. Thus, MIAB welding can be regarded as the future fast and cost-effective welding process without expensive use of filler materials and shielding gas.

**KEY WORDS:** pressure welding, magnetically impelled arc, seamless pipes, carbon steel, welded joints, mechanical properties

## INTRODUCTION

Magnetically impelled arc butt welding (MIAB) is an improved welding process, which is an alternative to such processes as friction, resistance and flash-butt welding. MIAB is a solid-state process of pressure butt welding of steel pipes and tubular pars [1–3]. In this process, the axes of the pipes clamped in the machine are aligned, and their ends are heated by the arc, rotating in the gap between the two pipes. Arc formation and its rotation speed are controlled by the magnetic force of the radial component of induction of the controlling magnetic field as a result of interaction of the arc current and the magnetic field in the gap. A scheme of magnetic control of the welding arc movement in the narrow gap of the pipes being welded was developed. The arc heats the pipe ends, causing a localized small band of melting and neighbouring softening in the HAZ, and then the pipes are upset to form a welded joint [4].

At MIAB welding the controlled magnetic field moves the arc in the gap between the pipe edges, as shown in Figure 1. Two pipes, ready for welding, are mounted coaxially. The magnetic systems, installed one opposite the other, form magnetic flows in the arc gap. The welding arc is excited by a short-circuit. The pipes to be welded are separated to create a certain arc gap (from 1.5 to 2.1 mm). The interaction between the axial component of welding arc current and the radial magnetic component, directed normal to the welding arc current, generates a force. This force moves the welding arc along the pipe ends. MIAB welding uses preprogrammed control of the arc current with arc movement, which may reach the linear speed of 270 m/s. This allows achieving uniform heating of the pipe ends, thus ensuring a sound welded joint. In this study, a model of MD 101 and MD 205 machine, developed at PWI, as shown in Figure 2, was used for welding seamless pipes, operating at high temperatures.

Determination of the respective welding parameter combinations for weld quality and strength, can be a lengthy process, associated with the essential trial-and-error method, starting from analysis of the preliminary specification of the welding procedure, and then making a test welded joint for performance of nondestructive and destructive testing, such as mac-

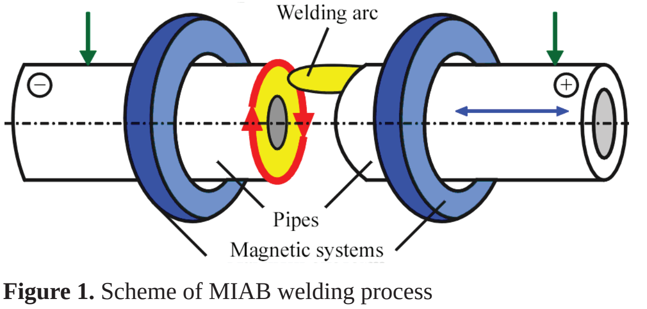



**Figure 1.** Scheme of MIAB welding process

**Figure 2.** MD-101 machine for MIAB welding of pipes

ro- and microetching for metallographic studies and tensile tests. Welding procedure specification (WPS) for MIAB is established on the base of a certificate of welding procedure approval, signed by an authorized person, such as a welding engineer, and appended to the qualification record of the welding procedure for the material to be welded [5]. In welded joint production, a written specification of the welding procedure is the “recipe” for achieving a certain weld quality, which corresponds to standard manufacturing requirements, such as API 1104.

Some studies on MIAB welding were performed. As this process is considered to be relatively new, there are very few publications on MIAB welding application in power plants, boilers, petrochemical plants, oil-and-gas plants and ships, where the pipeline should transport fluids and gases at high pressure and temperature. Taneko A., et al. [6] used voltage detector in different points inside the pipe from alloyed steel, an oscillograph and a high-speed video camera to measure the arc speeds and angles. In particular, they studied the interaction between the arc speed, its angle and the position, in which power is fed to the pipes. They came to the conclusion that because of the arc impact and the low electric resistance of the pipe, the arc current rises closer to the fastening connector on the pipe. Leigh F., et al. [7] presented a new perspective opened by the project of development of this technology introduction in the sector of new pipeline construction in Australia. In this study a prototype of MIAB welding machine was designed and built, which is capable of welding natural gas pipelines of 150 mm diameter, meeting the requirements of Australian oil pipeline standard AS2885.2. The results of investigations, conducted by Kachinskyi V.S., et al. [8], demonstrated the rationality of practical application of MIAB process for welding pipes and pipelines from steel X70. Edson D. [9] outlined the typical industrial applications in the automotive industry — MIAB welding for joining parts in the rear axle cover of Ford Transit car, which has two circular and two square butt welds. In works by Kachinskyi V.S., et al. [10] the results on weldability of car parts are given. The possibility of welding compact hollow car pars was studied, such as steering rod of the diameter of 22×2.2 mm, shock-absorber of the diameter of 40×2.2 mm. Beginning from 1994, MIAB-welded pneumatic springs and shock-absorbers, were manufactured in automobile plants, where more than 7.4 mln welded joints were made.

