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OPTIMIZATION OF CONDITIONS OF ELECTROSLAG WELDING OF BANDINGS OF ROTARY UNITS

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Abstract. The design of banding shells of rotary units is analyzed. It is shown that combined welding and cast manufacturing of bandings is used in the case of large structural sizes. The basic materials (30, 35, 25 HSL and 30 HML), being used in this process, are characterized by the tendency of forming of hardening structures due to the thermal cycle of welding. As a result of this, the cracks in the heat-effected zone, which lead to the destruction of the connection under the influence of welding residual stresses. The analysis of literature sources has shown that the usage of electroslag welding is perspective during the manufacturing and welding of operational cracks. Thus it is important to define the correct parameters of the welding conditions. In the case of electroslag method they are different from the arc methods and are characterized by the larger amount.

In the paper the technological process of welding of banding (tread) ring with the external diameter of 4600 mm, wall thickness of 300 mm and wideness of 500 mm, which is made of steel 35. The defining of regime parameters is made using the following recommended techniques: taking into account the chemical composition of the basic metal; according to the nomogram depending on the ratio of the thickness of the metal to the number of electrode wires; using the calculation (design) method according to the conditions of electroslag welding of the banding.

Taking into account the tendency of the steel 35 to cracks forming (cracking), the evaluation of the structure and phase composition and mechanical properties of metal of heat-effected zone of the weld. In order to define the microstructure, the cooling rate of the metal in the range of structural transformations was determined and the diagram of anisothermal decomposition of austenite was used. The technique of determination of the metal cooling rate as a result of the influence of thermal cycle of electroslag welding is proposed in the paper. It is based on the usage of special nomograms which characterize the specific features of the process being studied. The cooling rate equals $\omega = 0.1876$ degrees per second when using the developed process parameters. Also the investigation of temperature distribution in the cross-section of the weld has been carried out. It is shown that there are no significant deviations of temperature when using the proposed regime parameters. This influences the reduction of the level of residual stresses along the thickness of the weld.

The analysis of the diagram of austenite transformation has shown that the structure of the steel 35 in the initial state is ferrite one with the mixture of pearlite and bainite. As a result of welding carrying out the structure will have a similar composition with slightly larger content of perlite and bainite. It was defined that their content in the heat-effected zone is as follows: 39 % for ferrite, 61 % for the mixture of perlite and bainite. At the same time, the investigated technology of electroslag process ensures the slow heating and cooling of the areas around the weld and obtaining of satisfactory mechanical properties of the metal.

Therefore, the combined usage of existent techniques of regime parameters determination is expedient. Also it is necessary to carry out the verification of physical and chemical properties of the metal of heat-effected zone in order to prevent the formation of hardening structures.

Keywords: electroslag welding, banding, rotary unit, shell, residual stress, arc-welding, hardening, cast, forge, crack.

Introduction

The wide usage of rotary units in construction, chemical and mining industries for processing of various bulk materials causes a necessity of continuous searching of the ways of ensuring of long-term operation. Such mechanisms are characterized by large structural sizes (diameter – up to 7.5 m, length – up to 259 m; in Ukraine the largest furnace of diameter of 7 m and of length of 230 m is placed at Balakliya cement plant) and productivity (up to 3000 tons per day) [1]. That's why, the sudden stops in order to conduct unplanned repair works lead to large material and labor losses.

Problem statement

The banding shell (Fig. 1) is one of the elements which are influenced by considerable loading during the operation of rotary unit. Depending on the structural sizes they may be manufactured as completely cast or forged and welded and cast formed by two parts (if the diameter exceeds 4000 mm). Herewith the thickness of the elements being welded is large and equals 300–500 mm. The repair of all the types of bandings usually is being carried out with a help of welding technologies. In particular, it is allowed for the welding of radial cracks, which arise as a result of casting defects; overloading of some supports as a result of deformation of the unit rotation axis [2] or of irregularity of heating/cooling of the unit body [3] etc.

