Non-destructive testing of physical and mechanical properties of local zones in welded joints

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Abstract. The influence of the "saw-tooth" type electron beam sweep on the penetration shape during electron-beam welding of 30KhGSA high-strength steel with different welding modes was investigated. Using the instrumented indentation method, the distribution of Young’s modulus, as well as the characteristics of strength and plasticity in the welded joints cross-sections, was obtained. It has been found that in the weld metal there is a sharp increase in strength characteristics, while the plasticity ones are significantly reduced. The values of the Young’s modulus also varied over the cross-sections. The considerable decrease in this characteristic (up to 20%) was registered in the weld metal in comparison with the parent metal results.

1. Introduction

The structure, physical and mechanical properties of the material in different local zones of welded joints depend mostly on a welding method. Electron beam welding (EBW) is not an exception. The less this difference, the better in quality the welded joint is. Having information about the distribution of metal mechanical properties throughout the welded joint, namely in the parent metal, heat-affected zone, and weld metal, it is possible to choose welding modes more reasonably. Thus, the welded joint with a practically uniform distribution of mechanical properties in discrete local zones can be produced. It should be noted that in welded joints of carbon and low-alloyed steels, an abrupt growth in the hardness and strength of the weld metal and other zones is accompanied, as a rule, by a decline in the plasticity and crack resistance characteristics.

In traditional tension tests of specimens cut from welded joints, it is possible to determine only the properties of the weakest area of the welded joint. When loading the entire welded joint, crack generation and then destruction occurs initially in the tensest local zone, in which the metal may be in an embrittled state or has lower strength compared to other metal zones. Therefore, it is necessary to know the distribution of mechanical properties through all local zones of the welded joint to avoid sudden destruction of the whole welded structure. Moreover, this information can lead to a more precise estimation of the structural strength of the welded joint.
Since it is impossible to produce specimens for mechanical testing from separate local zones of the welded joint due to the limited volume of metal, implementation of other tests is needed. For instance, instrumented indentation is considered to be the most effective one. This method includes the instrumented indentation diagram “load \(F\) – elastoplastic displacement \(\alpha\)” registration with the loading and unloading curves. The most informative instrumented indentation diagram can be obtained with the implementation of a ball indenter. It can be explained by the fact that during a single immersion of such an indenter into the test material, the angle of indentation continuously increases, which depends on the relative indent depth \(t/R\) (where \(t\) is the indent depth, and \(R\) is the indenter radius) and consequently, the plastic deformation of the test material increases.

Currently, the instrumented indentation method has bloomed with an outburst of new techniques and devices for recording and processing indentation diagrams [1–4]. However, as follows from the existing standards (ISO 14577, GOST R 56232), only hardness and Young’s modulus can be determined from these diagrams. Typically, incorrect results are obtained when determining the Young’s modulus. This can be described by the complex assessment of the plastic deformation effect during indentation.

In Moscow Power Engineering Institute (MPEI), new methods and techniques for defining the mechanical properties including the Young’s modulus, yield strength, ultimate tensile strength, ultimate elongation, crack resistance based on instrumented indentation diagram have been developed [1; 5]. These techniques are based on the interrelation between the “Brinell hardness \(HB_i\) – relative indent depth \(t/R\)” diagram and the stress-strain curve “stress \(\sigma\) – elongation \(\delta\)”.

The main similarity condition required to recalculate the current values of hardness \(HB_i\) to the values of stress \(\sigma\) is to provide the same values of deformation during indentation and tension. Figure 1 shows the stages of the instrumented indentation diagram transformation into a tensile diagram within a uniform deformation according to the proposed method.

![Figure 1](image1.png)

**Figure 1.** Stages of the instrumented indentation diagram “\(F - \alpha\)” (a) transformation into the diagram “\(HB_i - t/R\)” (b) and into the stress-strain curve “\(\sigma - \delta\)” (c) according to the proposed method: \(F_{\text{max}}\) – ultimate indentation load; \(\alpha_{\text{max}}\) – ultimate elastoplastic displacement; \(F_u\) – load corresponding to the ultimate uniform strain; \(F_y\) – load corresponding to the yield strength; \(F_{el}\) – load corresponding to the elastic limit; \((HB_i)_{\text{U}}\) – ultimate hardness; \((HB_i)_{\text{y}}\) – hardness with the yield stress; \(\sigma_U\) – ultimate tensile stress; \(\sigma_y\) – yield stress; \((t/R)_{\text{U}}\) – relative indent depth corresponding to ultimate uniform strain; \(\delta_U\) – ultimate uniform strain.

In this paper, determination of the above-listed mechanical properties of local zones in welded joints made of 30KKhGSA steel was performed by the instrumented indentation method. Samples were welded by electron beam welding with different modes.
2. Materials and Methods
The studies were carried out on a plate made of 30KhGSA steel with a thickness of 22 mm. Three EBW modes were tested to study the influence of the “saw-tooth” type electron beam sweep (Figure 2) on the weld shape with guaranteed full joint penetration. Electron-beam welding was carried out on the AELTK-344-12 electron beam plant with an accelerating voltage of 60 kV. Welding modes parameters are presented in Table 1.