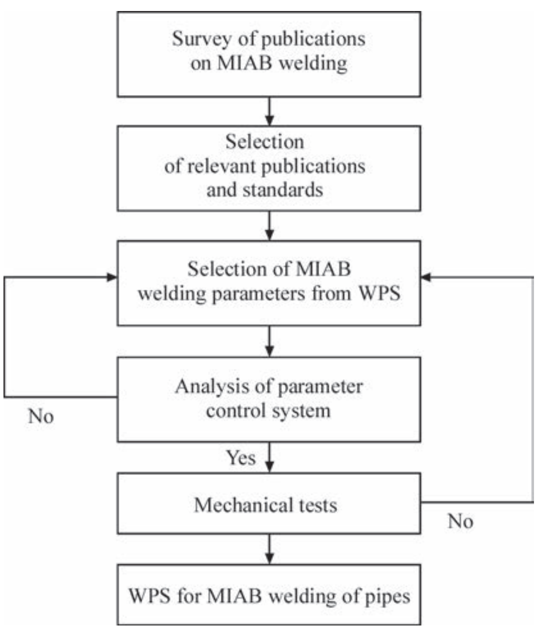



**Figure 3.** Block diagram of the study

MIAB welding application in manufacture of components for truck cabs of Thyssen Krupp Automotive Systems Company was described by Hiller F., et al. [11]. Jenicek A., et al. [12] demonstrated that tubular hollow bodies, such as nuts, sleeves and bushings, can be fastened to sheets using this process with particularly high cost-effectiveness. Expanded devices for welding by arc-like pins were used to weld aluminium components with internal thread between M8 and M24 to perforated sheets. Mori S., et al. [13] evaluated the rationality of the process of MIAB welding with aluminium and aluminium-copper joints. In this structure it was difficult to achieve the required density of the magnetic flow in the butt with nonferrous materials, compared to ferrous materials. Therefore, a ferromagnetic rod was often placed inside the tube. In the study, information about the MIAB welding method developed for welding nonferromagnetic metals, is given, and the conditions and methods of butt welding of tubes from aluminium to aluminium (Al–Al) and to copper (Al–Cu) are investigated.

The work presents the results of the performed studies on MIAB welding of seamless pipes of 42 to 200 mm diameter from ASTM A106/API 5L carbon steel for high-temperature service and production,

**Table 1.** Mechanical properties of ASTM A106/API 5L steel

| Diameter, mm | Wall thickness, mm | Ultimate strength, MPa | Yield limit, MPa | Elongation, % |
|---|---|---|---|---|
| 42.7 | 3.83 | 415 | 294 | 31 |
| 114.3 | 6.02 | 423 | 305 | 37 |
| 168.3 | 10.00 | 429 | 309 | 39 |

**Table 2.** Chemical composition of ASTM A106/API 5L, wt.%

| C | Si | Mn | P | S | Cr | Ni | Cu | Mo |
|---|---|---|---|---|---|---|---|---|
| 0.28 | 0.25 | 1.20 | 0.030 | 0.030 | 0.50 | 0.50 | 0.50 | 0.15 |

which were aimed at development of a specification of MIAB welding parameters for high-temperature seamless pipes. Figure 3 shows the block diagram of the study.

## IDENTIFICATION OF THE PARAMETERS OF MIAB WELDING PROCESS FOR ASTM A106/API 5L MATERIAL

### SEAMLESS PIPES FROM ASTM A106/API 5L CLASS B, OPERATING UNDER PRESSURE

In this study ASTM A106/API class B material was used. It was specially developed for application in electric power plants, boilers, petrochemical plants, oil-and-gas plants and ships, where the pipelines should transport fluids and gases, having high pressure and temperature. This material lends itself to bending, flanging and similar forming operations. Mechanical properties and chemical composition of this material are given in Tables 1 and 2, respectively.