Fig. 1. *Supporting part with banding and body of the rotary unit*

The manufacturing of banding shells is carried out on the basis of average-carbon and low-alloyed steels of 35, 30, 25 HSL and 30 HML type. The large content of carbon ensures the necessary strength but causes the formation of cracks as a result of the influence of welding thermal cycle, especially when the parts thickness is large and the arc-welding is used [4; 5]. The forming of low-plastic structures of hardening combined with large loading negatively affects the operational properties of the structure.

Analysis of modern information sources on the subject of the article

The existent methods of prevention of forming of hardening structures and ensuring of unit safe operation when using of the mentioned steels during welding first of all consist of controlling of welding thermal cycle by means of preheating and after-welding heat treatment of the weld [4–6]. Also the usage of technological process of forging of metal of the weld and surrounding areas, the usage of plastic welding materials (with austenite structure of the weld), the realization of welding technology of cascade and block (modular) methods, of reciprocating (back-and-forth) method, of the method of transversal hump etc. are being used in practice [6; 7].

If it is necessary to make the welds of large thickness we need to form the edges according to the regulatory (normative) documents [6; 7]. This ensures the access of the welding torch to the weld root, prevents the formation of burn-through and allows to form the high-quality weld. However, at the same time, depending on the welding methods (especially, arc ones) the cross-section of the weld is being enlarged since the thickness of the elements increases [7]. This causes the increasing of labor input and worsens its economic indicators. That's why the usage of electroslag welding is expedient for welding of bandings. It doesn't require special forming of edges, doesn't have any limitations on the thickness of welded elements and is characterized by a strong thermal process [6; 8; 9]. However, one of its specific features consists in its continuity and the necessity to weld in a single pass in vertical position. That's why it is important to determine the optimal parameters of the welding conditions, because the correction of defects is expensive operation which can't always ensure the prescribed properties of the weld material.

Herewith it is necessary to take into account the specific features of the thermal influence zone formation process and the effect of the welding cycle. In particular, the presence of welding residual stresses causes the formation and growth of cracks [10; 11]. It is known [10] that the value of non-relaxed residual stresses at the weld zone is in the range of 50–120 MPa even after high-temperature tempering of the weld. Such combination with low-plastic structures of hardening leads to negative consequences in terms of complicated loading and operational conditions. That's why it is necessary to use the criterions of fracture mechanics for evaluation of cracks types and choosing the method of calculation of welded structure when defining the defects [11].

The purpose and problems of research

In the specialized literature the various techniques of determination of the welding conditions parameters by means of calculation, graphic and combined methods are considered. Herewith it is difficult to define the expediency of choosing of the appropriate method which may be used in specific situation. That's why the purpose of the article consists in optimization of parameters of electroslag welding conditions taking into account physical and chemical properties of the weld metal. To achieve this purpose, it is necessary to define the parameters of welding conditions, to investigate thermal processes which take place during the electroslag welding and to evaluate their influence on the characteristics of weld forming.

The technique of research carrying out

The technological process of welding of banding (tread) ring with external diameter of 4600 mm, wall thickness of 300 mm and width of 500 mm, made of steel 35, is considered in the paper. The techniques, which are based on defining of the dependence of the electrode wire feed and welding rate on the weld crack resistance, and the nomograms, which take into account the thickness of elements and the number of electrode wires, and the empirical dependencies of the process parameters are used for determination of parameters of welding conditions [6; 7].

The evaluation of the influence of the welding thermal cycle is carried out according to technique which takes into account the formation of temperature field depending on the influence of the molten slag and separate drops of metal electrode [12]. For microstructure analysis of the heat influence zone of the weld it is necessary to determine the cooling rate in a range of metal structural transformations. That's why in the article the weld formation time and coordinates, where the critical temperatures are being reached in accordance with the linear welding energy, are being defined taking into account the special nomograms.

