Development of electron-beam welding method with inserts

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Abstract. The paper is devoted to the study of welded joints formation process both from homogeneous and dissimilar materials. The investigated welded joints were made by an electron beam using intermediate inserts of small thickness in a narrow gap. The influence of insert size as well as gap size on the stability of weld formation is shown. Electron beam oscillation configurations which eliminate incomplete penetration in weld root are determined. Values of thermal efficiency are experimentally found for different welding speeds. The results of structure study for dissimilar welded joints of plates from carbon steel 20 and austenitic corrosion-resistant AISI 316L steel are presented. The values of penetration rate for base and filler metal are calculated and experimentally confirmed.

1. Introduction
Currently, in spite of all existing difficulties of welding dissimilar materials, different combined constructions are widely used in modern industry. This tendency is specified not only by economic factors, which often play one of the most important roles in such construction creation and development, but also by operational requirements. Improvement of performance parameters of various power plants necessitates the use of modern expensive materials. However, in market economy conditions, cost of expensive materials can greatly restrain release of new products as well as increase cost of finished product. Therefore, it is necessary to rationally develop such constructions in which not the whole product is manufactured from more expensive and scarce materials, but only those components or parts that directly reside in specific operating conditions (high loads, temperatures or corrosive environments) [1]. In combined constructions it is advisable to join individual parts by welding because their mechanical connection is often difficult and unreliable in operation. For connection dissimilar metals various methods of welding in solid phase and fusion are used.

Use of an electron beam as a heat source during welding solves a number of very important problems of joining dissimilar materials. Since electron beam is independent source according to the nature of heat exposure, melting processes for base and filler metal can be regulated independently of each other. As a result, penetration rate of base metals can be adequately regulated, thereby ensuring formation of required chemical composition and structure of weld metal by changing electron beam position relative to the joint [2]. But this method has several disadvantages: in addition to the possibility of incomplete penetration in weld root, there is impossible to use this method for all pairs of materials to be welded. The most widely used method for regulating chemical composition in welding dissimilar metals is based on the use of intermediate inserts between the parts to be welded. This method allows welding such materials, direct connection of which is impossible. Inserts can be
used as transition layer or as filler material, the main purpose of which is weld metal alloying. Also the weld can be alloyed by pre-applied of a thin coating by galvanic method [3] or by surfacing [4]. But the use of these techniques leads to a serious rise in cost of finished product as well as a decrease in productivity.

Nowadays, all existing techniques used in electron-beam welding cannot fully provide the required physical and chemical properties of the weld. In this regard, development of new techniques to ensure required composition and structure of weld metal due to its alloying has scientific and practical significance.

The aim of this work is to study the process of welded joints formation both from homogeneous and dissimilar materials. The investigated welded joints were made by an electron beam using intermediate inserts of small thickness in a narrow gap.

2. The research methods
For our research the ELA-60/15 power supply was used. As the base material for welding plates with a thickness of 20 mm from steel 20 and corrosion-resistant austenitic AISI 316L steel were used. Intermediate inserts were made of plates with a thickness of 1 mm and 1.5 mm from steel 20 and precision 36NKhTYu alloy (Table 1). Intermediate insert was installed in a slot weld groove with a gap. Weld groove was made of two types: square and V-shaped (Figure 1).

| Material       | C  | Mn | Cr | Ni | Ti | Mo | Si | Al | Fe |
|----------------|----|----|----|----|----|----|----|----|----|
| 20             | 0.20 | 0.5 | –  | –  | –  | –  | –  | –  | –  | base |
| AISI 316L      | 0.02 | 1.5 | 17 | 12 | 0.3 | 2.5 | 0.8 | –  | –  | base |
| 36NKhTYu       | 0.04 | 1.2 | 12.5 | 36 | 3  | –  | 0.5 | 1.1 | –  | base |

To determine the optimal geometric parameters of welded joints, weld groove width was changed. Insert width and height were chosen from the condition of obtaining the necessary volume to fill weld groove (Figure 2).

