Development of methods for forecasting the microstructure of the welded joint with reference to the temperature-time modes of electron-beam welding

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Abstract. The research is devoted to the development of methods for forecasting microstructure of a welded joint in relation to the temperature-time modes of an electron-beam welding (EBW). The analysis of the simulation models and methods existing in the practice of thermal treatment and relating to austenite decomposition kinetics during cooling was carried out to choose methods for forecasting the forming microstructure in a welded joint at EBW. On the basis of these models one method for forecasting the microstructure of welded joints at EBW is offered in this work.

1. Introduction
An electron-beam welding is considered to be one of the advanced ways of the production of welded joints. The weld formation is essentially dependent on the forming microstructure, being one of the main forecasted joint quality criteria. To forecast the microstructure of a weld metal and a heat-affected zone it is necessary to know thermal cycle for a given section of a welded joint and the criteria by which means the percentage ratio of structural components is estimated.

Generally the criteria for forecasting metal microstructure of a weld and a heat-affected zone are cooling time within a temperature range of 800-200 °C (t8/2) and cooling rate within a range of 600-500 °C (w5/6), which are determined with the use of thermal welding cycle for the analyzed area. However the heating and cooling rates vary in time nonlinearly during welding, so instantaneous process rates should be applied.

2. Problem identification, materials and methods
The equations for determining the instantaneous heating and cooling rates are derived from thermal problems equations [1]:

\[ W(x, y, z, \tau) = \frac{dT(x, y, z, \tau)}{dt} \quad \text{at} \quad dt = \frac{dx}{V} \quad W(x, y, z, \tau) = \frac{dT(x, y, z, \tau)}{dx} \cdot V. \]

In the planned research the thermal cycles and instantaneous heating and cooling rates were calculated and their analysis was taken to choose the basic criteria for forecasting microstructure formed at EBW. The calculation and the analysis were carried out with the use of the welded joint of the steel 20Cr3MoNbW produced by the serial factory technology (figure 1 and figure 2).
3. Discussion of results

The comparative analysis of mentioned thermal cycles \( t_{8/2}, w_{6/5}, \text{max } W_{\text{cooling}} \) calculated for different areas of the welded joint showed the following information. The cooling time within the temperature range of 800-200 °C \( t_{8/2} \) differs by tenths of a second and the cooling rate at the temperature 550°C \( w_{5/0} \) varies up to 3 °C/s for the weld areas having the same temperature and being located at different depths (table 1).

A similar trend is observed when comparing the data for the weld metal, overheating zone and complete recrystallization that are located at the same depth of the welded joint. In accordance with the obtained \( t_{8/2} \) and \( w_{6/5} \) data the process of the weld cooling, which is below the temperature of the phase transformation \( \Delta \varepsilon_3 \), occurs under the same conditions, and therefore the structure in the weld metal and in the heat-affected zone throughout the depth of the welded joint should be the same. However, the metallographic analysis showed that different microstructure was formed throughout the depth of the weld metal (figure 3). An almost martensitic structure with small bainite precipitates is formed in the lower area of the weld, more bainite is located in the upper area of the weld and it precipitates mainly along the boundaries of primary dendritic grains.

![Figure 1](image_url)

**Figure 1.** Macrostructure of the welded joint and design shape of the weld; steel 20Cr3MoNbW: \( I_b = 100 \text{ mA}; U = 30 \text{ kV}, V_w = 10 \text{ m/hr}, \) points 1,2,3 at \( h = 1.5 \text{ mm} \); points 4,5,6 at \( h = 6 \text{ mm} \); 1, 4 – weld metal; 2, 5 – overheating zone; 3, 6 – zone of complete recrystallization.
Figure 2. Calculated thermal welding cycles (mathematical dependencies $T/\tau$) and instantaneous cooling rates (mathematical dependencies $W/T$) ; (a) - at depth $h = 1.5$ mm; (b) - at depth $h = 6$ mm. Curves 1, 4 - weld metal; 2, 5 - overheating zone; 3, 6 - zone of complete recrystallization.

Figure 3. Cooling curves from 1750 °C temperature and weld metal microstructure for different depths (Krupp reagent).
Table 1. Parameters of the cooling process for the welded joint, the steel 20Cr3MoNbW.

| Cooling parameters | Analyzed weld sections | Overheating zone, $T = 1350^\circ$C | Zone of complete recrystallization, $T_n = 1000^\circ$C |
|--------------------|------------------------|-----------------------------------|--------------------------------------------|
|                    | Weld metal             | $h = 1.5$mm, $h = 6$mm            | $h = 1.5$mm, $h = 6$mm                     |
| $t_{82}$, s        | 20.2                   | 20                                | 20.3                                       |
| $w_{506}$, °C/s    | 26                     | 28.5                              | 29                                          |
| $w_{\text{max}}$, °C/s | 414               | 321                               | 153                                         |

Significant differences in thermal cycles and cooling rates are observed in the high-temperature region at $T > 800$ °C (figure 3). The comparative analysis of maximum values of an instantaneous cooling rate ($\text{max } W_{\text{cooling}}$) showed that maximum values $W_{\text{cooling}}$ vary from each other in different areas of the welded joint. At the same time, an increase of $W_{\text{cooling}}$ is observed in the overheating zone, and it rises more than 1.5 times in the overheating zone, and it rises more than 1.7 times in the zone of complete recrystallization (table 1). The values $\text{max } W_{\text{cooling}}$ decrease along the width of the welded joint.