![Figure 2. A “saw-tooth” voltage waveform (where \( T = 1/f \) is the sweep period, \( f \) is the sweep frequency, \( \tau \) is the current time, \( x \) is the beam coordinate).](image)

| Mode number | Sweep amplitude \( A, \text{ mm} \) | Sweep frequency \( f, \text{ Hz} \) | Average weld width \( B, \text{ mm} \) | Weld reinforcement \( \Delta F, \text{ mm}^2 \) |
|-------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| I           | –                                 | –                                 | 1.59                              | –2.36                             |
| II          | 1.5                               | 35                                | 2.08                              | 1.98                              |
| III         | 1.2                               | 37.50                             | 2.34                              | –0.33                             |

The welding mode which ensures full joint penetration has the following parameters: beam current \( I = 90 \text{ mA} \); welding speed \( v = 15 \text{ m/h} \); focusing current \( I_f = 757 \text{ mA} \); working distance \( L = 150 \text{ mm} \). When a complete penetration is implemented without the application of electron beam sweep, a “sink” at the weld top is formed. It is advisable to make an assessment of welds made with electron beam sweep by the value of the reinforcement area \( A_r \) (or undercut \( A_u \)) on the front surface of the weld. If the seam reinforcement value is \( \Delta F > 0 \), such metal formation is considered favorable (Figure 3).

![Figure 3. Scheme of reinforcement and undercuts formation in a weld.](image)

To evaluate the complex of mechanical properties in local zones of welded joints an instrumented indentation was carried out on a testing machine Instron 5982 using a compression mode. A ball indenter with a diameter of \( D = 2.5 \text{ mm} \) (\( R = 1.25 \text{ mm} \)) was used to register the instrumented indentation diagrams. The speed of the indenter movement was 0.5 mm/min.
3. Results and Discussion

Figure 4 shows the external formation images of welds obtained by modes I, II, and III (from the face and back sides, as well as its cross-section area).

![Mode I Image]

![Mode II Image]

![Mode III Image]

**Figure 4.** Welds formation: 1 – front side; 2 – reverse side; 3 – macro-section.

The electron beam sweep parameters significantly affect the form of the weld, and with a sweep amplitude of 1.5 mm and frequency of 35 Hz, the weld has a reinforcement $\Delta F$ of about 2 mm$^2$, which is consistent with previous studies [6–7].

Figure 5 shows a map of the indents made in welded joints and graphs of mechanical properties distribution in various zones of these welded joints.

As follows from Figures 4 and 5, uneven distribution of mechanical properties is observed for all welds. In the weld metal, there is a rapid increase in the yield strength $\sigma_{0.2}$ and the ultimate tensile strength $\sigma_u$, while the ultimate uniform elongation $\delta_u$ falls up to 2...3% under modes I and II. Mode III is characterized by a less sharp rise in $\sigma_{0.2}$ and $\sigma_u$. As for the uniform ultimate elongation indicator, it grows to 6% compared to modes I and II.

However, of particular interest is the distribution of the Young’s modulus $E$ in the local zones of welded joints. It is generally assumed that the Young’s modulus is a low-sensitivity physical and mechanical characteristic to any changes in the chemical composition and microstructure of steel, the presence of a cold-hardening, and the impact of different technological factors. At the same time, experiments prove that there is a significant difference in the values of the Young’s modulus $E$ in different zones of the welded joint.
Figure 5. Map of the indents made in welded joints (a) and the graph of mechanical properties distribution of welded joints obtained by EBW under modes I (b), II (c), III (d).

For modes I and II, the Young’s modulus $E$ in the weld metal was constituted 20% less compared with the base metal. In mode III, this decrease is not so obvious – about 10%. This fact should be considered when evaluating the structural strength of the entire welded structure.

It also should be noted that attention has already been paid to a significant change in the Young’s modulus under the influence of technological factors. Thus, in [8], the term “elastic modulus defect” was introduced, which can be calculated by the ratio of the initial and actual values of the modulus. This ratio can be used as an important diagnostic parameter when evaluating the structural and mechanical state of the metal after its processing or long-term operation.

4. Conclusion
Various EBW modes were tested to study the influence of the “saw-tooth” type electron beam sweep on the weld shape during electron-beam welding with guaranteed full joint penetration. The studies were carried out on a plate made of 30KhGSA steel with a thickness of 22 mm. The mechanical properties of local zones in welded metal were determined using instrumented indentation.

The weld metal strength characteristics significantly exceed the corresponding values of the base metal ones. At the same time, the seam is characterized by lower uniform ultimate elongation $\delta_u$. When electron-beam welding is carried out without using a beam sweep, the values of $\delta_u$ are equal to 2–3%. This fact makes the welded joint prone to brittle fracture, despite the high strength of the weld metal (the ultimate tensile strength can reach 1600 MPa).
It is established that there is an uneven distribution of the Young’s modulus values in the weld metal. The highest drop in relation to the base metal equals 20% depending on the EBW modes.

The use of electron beam sweep contributes to the plasticity growth in the weld metal (the value of $\delta_u$ reaches 6%) and a more uniform distribution of strength characteristics and Young’s modulus over the welded joint cross-section.

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