Main material presentation

The electroslag welding is characterized by the usage of regime parameters which differ prom arc ones. The main parameters are: the voltage of the slag bath ($U_{ш}$), the feed rate of the electrode wire ($V_{ел.др}$), the strength of welding current ($I_{зв}$), welding speed ($V_{зв}$), the depth of slag bath ($h_{ш}$), the speed of transversal displacements of the electrode ($V_{п.п.}$), the number of electrodes (n), the duration of electrode stopping in sliders ($t_{в}$), the value of the clearance between the edges ($b_{з}$) etc. [6–8]. Taking into account the thickness of welded elements (300 mm) one may define that in this case it is necessary to use 3 electrode wires of diameter of 3 mm. They have to perform transversal oscillatory motion in order to form the necessary cross-section and shape coefficient of the weld. In this case the clearance between the banding faces ($b_{з}$) equals 30 mm [6; 8; 9].

The determination of the dependence of electrode wire feed rate on the content of carbon in steel is carried out by the plot (Fig. 1), which is recommended in the literature [6]. In this work the limiting values are defined taking into account the possible content of carbon in the banding steel (which is in the range of 0.3–0.37 %). Therefore, the range of admissible electrode wire feed rate is 2.8–3.6 m/hour on 1 mm thickness of the banding. Furthermore, taking into account the thickness of welded elements and the recommended technique, we may determine the total electrode wires feed rate ($V_{ел}^{c}$), the feed rate of separate wire ($V_{ел}$) and the welding speed ($V_{зв}$). If the thickness is larger than 200 mm, it is recommended to carry out the correction of obtained data [6]. The results of the plot usage in conditions of various reduction of electrode wire are presented in the Table 1.

Table 1

Dependence of parameters of electroslag welding conditions on the critical electrode wire feed rate

Feed rate, m/hour	$V_{ел}^{c}$, m/hour	$V_{ел}$, m/hour	$V_{зв}$, m/hour
$V_{кр}^{ел}$ (2.8 … 3.6)	840 … 1080	280 … 360	0.653 … 0.840
$0.9 \cdot V_{кр}^{ел}$	756 … 972	252 … 324	0.588…0.756
$0.8 \cdot V_{кр}^{ел}$	672 … 864	224 … 288	0.523 … 0.672

The analysis of obtained data shows that it may vary by up to 20 %. Herewith, the other parameters of the welding conditions may be determined depending on the carrying out of specific technological process. However, they also influence the ensuring of crack resistance of the weld. That’s why it is expedient to carry out the clarification of actual and the determination of other parameters of the process.

The determination of parameters according to the process nomogram is carried out if the ration of elements thickness to the number of electrodes is known: s/n = 300 / 3 = 100 mm. In this case one may determine the basic parameters of electroslag welding using the corresponding plot (Fig. 2) [8].

Here the welding current, the depth of slag bath and the electrode wire feed rate are being changed in a certain range. It is specified by permissible welding speed for the prescribed ration. However, taking into account the obtained data we may accept the smaller values of determined parameters for the further research (Table 2).

Table 2

Determination of parameters of electroslag welding in accordance with the nomogram