### PRELIMINARY SPECIFICATION OF THE WELDING PROCEDURE

Preliminary specification of the welding procedure is an important step in WPS. This is a document, which includes the required variables of welding procedure, which must be qualified, in order to create a qualified welding procedure specification. At this stage, selection of current, time, upset pressure and arc gap is, mainly, performed by trial-and-error method in the welding machine. The research engineer also refers to the manufacturer recommendations as to the parameters. First visual examination of the welded joint is performed for five sets of process parameters. General comments for each test are given in Table 3.

The result shows that a good weld with uniform penetration is produced in the case of weld 5, as shown in Figure 4.

**Figure 4.** Uniform formation of the welded joint

**Table 4.** Results of rupture testing of the welded joint of pipes of ASTM A106/API 5L grade

| Outer diameter, mm | Thickness, mm | Cross-sectional area, mm$^2$ | Yield limit, MPa | Ultimate strength, MPa |
|---|---|---|---|---|
| 42.7 | 3.83 | 467 | 344.93 | 459.88 |
| 114.3 | 6.02 | 2048 | 351.28 | 448.93 |
| 168.3 | 10.00 | 4971 | 354.37 | 461.84 |

**Table 5.** Results of bend tests of the inner and outer surfaces of ASTM A106/API 5L grade material

| Width, mm | Thickness, mm | Test results | Remarks |
|---|---|---|---|
| 25.0 | 3.83 | Satisfactory | No crack in the butt joint |
| 12.0 | 10.00 | Same | Same |

### MECHANICAL TESTING RESULTS

Mechanical tests, such as stretching, bending, rupture, hardness and macroetching, were conducted to API 1104 standard [14]. The rupture nsile testing results are given in Table 4. They show that the sample strength is equal to 459.88 MPa, which corresponds to that of the pipe base metal of 415 MPa, and the sample failed in the base metal, as shown in Figure 5. Absolutely acceptable results proved that the parameters of MIAB process, used for welding of ASTM A106/API 5L material, were correctly selected in terms of technology.

**Table 3.** Trial observation of welded joints on pipes of ASTM A106/API 5L grade

| Test number | Current, A | | | Welding time, s | | | | Upset pressure, bar | Arc gap, mm | Visual inspection |
|---|---|---|---|---|---|---|---|---|---|---|
| | $I_1$ | $I_2$ | $I_3$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ | | | |
| 1 | 230 | 170 | 500 | 1 | 2.75 | 10.5 | 0.18 | 4.5 | 1.4–1.6 | Nonuniform welded joint reinforcement |
| 2 | 230 | 180 | 520 | 1 | 2.6 | 10.5 | 0.2 | 4.4 | 1.4–1.6 | Excessive pressed-out metal in the weld |
| 3 | 230 | 190 | 550 | 1 | 2.6 | 9.0 | 0.2 | 4.3 | 1.4–1.6 | Same |
| 4 | 230 | 210 | 570 | 1 | 2.5 | 8.5 | 0.3 | 4.3 | 1.4–1.6 | ” |
| 5 | 230 | 215 | 600 | 1 | 2.5 | 8.0 | 0.3 | 4.2 | 1.4–1.6 | Sound weld, uniform reinforcement |

**Figure 5.** Rupture testing of a welded pipe sample

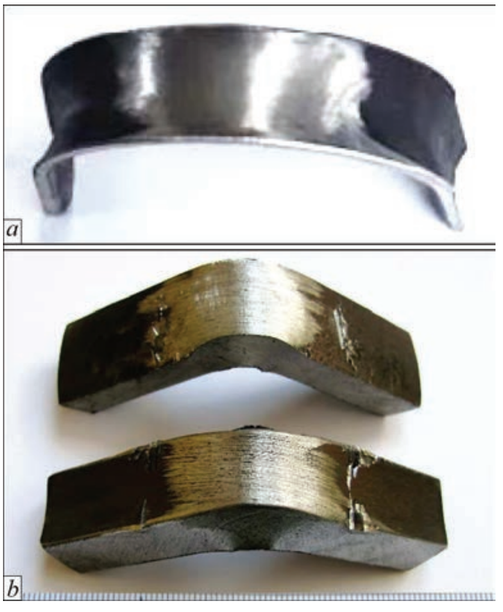


**Figure 6.** Inner and outer bend testing of a welded sample: *a* — pipe of the diameter of 42.7×3.83 mm; *b* — 168.3×10.00 mm

Results of side bend tests for determination of the strength of pipe welded joint are given in Table 5. As one can see from Figure 6, the sample is in an excellent state, without any signs of cracks or defects in the bending zone.