To study weld formation during welding of homogeneous materials, different process parameters were changed: beam current, beam focusing, welding speed, type of beam oscillation. Beam current and welding speed were determined from the condition of joint complete penetration. Electron beam focusing was set in such a way that ensures maximum penetration depth at the selected welding modes. Electron gun was placed vertically. Welding was performed both with beam oscillation along various trajectories with different parameters and without it. Oscillation parameters were chosen from

Figure 1. Schemes of square (a) and V-shaped (b) weld groove: 1 – materials to be welded; 2 – intermediate insert; 3 – backing plate.
the condition of elimination poor fusion in weld root. Electron-beam welding (EBW) modes are presented in Table 2. After welding macro-sections were made from welded samples and macrostructure of welded joints was investigated. Investigation of homogeneous welded joints formation was carried out on the plates from carbon steel 20. An insert for regulation weld chemical composition and structure was made also from steel 20.

![Welding samples](image)

**Figure 2.** Welding samples.

**Table 2.** Electron-beam welding modes

| Number of mode | $U$ (kV) | $I$ (mA) | $v$ (m/h) | Welded materials | Beam oscillation | Weld groove type | Section number |
|---------------|-----------|-----------|-----------|------------------|------------------|-----------------|----------------|
| 1             | 195       | 30        |           | steel 20         | Transverse line segment, Amplitude 1 mm, Frequency 400 Hz | Squared shape    | 3(a)           |
| 2             | 115       | 15        |           | steel 20         | Transverse line segment, Amplitude 0.8 mm, Frequency 400 Hz | Squared shape    | 3(b)           |
| 3             | 60        | 185       | 30        | steel 20         | Transverse line segment*, Amplitude 0.8 mm, Frequency 400 Hz | V-shaped         | 3(c)           |
| 4             | 190       | 30        |           | steel 20 and AISI 316L steel | Transverse line segment, Amplitude 1 mm, Frequency 400 Hz | Squared shape    | 4(a)           |
| 5             | 195       | 30        |           | steel 20 and AISI 316L steel | Transverse line segment*, Amplitude 1 mm, Frequency 400 Hz | Squared shape    | 4(b)           |

*a Sinusoidal signal change in the deflection system

The most important characteristic of any process is its efficiency. In electron-beam welding, thermal efficiency characterizes penetration efficiency. This characteristic was based on the heat balance condition [5, 6]:

$$
\eta_T = \frac{F v \rho \cdot (c (T_m - T_0) + L)}{\eta_{ef} IU},
$$

where $\eta_T$ is thermal efficiency; $F$ is penetration area (mm²); $v$ is welding speed (mm/s); $\rho$ is metal’s density (g·mm⁻³); $c$ is specific heat capacity (J·kg⁻¹·K⁻¹); $T_m$ is melting temperature (K); $T_0$ is initial
temperature (K); \( L \) is specific heat of fusion (J/g); \( \eta_{\text{eff}} \) is EBW efficiency ratio; \( I \) is beam current (mA); \( U \) is accelerating voltage (kV).

Investigation of dissimilar welded joints formation was carried out on the plates from carbon steel 20 and austenitic corrosion-resistant AISI 316L steel. An insert made of high-nickel 36NKhTYu alloy was used for regulation weld chemical composition and structure.

One of the important characteristics of dissimilar weld is penetration rate, which shows filler metal contribution in the whole weld volume. The following relation was used for its determination:

\[
\gamma_{\text{ins}} = \frac{F_{\text{ins}}}{F},
\]

where \( \gamma_{\text{ins}} \) is filler metal contribution in weld metal; \( F_{\text{ins}} \) is cross-sectional area of insert material (mm\(^2\)); \( F \) is total penetration area (mm\(^2\)).

After welding metallographic sections were made of weld samples and macrostructure and microstructure of welded joints were studied.

3. Results of studies

As a result of the analysis of welds obtained from homogeneous steels, the criteria of assembling for welding were determined. It has been found experimentally that the key condition for quality formation of any thickness welded joints is presence of a protruding insert's part above the surface of welded samples. Protrusion size should not exceed 12 mm. Under these conditions, metal completely fills the entire weld groove volume. Sizes of gap and insert are selected according to geometrical parameters of welded materials (Table 3). The optimum gap size between base material and insert is 0.3–0.5 mm. Reducing the gap size in the root part of the weld leads to cavities formation, not filled with liquid metal. To eliminate this problem, it is necessary to increase input power by 15–20%. Insert size is chosen on the basis of required volume to fill the entire weld groove. The optimal expansion angle of V-shaped weld groove is 1.5–2º.