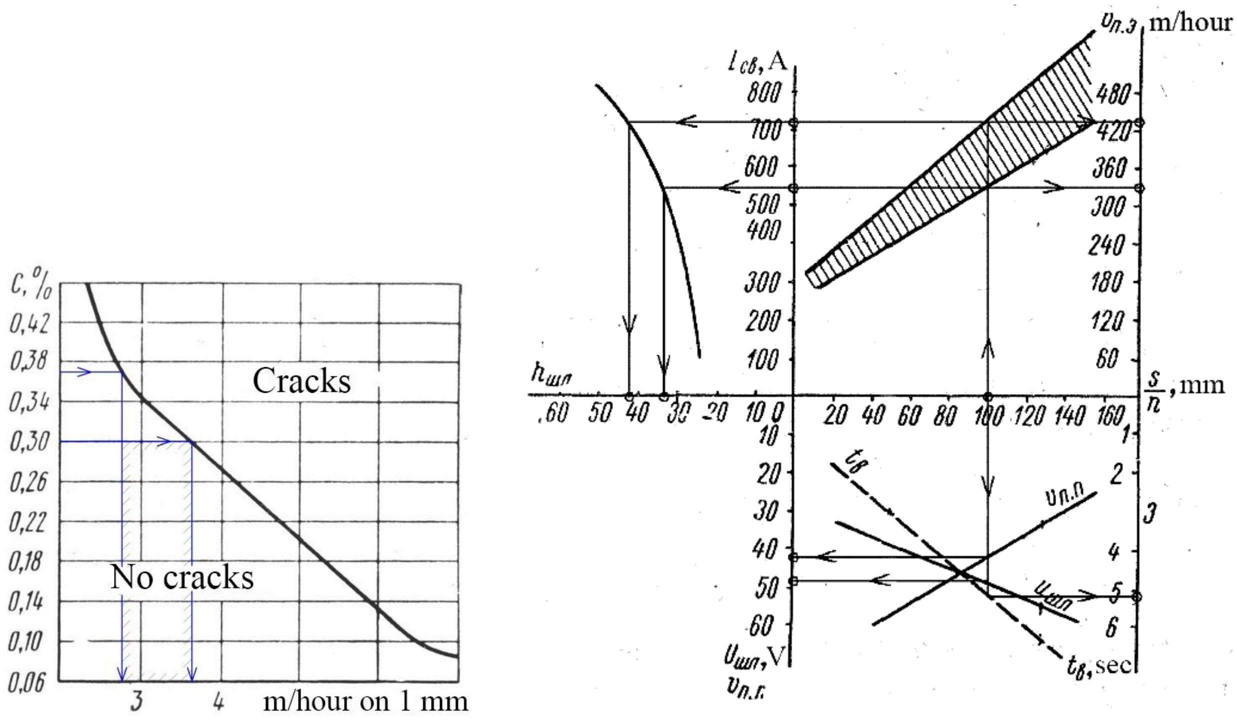
$I_{зв}$, A	$U_{ш}$, V	$V_{ел}$, m/hour	$h_{ш}$, mm	$t_{в}$, sec	$V_{пп}$, m/hour
530 … 710	49	330…410	33 … 41	5	41

The calculation technique is based on the empirical dependencies for such method [7]. In particular, the welding current as a function of the ratio of the thickness of welded metal to the number of electrodes is as follows:

$$I_{зв} = A + B \cdot \frac{S}{n_{ел}} = 230 + 3,4 \cdot \frac{300}{3} = 570 \text{ A}, \tag{1}$$

where A and B are empiric coefficients (A = 220–280, B = 3.2–4); S is thickness of the welded metal, mm; $n_{ел}$ is the number of electrodes.

The other parameters of the process may be calculated similarly. However, the drawback of this technique is the complexity of choosing of optimal values of empiric coefficients.



a *b*

***Fig. 2.** Dependence of critical feed rate of electrode wire on the content of carbon (a) and the nomogram of electroslag welding conditions depending on the ratio of elements thickness to the number of electrodes (b)*

The carried out analysis of obtained results has shown that the combined usage of various techniques is necessary in order to correct some results and to take into account the requirements of ensuring of crack resistance of the weld. The recommended parameters of the electroslag welding conditions are presented in the Table 3.

Table 3

Parameters of electroslag welding obtained on the basis of determination using the following techniques: the plot of crack resistance, the nomogram of regimes (conditions), the calculation and empirical one

n, pieces	$I_{ЗВ}$, A	$U_{Ш}$, V	$V_{ел}$, m/hour	$h_{Ш}$, mm	$V_{ПП}$, m/hour	$V_{ЗВ}$, m/hour	d, mm	$t_{В}$, sec
3	530	49	320	36	42	0,68	105	5

Taking into account the tendency of steel 35 to form cracks, it is necessary to evaluate the structure and phase composition and mechanical characteristics of the heat influenced zone of the weld. The defining of the microstructure requires the determination of the metal cooling rate in the range of the metal structural transformation and the usage of the plot (diagram) of anisothermal decomposition of austenite [13; 14].