Fracture tests were performed to assess ruptures and defects of the welded sample. As one can see in Figure 7, the sample is in good condition, without porosity or lacks-of fusion on the open surface of the weld.

Hardness was checked in keeping with ASTM E92. Measurement was taken in the weld, HAZ and base metal, using Vickers *HV* 10 method, as shown in Figure 8. The measured values in the test samples were as follows:

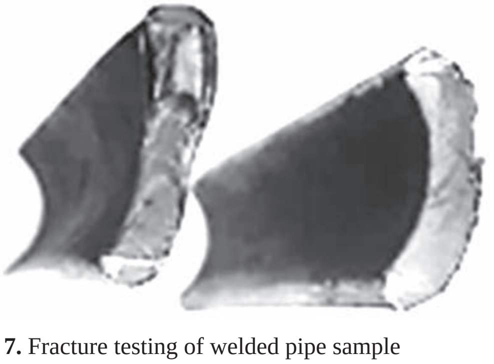


**Figure 7.** Fracture testing of welded pipe sample

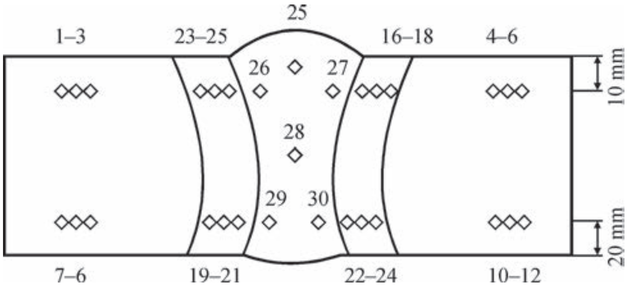



**Figure 8.** Results of Vickers hardness testing of a welded sample: *1* — weld; *2* — HAZ; *3* — base metal

- weld — *HV* 10–183–232;
- HAZ — *HV* 10–153–170;
- base metal — *HV* 10–145–169.

These measurement results proved that the welded joint is made using the optimum selected parameters of MIAB welding [15].

For metallographic testing the sample was prepared and etched from one side to API 1104. Examination revealed that the sample was completely fused and free from cracks, as shown in Figure 9.

## RESULTS AND DISCUSSION

Recording of the welding procedure was performed for actual registration of MIAB process parameters, used for test purposes. Based on visual and mechanical testing, the recording of the welding procedure was further developed into welding procedure specification. In the working environment these parameters change, depending on many factors. So, in WPS the parameters were indicated in the range, which still would have ensured the best welding for this material. Figure 10 shows the parameters of WPS, developed for pipes from ASTM A106/API 5L material.

This information is useful in pipeline design, when engineers often face difficulties in selection of the welding process. It will help determine MIAB welding applicability for pipe industry. The given welding parameters and production data will be useful for application of pipe welding methods in a practical situation. Move over, it will help engineers to avoid mistakes, which may be costly, or to overcome problems, when a welding defect arises in production.

Welding current at MIAB welding can be divided into three stages, and welding time — into four stages. For welding ASTM A106/API 5L pipes of 42.2 mm

