Impact of amplitude modulation of heteropolar square current pulses on formation of permanent joints in metal structures under residual magnetization

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Abstract. The work studies the impact of amplitude modulation of heteropolar current pulses on the formation of permanent joints of main pipelines done by manual shielded metal-arc welding. The results show that square pulsed current together with additional low-frequency current modulation facilitates formation of all weld layers in pipelines with residual magnetization. The work establishes that varying residual magnetization degree has no adverse effect on the quality of all layers of the permanent joints realized by modulated alternating square current, including their macrostructural and microstructural characteristics. This increases the technological stability of welding through elimination of electrode freezing during low-energy periods.

1. Introduction
In Russia, to transport oil and natural gas, large-diameter (1200–1420 mm) pipelines are used. Their condition during operation is monitored, as a rule, by pipeline magnetic pigs \([1]\) that promote residual magnetization in the pipe. After assessing the condition of a pipe, damaged parts are replaced using manual shielded metal-arc welding. However, the residual magnetization in the pipeline after such inspection causes unstable arc due to magnetic blowing during root layer welding. To eliminate such adverse effect, special equipment is used that lowers or cancels the strength of lateral magnetic field in the welding zone below critical 2 mT \([2–6]\). We should note that this method is fairly labor-intensive and has low efficacy due to application of special equipment which requires long preparation.

Therefore, an innovative engineering solution was suggested based on application of shielded metal arc welding by heteropolar square current pulses \([7]\). A special current switching principle in the welding circuit during polarity switch facilitates stable reinitiation of the arc and provides its spatial stability, including the cases of disturbing magnetic field with a strength of up to 100 mT \([8, 9]\). To implement the suggested technology, a special device IST-201 was developed that is connected to the welding circuit of a standard power supply. This appreciably increases the performance of repair works in main pipelines due to the absence of demagnetization operation. Nevertheless, despite the positive effect of heteropolar square current pulses on welding of magnetized parts by shielded electrodes, the issues of amplitude current modulation effect on the formation of permanent joints remain understudied. This is especially relevant to one-side welding of a root weld with formation of a back bead without back root pass or application of special backing.

At the same time, the amplitude modulation during shielded-electrode welding by unipolar current without external magnetic field has additional positive effect of arc reinforcing action on the molten
pool. This guarantees formation of the root backing layer bead, simplifies welding process in all spatial positions, reduces requirements to the gap between the edges and their displacement, and eliminates freezing of the electrode [10, 11].

**Aim of the work:** to study the effect of amplitude modulation of heteropolar square current pulses on the weld seam formation during manual shielded metal-arc welding of magnetized pipelines.

2. **Experimental.**
To extend the technological capabilities of manual shielded metal-arc welding under magnetic field action, experiments were carried out on the impact of amplitude of heteropolar square current pulses on the formation of permanent joints. The functional scheme of the testbed is presented in Fig. 1.

![Functional scheme of testbed](image)

**Figure 1.** Functional scheme of testbed:
1) welding rectifier VD-306; 2) control unit; 3) voltage limiter; 4) welding current inverter; 5) electrode; 6) part; R1) pause current regulator; R1+R2) pulse current regulators; VD) bypass diode; VT) shunting transistor.

The root welding seam was done by 2.6-mm LB-52U electrodes. The initial magnetic field strength between welded edges (B = 100 mT) was set by an external inductor. The power supply was WD-306 device with a preset maximum current, which corresponding energy level (high or low) was limited by ballast resistors. The amplitude current modulation in the welding circuit was performed by a shunting transistor VT. The polarity was switched with the frequency of 500 Hz by IST-201 welding current inverter. A typical oscillogram of modulated alternating current is presented in Fig. 2. The welding regimes are presented in Table 1.

The testbed was used to weld 530-mm pipes from 12G2SB steel with the length of 1 meter and wall thickness of 10 mm. The mechanical properties are presented in Table 2.
Figure 2. Oscillogram of current in welding circuit (\(\mu_i = 50 \text{ A/unit}, \mu_t = 0.1 \text{ s/unit}\)).

Table 1. Parameters of root layer welding regime for permanent joint

| No. | Current type and shape                          | Parameters of welding current | \(d_{el}\) [mm] | Electrode type |
|-----|------------------------------------------------|-------------------------------|----------------|---------------|
| 1   | Unipolar, reverse                              | \(I_{\text{weld}} = 116 \text{ A}\) |               |               |
| 2   | Unipolar modulated                             | \(I_{\text{weld}} = 138 \text{ A}; I_{\text{pulse}} = 192 \text{ A}; I_{\text{pause}} = 30 \text{ A}\) |               |               |
| 3   | Heteropolar, square                            | \(I_{\text{weld}} = 137 \text{ A}; \text{frequency is 500 Hz}\); \(I_{\text{pulse}} = 192 \text{ A}; I_{\text{pause}} = 30 \text{ A}\) | 3.2           | LB-52U        |
| 4   | Heteropolar, square, modulated                 | polarity switch frequency is 500 Hz; \(t_{\text{pulse}} = 0.3 \text{ s}; t_{\text{pause}} = 0.3 \text{ s}\) |               |               |

The pipe edges were prepared and assembled as per requirements of STO Gazprom 2-2.2-136-2007 standard. The initial magnetic field strength between welded edges (\(B = 100 \text{ mT}\)) was set by an external inductor. The pipe was welded in non-revolution position in three passes (Figure 3). The electrodes and welding parameters were selected according to item 10.4 of STO Gazprom 2-2.2-136-2007 requirements.