The existent approaches to calculation of heat processes during the welding are usually based on the research of arc methods of welding [4; 12; 13]. Herewith, nowadays the investigation of electroslag process is far from being full and complete. The specific feature of its flowing is the presence of large thermal (heat) power and complexity of determination of specific parameters: temperature field, linear welding energy, weld cooling rate etc. The recommended in [12; 13] model of simultaneous influence of various heat sources was used for their determination. The heating scheme is approximately presented as the motion of three separate heat sources (two of which are of slag type and one of metal type). This causes other than accepted character of temperature distribution in welded elements. The isotherms approach to welding edges at an angle which is smaller than right one. In this case the heating of edges is carried out in advance of their melting-down (fusion). The rate of temperature increasing is close to the cooling rate of the weld metal. This is caused by large power of heating source, small welding speed in comparison with arc methods [12; 13]. The following technique of determination of the cooling rate during the electroslag welding is proposed bellow. It is based on the usage of special nomograms [12], which characterize the electroslag process. The essence of the technique is as follows:

– to calculate the parameter $(T \cdot 2\pi\lambda\delta)/q$ for determined temperatures;

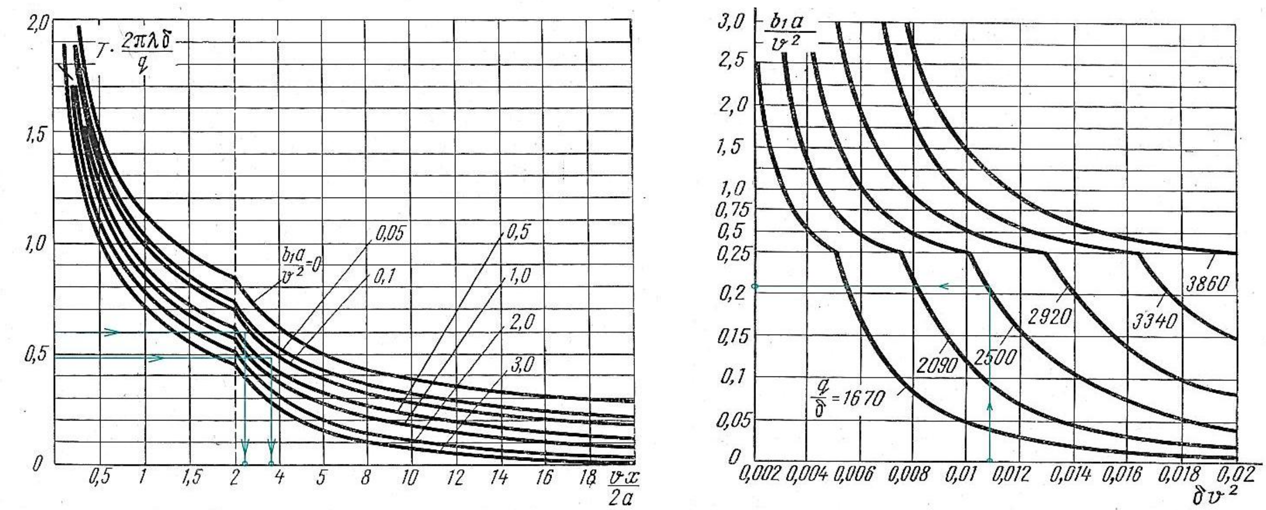
– to determine the parameter $(vx)/2a$ for linear welding energy (q) and parameter $(T \cdot 2\pi\lambda\delta)/q$ in accordance with the special nomogram (Fig. 3, *a*);

– to calculate the coordinate (x) where the critical temperature is stated;

– to determine the time required to reach the critical temperature $t = (x)/v$ for the known welding speed and coordinate (x);

– to carry out the above presented operations for determined limiting values of temperature interval;

– to determine the ratio of the critical temperatures differences (in the studied case we accept 500 °C and 600 °C) to the time, which characterizes the weld cooling rate $\omega = \Delta T/\Delta t$, deg/min.



a *b*

***Fig. 3.** Nomograms for determination of the temperature on the cooling stage during the electroslag welding (a) depending on the criterion of heat emission (b) [12]*

This technique has been used for the studied case of electroslag welding of the banding of rotary unit. The heating source power $(q_{еш з})$ equals 76353 J/sec for the welded elements of 300 mm thickness which are welded at a speed of 0.68 m/hour.