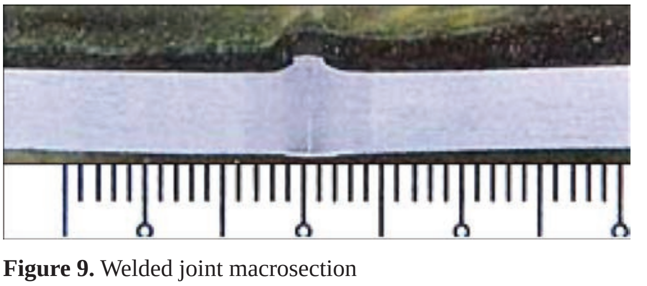


**Figure 9.** Welded joint macrosection

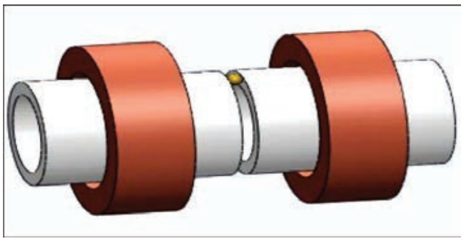
<table>
<tr><td colspan="6">E.O. Paton Electric Welding Institute of the NAS of Ukraine</td></tr>
<tr><td colspan="6">Specification of MIAB welding procedure</td></tr>
<tr><td colspan="3">Specification: API 1104<br>Welding process: Magnetically-impelled arc butt welding (MIAB)<br>Steel grade: ASTM A106/API 5L<br>Group: class B<br>MIAB welding machine model: MD-101; MD-205</td><td colspan="3">MIAB welding WPS No.: PWI WPS/MIAB – 001<br>Process method: Automatic<br>WPS purpose: Procedure for carbon steels<br>Pipe diameter: 40–200 mm<br>Wall thickness: 325–10 mm</td></tr>
<tr><td colspan="3">Joint configuration</td><td colspan="3">Joint parts</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">Joint characteristic</td><td colspan="3">Shielding gases and materials</td></tr>
<tr><td colspan="3">Joint type: butt joint</td><td colspan="3">Shielding gases: not used<br>External blowing – not used<br>Inner blowing: not used<br>Welding wire: not used</td></tr>
<tr><td colspan="6">Welding parameters for pipes of 42.7 mm diameter</td></tr>
<tr><td>Stage number</td><td>Welding current, A</td><td>Welding time t, s</td><td>Arc voltage, V</td><td>Arc gap, mm</td><td>Upset force, kN</td></tr>
<tr><td>1</td><td>220–240</td><td>2.5–2.7</td><td rowspan="3">24–27</td><td rowspan="3">1.6–1.8</td><td rowspan="3">41–44</td></tr>
<tr><td>2</td><td>180–190</td><td>10–12</td></tr>
<tr><td>3</td><td>570–610</td><td>0.2–0.4</td></tr>
<tr><td colspan="3">Prepared by: _______________</td><td colspan="3">Certified by: ______________</td></tr>
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**Figure 10.** WPS for MIAB welding

diameter and 3.56 mm wall thickness current I1 is used for approximately 1 s, during which the welded pipes are briefly compressed up to a short-circuit and the welding rectifier is switched on. T2 (2.4–2.6 s) is the time period during which the short-circuited pipe ends are moved back for the width of the arc gap, which is followed by arc excitation between them. More over, at this time stage the arc starts accelerating in the gap along the pipe ends. During this time period, current I1 (220–240 A) is used. At T3 stage (7–9 s) the arc accelerates and rotates at a relatively high speed along the pipe ends, while heating the pipe end surfaces up to the temperature of plastic deformation to the depth of 4–7 mm. During T3 stage a current of 180–190 A (I2 current) is supplied. The welding cycle is completed by upsetting, which proceeds during time T4 (0.2–0.4 s), with feeding of higher current of 590–610 A. The general time of MIAB welding for this sample is equal to approximately 10–12 s.

From the results of mechanical tests and metallurgical examination of a MIAB welded joint (process parameter is keeping with the fifth test in Table 3) one can understand that quality, strength and hardness are within the admissible limits, as applied in the industry of Ukraine and other countries. These results clearly emphasize that MIAB process is suitable for welding high-temperature seamless pipes.

## CONCLUSIONS

In this study a steel pipe of ASTM A106/API 5L grade was welded by MIAB process, which is usually used under high-temperature conditions. Quality was checked visually and by mechanical testing, to make sure that the weld is sound. The welding process specification was developed for application in the working environment, in compliance with the standard of Ukraine and other countries. The following conclusions were made from this research:

- using MIAB process the welding time can be shortened by 80 %, compared to the conventional welding process;
- MIAB welding requires simple surface preparation and does not require any treatment;

● arc rotation during heating in air provides cleaning of the surface to be welded, thus ensuring the welding quality;

● WPS was developed for MIAB welding;

● MIAB welding complies with API 1104 standard, which is used in welding pipelines in different countries.

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## CONFLICT OF INTEREST

The Authors declare no conflict of interest


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