Figure 3. Scheme of manual arc welding of pipe joints

Table 2. Mechanical properties of 12G2SB steel (as per GOST 10705-80)

| Ultimate tensile strength \(\sigma_u\) [MPa] | Yield stress \(\sigma_{02}\) [MPa] | Relative elongation \(\delta\) [%] |
|--------------------------------------------|----------------------------------|----------------------------------|
| 490                                        | 343                              | 20                               |
Under the absence of magnetic field in the welding zone, direct current of inverse polarity was used. At initial magnetic field strength of 100 mT, amplitude modulation of heteropolar square current pulses, formed by IST-201 together with VD-306, were used. Chemical composition of the basic metal is presented in Table 3, while that for the seam metal is given in Table 4.

**Table 3. Chemical composition of main 12G2SB steel**

| Elemental composition [%] (GOST 19281–89) | C   | Si   | Mn   | Cr  | Ni  | Co  | Cu  | Nb  | Ti  | V  |
|------------------------------------------|-----|------|------|-----|-----|-----|-----|-----|-----|----|
| C                                        | 0.12| 0.42 | 1.46 | 0.12| 0.08| 0.01| 0.15| 0.05| 0.01| 0.06|

**Table 4. Chemical composition of seam metal**

| Welding conditions                                           | Chemical composition of seam metal [%] | C   | Si   | Mn   | Cr  | Ni  | Co  | Cu  | Nb  | Ti  | V  |
|-------------------------------------------------------------|---------------------------------------|-----|------|------|-----|-----|-----|-----|-----|-----|----|
| Magnetized pipe, heteropolar amplitude-modulated square current pulses |                                       | 0.12| 0.3  | 1.07 | 0.02| 0.01| -   | 0.07| 0.01|
| Demagnetized pipe, unipolar reverse-polarity current         |                                       | 0.12| 0.3  | 1.20 | 0.04| 0.02| 0.01| 0.04| 0.02|

The weld joints were initially subjected to visual measurement and x-ray inspection that revealed no defects. To analyze the impact of current type on the metal seam properties, its macro- and microstructure were investigated. The specimens for mechanical testing of the welded seams were cut from the pipe butt joints.

To determine the mechanical properties of the welded joints, the specimens were prepared as per STO Gazprom 2-2.2-136-2007 standard. The number of specimens and types of mechanical tests were chosen for 530-mm pipe with a wall thickness of 10.0 mm (Fig. 4).

![Figure 4. Scheme of specimen cutting for mechanical testing of round joint welds with a diameter of 530 mm: 1) specimen for static tension testing; 2) specimen for static face bend or fin bend testing; 3) specimen for static root bend or fin bend testing; 4) specimens for impact bending testing (along weld axis); 5) specimens for impact bending testing (along welding line); 6) specimen for hardness testing.](image-url)
3. Results and Discussion.

The results demonstrate insignificant effect of welding conditions on the content of alloying elements in the seam metal. Indeed, static tension tests (Table 5) testify that regardless of the welding conditions, the basic metal of the specimens failed. Static bending tests showed no failure at a bending angle of 140° (Table 6). The impact bending tests of the welded joint demonstrated that at a temperature of minus 40 °C, the impact ductility of the seam metal in the case of amplitude modulation of heteropolar square current pulses is 1.12–1.8 times larger than that in the case of unipolar reverse-polarity current (Table 7). The application of amplitude-modulated heteropolar square current pulses increases the impact ductility of the metal from the heat affected zone.