| Weld thickness (mm) | Insert size (mm) | Gap size (mm) |
|--------------------|-----------------|---------------|
| 10 − 20            | 0.5 − 1.0       | 0.2 − 0.3     |
| 20 − 25            | 1.0 − 1.5       | 0.3 − 0.5     |
| 25 − 30            | 1.5 − 2.0       | 0.3 − 0.5     |
| >30                | >2              | 0.5           |

Macrostructures of welded joints, obtained at the modes 1, 2, 3 (Table 2), are shown in Figure 3. In welded joints made without beam oscillations, incomplete penetrations in weld root were found. The reason is that in this case all input energy is spent on insert heating, and base metal heating and melting occur only due to heat transfer from molten insert.

![Figure 3](image-url)
The use of beam oscillations makes it possible to distribute input energy between base metal and insert in such a way that common weld pool is formed and such defects as incomplete penetration are eliminated. For example, use of a sinusoidal signal in deflecting system at transverse beam oscillation leads to a change in power density distribution: maximum value will be observed at maximum beam deflection, and minimum will be observed in the insert center. Thus, insert material isn’t overheated and uniform melting of the edges being welded and filler material is achieved.

The values of thermal efficiency for welding process at the selected welding modes are presented in Table 4. Comparison of the results obtained in our case and presented in the paper [5] shows that thermal efficiency value for welding process with an intermediate insert is 4–5% higher than without it. Improving efficiency at the mode No. 3 compared to the mode No. 1 is due to the type of beam oscillation.

| Number of mode | Effective power (kW) | Penetration area (mm²) | Thermal efficiency |
|----------------|----------------------|------------------------|-------------------|
| 1              | 10.6                 | 78.3                   | 0.46              |
| 2              | 6.8                  | 81.2                   | 0.41              |
| 3              | 10.1                 | 77.9                   | 0.48              |

When welding dissimilar materials, in addition to changing the conditions of welded joints formation, the use of insert makes possible to effectively alloy weld metal. Figure 4 shows macrostructure and microstructure of dissimilar welded joints obtained at the modes No. 4 and No. 5. Weldability analysis, realized using Schaeffler structural diagram (Figure 5), shows as follows: if penetration rate of welded materials is equal 0.5, then without use of an insert quenching structures inevitably form in weld metal.

**Figure 4.** Macrostructure (a, b) and microstructure (c) of welded joints, obtained at the modes 4 and 5.

It is possible to eliminate the appearance of such structures in the weld by ensuring penetration rate of austenitic steel equal to 0.9. However, in practice, it is difficult to obtain such penetration rate due to displacement of electron beam because in such case the probability of root defects formation is high. Therefore, for obtaining the austenitic structure of weld metal, inserts from precision 36NKhTYu alloy were used. In this case, for the obtained penetration areas (weld cross-sections) (Table 5), austenitic structure of weld metal will be formed, if the part of filler material (precision 36NKhTYu alloy) in it is at least 23%.
Study of welded joints microstructure showed that all the welds have an austenitic structure. Penetration rate of insert material for studied welded joints is 35–40% (Table 5). In Figure 5, point 5 in the austenitic region on Schaeffler structural diagram corresponds to such weld composition.

**Table 5.** Part of filler material in weld metal

| Number of mode | Original transverse area of insert (mm$^2$) | Fusion area (mm$^2$) | Part of filler metal (%) |
|----------------|---------------------------------------------|----------------------|--------------------------|
| 4              | 28                                          | 75.5                 | 37                       |
| 5              | 29                                          | 76.2                 | 39                       |

**Figure 5.** Schaeffler structural diagram: 1 – steel 20; 2 – austenitic AISI 316L steel; 3 – weld metal without alloying (penetration rate is 0.5); 4 – precision 36NKhTYu alloy; 5 – weld metal with additional alloying.

4. Conclusions

Study the process of welded joints formation both from homogeneous and dissimilar materials was realized. The investigated welded joints were obtained by an electron beam using intermediate inserts up to 1.5 mm thick in a gap, which size was approximately 2.5 mm. As a result of the study, maximum size of intermediate insert has been established. Its protruding part should not exceed 12 mm for all weld thicknesses, and optimum gap size between insert and welded edges of base metals should be 0.3–0.5 mm. Under these conditions, metal completely fills the entire weld groove volume. For elimination lack of fusion in the root part of welded joints beam oscillation are required.

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