When forecasting the microstructure of a welded joint metal and a heat-affected zone forming at EBW the criteria should cover the entire cooling history, starting with the maximum temperature reached during heating. Such criteria can be a crystallization temperature and an instantaneous cooling rate at this temperature for a weld metal, and maximum heating temperature and the highest instantaneous cooling rate, in relation to a given thermal cycle, for a heat-affected zone.

The analysis of existing in the practice of heat treatment models and methods of the simulation concerning austenite decomposition kinetics during cooling was carried out to choose the method of forecasting the forming microstructure in a welded joint at EBW. On the basis of the analysis, two types of models were selected for their subsequent adaptation in relation to the thermal cycles of EBW:
- semi-empirical models for constructing diagrams of isothermal and thermo-kinetic decomposition of austenite, developed in [2, 3], and then particularized by the author of [4].
- regression models of transformation of supercooled austenite at continuous cooling, obtained by the authors of [5] with the use of artificial neural networks.

On the basis of these models, one method of forecasting the microstructure of welded joints at EBW is proposed.

The method applies a semi-empirical model for constructing diagrams of austenite isothermal decomposition. This model is based on a general equation for describing austenite transformation curves in a diagram. The equation calculates the time $\tau$ required for the formation of ferrite, pearlite and bainite at the temperature $T$:

$$\tau(X, T) = \frac{F(G)}{F(G)D\Delta Tq} \int_0^X \frac{dx}{x^{2(1-x)}(1-x)^{2x/3}}$$

where $F(G) = \beta^2 (G - 1/2)^2$, $\beta$ – empirical coefficient; $G$ – austenitic grain size (according to ASTM); $D$ – effective diffusion coefficient; $\Delta T$ – overcooling; $q$ – indicator, which depends on the effective diffusion mechanism; $F(C,Mn,Si,Cr,Mo)$ – function of the steel composition, expressed in % by weight; integral describes the rate of the reaction of volume fraction transformation and takes into account the sigmoidal effect of phase transformation.

After testing a number of physical models for constructing isothermal and thermo-kinetic diagrams of austenite decomposition, as well as the relations required for their construction, the equations with particularized empirical coefficients were suggested in the studies. The suggested equations, involving
the determination of the equilibrium temperatures of austenite transformation $A_1$ and $A_3$, the determination of the start temperatures of bainite and martensitic transformations, the calculation of the time of ferrite, perlite and bainite formation, more accurately describe isothermal diagrams of austenite decomposition for low- and medium-alloyed steels.

With the use of these equations the austenite decomposition diagram is plotted for a qualitative estimation of the forming structure at EBW, and the calculated cooling curves for the appropriate thermal cycle are marked on it.

The transformations of the semi-empirical model (1) were performed, taking into account the additivity rule, in order to forecast the microstructure quantitative composition of the welded joints and to construct structural diagrams of austenite decomposition for a given thermal cycle. After these transformations the equations determining the volume fraction of the formed ferrite, perlite, and bainite for a given thermal cycle were obtained. In general, these equations are represented as follows:

$$\int_0^X \frac{dX}{X_i^2(1-X_i)^2/3} = \frac{F(G) \cdot F(C)}{\tau_i},$$

where $F(T_i) \cdot \tau_i = D(T_i) \cdot \Delta T(T_i) \cdot \tau_i$, and it is calculated taking into account the numerical data variety including temperature and time variations determined from the thermal welding cycle for a specific section of the welded joint, $X_i$ is a volume fraction of the forming structure at the $i$ moment of time of this cooling curve.

The values of a volume fraction of the formed microstructure $X_i$ are determined in the MathCAD mathematical package with the use of Given and Find functions, the equation (2) being solved as a system of equations for each $i$ point. The graphs showing the kinetics of the ferrite, perlite, bainite and martensite formation in the cooling process on a given thermal cycle are the result of the salvation of these equations (figure 4). On the basis of the obtained results, a diagram representing the percentage of structural components formation in dependence on the cooling time is constructed (figure 5).

**Figure 4.** Kinetic diagrams of the formation of bainite depending on the cooling time, calculated from the thermal cycles for the weld metal (points 1 and 4 in Figure 1).
Quantitative estimation was performed with the use of the VideoTest Metal software, which allows painting the phases in accordance with their brightness range and determine the volume fraction of the selected phase. A quantitative estimation of the structural components in the weld metal and the heat-affected zone was carried out to verify the adequacy of the suggested methods for forecasting the microstructural composition. In order to differentiate structural components that are close in morphological structure, such as bainite and martensite, the surface of microsections was alternately treated with two reagents and it was multiple repolished. The analysis was carried out on an optical microscope with the use of polarized light (figure 6).

![Graph](image)

**Figure 5.** Structural diagrams for weld metal, steel 20Cr3MoNbW, (a) - depth h = 1.5 mm, (point 1 in Figure 1); (b) - depth h = 6 mm, (point 4 in Figure 1); B – bainite, M – martensite, A – austenite.

![Microstructure](image)

**Figure 6.** Microstructure of welded joint metal (Figure 1), 20Cr3MoNbW steel, weld upper part, B - bainite, M – martensite.

Table 2 presents the experimentally determined and calculated structural composition of the welded joint obtained on the basis of the physical model of the suggested method. The method allows making a quantitative prognosis of the microstructure of the weld metal and the heat-affected zone at EBW of low- and medium-alloyed steels.
4. Conclusion

Thus, the method of forecasting the microstructure formed at EBW of medium-alloyed steels was suggested taking into account special characteristics of thermal cycles variations along the width and the depth of a welded joint. The suggested method is based on the construction of the structural diagrams describing the austenite transformation kinetics during the continuous cooling in the dependence on the thermal cycle of EBW.

References

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