Table 5. Welded joint static tension testing results

| Welding conditions                                      | Butt/quarter/specimen | Ultimate tensile strength $\sigma_u$ [N/mm$^2$] | Relative elongation $\delta$ [%] | Relative reduction $\Psi$ [%] |
|--------------------------------------------------------|------------------------|-----------------------------------------------|---------------------------------|-----------------------------|
| Magnetized pipe, amplitude modulation of heteropolar    | b. 1/I/1               | 600                                           | 23                              | 61                          |
| square current pulses                                   |                        |                                               |                                 |                             |
|                                                        | b. 1/II/1              | 600                                           | 25                              | 58                          |
|                                                        | b. 1/III/1             | 605                                           | 23                              | 58                          |
|                                                        | b. 1/IV/1              | 572                                           | 30                              | 66                          |
| Demagnetized pipe, unipolar reverse-polarity current    | b. 2/I/1               | 583                                           | 23                              | 61                          |
|                                                        |                        |                                               |                                 |                             |
|                                                        | b. 2/II/1              | 600                                           | 25                              | 66                          |
|                                                        | b. 2/III/1             | 588                                           | 25                              | 58                          |
|                                                        | b. 2/IV/1              | 588                                           | 23                              | 61                          |

Table 6. Welded joint static bending testing results

| Welding conditions                                      | Butt/quarter | Bending angle [deg] | Specimen 2 Specimen 3 |
|--------------------------------------------------------|--------------|---------------------|-----------------------|
|                                                        |              | Specimen 2 face bend | Specimen 3 root bend |
|--------------------------------------------------------|--------------|---------------------|-----------------------|
| Magnetized pipe, amplitude modulation of heteropolar    | b. 1/I       | 124                 | 133                   |
| square current pulses                                   | b. 1/II      | 126                 | 125                   |
|                                                        | b. 1/III     | 127                 | 125                   |
|                                                        | b. 1/IV      | 126                 | 124                   |
|                                                        | b. 2/I       | 128                 | 126                   |
|                                                        | b. 2/II      | 128                 | 124                   |
|                                                        | b. 2/III     | 134                 | 126                   |
|                                                        | b. 2/IV      | 125                 | 134                   |

Table 7. Welded joint impact bending testing results

| Welding conditions                                      | Location of concentrator | Butt/quarter | Quarter/specimen | KCV$^{-40\text{C}}$ [J/cm$^2$] |
|--------------------------------------------------------|--------------------------|--------------|------------------|--------------------------------|
| Magnetized pipe, amplitude modulation of heteropolar    | along weld axis          | II/4         | II/4             | 142                            |
| square current pulses                                   | b. 1                     | III/5        | III/5            | 213                            |
|                                                        | near-weld zone           | III/5        | III/5            | 128                            |
|                                                        |                           | III/5        |                  | 219                            |
Demagnetized pipe, unipolar reverse-polarity current

|                  | II/4 | II/4 | III/5 | III/5 |
|------------------|------|------|-------|-------|
| along weld axis  | 97   | 133  | 118   | 118   |
| near-weld zone   | 168  | 

Fig. 5 depicts macrostructure of root weld of permanent joints received at different levels of residual magnetization. Their analysis showed that the amplitude modulation of heteropolar square current pulses has no impact on the dimensions of the heat affected zone and does not deteriorate root welds of permanent joints in the case of parts with different residual magnetization level.

**Figure 5.** Macrostructure of root weld layers after vertical welding: a) demagnetized parts, unipolar current; b) demagnetized parts, unipolar modulated current; c) demagnetized parts, heteropolar square current pulses; d) demagnetized parts, amplitude modulation of heteropolar square current pulses; e) magnetized parts (initial magnetic field strength is 100 mT), amplitude modulation of heteropolar square current pulses; f) magnetized parts (initial magnetic field strength is 100 mT), heteropolar square current pulses.

Fig. 6 shows the macrostructure of the weld after consequent root, filler and cap passes under demagnetized and magnetized conditions.
Figure 6. Macrostructure of consequent formation of permanent joint layers: a, d) weld pass; b, e) root and fill passes; c, f) root, fill and cap passes; a, b, c) demagnetized parts; d, e, f) magnetized parts.

Fig. 7 depicts microstructure of root weld of permanent joints received at different levels of residual magnetization.

Figure 7. Microstructure of weld metal: a) unipolar reverse-polarity current; b) unipolar modulated current; c) heteropolar square current pulses (500 Hz); d) heteropolar amplitude-modulated square current pulses (500 Hz).

The analysis of microstructure of weld metal demonstrates that consequent transition from unipolar reverse-polarity current, unipolar modulated current, heteropolar square current pulses to heteropolar amplitude-modulated square current pulses diminishes structural components at least 3–4 times. Interestingly, additional amplitude modulation of heteropolar square current pulses appreciably alters the structure of near-weld zone and provides smooth transition from large-grain structure of the weld metal to fine structure of the base metal [12, 13]. This evidences general decrease of structural nonuniformity, which justifies higher mechanical characteristics of permanent joints obtained by square current welding with additional low-frequency modulation.

4. Conclusion
Welding by heteropolar amplitude-modulated square current pulses is an effective technique that allows increasing the quality of root welds of main pipelines with residual magnetization. Variation of the residual magnetization degree has no adverse effect on the quality of all layers of the permanent joints, including their macrostructural and microstructural characteristics. In addition, the amplitude modulation of heteropolar square current pulses according to a preset algorithm improves stability of welding by eliminating electrode freezing during low-energy period.

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