The thermophysical coefficients of the material are as follows [9]: $\lambda = 0.4$ J/cm $\cdot$ sec $\cdot$ deg ; $c\rho = 5.0$ J/cm^3 $\cdot$ deg ; $a = 0.08$ cm^2 /sec . The coefficient of the total heat emission essentially depends on the temperature increasing. That's why it is expedient to use the presented in literature [9] plot for its determination. So $\alpha = 6.0 \cdot 10^{-3}$ J/cm $\cdot$ sec $\cdot$ deg .

The average temperature (T) is to be defined with a help of corresponding nomogram (Fig. 3, *a*). It is necessary to determine the non-dimensional parameter of heat emission $\left(\frac{b_1\alpha}{v^2} = 0.21\right)$, which depends on the power of heating source (Fig. 3, *b*). We accepted the following notations and values: $\frac{q_{еш3}}{\delta} = \frac{76353}{30} = 2545$ J/cm $\cdot$ sec ; $\delta \cdot v^2 = 30 \cdot 0.0189^2 = 0.01072$ cm^3/sec^2 .

The results of the usage of developed technique are presented in the Table 4. Therefore, the cooling rate equals $\omega = 0.1876$ deg/ sec if we use the determined process parameters.

Table 4

Parameters for calculation of cooling rate of the banding weld

$(T_{600} \cdot 2\pi\lambda\delta)/q$	$(T_{500} \cdot 2\pi\lambda\delta)/q$	$(vx_{600})/2a$	$(vx_{500})/2a$
0.5922	0.4935	2.43	3.62
x_{600}, cm	x_{500}, cm	t_{600}, sec	t_{500}, sec
20.5714	30.6450	1088.44	1621.45

Also the research of temperature distribution in the weld cross-section was carried out. It has been defined that there are no significant deviations of temperature when using the proposed regime parameters. In particular, the calculation of temperature of areas closed to the weld at a distance of 250 mm from the heating zone shows that it equals 516 °C. Herewith, the temperature changes in the weld cross-section of the banding shell don't exceed 68 °C. Therefore, the value of welding stresses along the thickness isn't large. This ensures the reduction of residual level of volumetric stress state and facilitates the increasing of crack resistance [10; 11].

The determined cooling rate is used for evaluation of the metal structure in the area of thermal influence. The optimal range of the cooling rate during the welding at the area around the weld equals 0.12–7.0 deg/sec according to the data of changing of the structure and properties of steel 35 [14]. Therefore, when using the proposed parameters of electroslag process we observe the formation of high-quality weld.

In order to define the structure and phase composition, it is expedient to use the corresponding diagram for particular steel (Fig. 4) [14]. Its analysis has shown that the steel structure at the initial state is ferritic one with the mix of perlite and bainite. Herewith, the range of existing of such structural components is rather small. The increasing of the cooling rate from 1.0 deg/sec causes the formation of martensite. In the optimal range of the cooling rate its quantity may vary up to the 30 % when the rate equals 7 deg/sec. The usage of electroslag welding and the determined regime parameters ensures the reduction of the material cooling rate up to the fixed values of the initial state.

The vertical line which defines the cooling rate for the accepted welding conditions is shown in the Figure 4. After the welding carrying out the structure will be of ferritic type with slightly larger content of perlite and bainite. The following ration of structural components has been determined: ferrite – 39 %, the mix of perlite and bainite – 61 %.

The influence of the proposed parameters of electroslag welding on the strength of metal of the areas around the weld has been determined with a help of corresponding dependencies (Fig. 5) [14]. In particular, it has been defined that the increasing of the cooling rate of the weld metal of steel 35 causes the reduction of the plasticity characteristics and increasing of the metal strength. This may be explained by the redistribution of the structural components which leads to increasing of the content of perlite and bainite.

Herewith, these changes are not critical in the optimal range of the cooling rate. However, the increasing of the content of martensite structural component causes a sharp reduction of plasticity characteristics when the rate exceeds 8 deg/sec. Herewith, the ultimate strength and the hardness of material are sharply increasing. The investigated technology of electroslag welding (which is shown by the vertical line) ensures slow heating of the ares around the weld and obtaining of satisfactory plasticity characteristics.

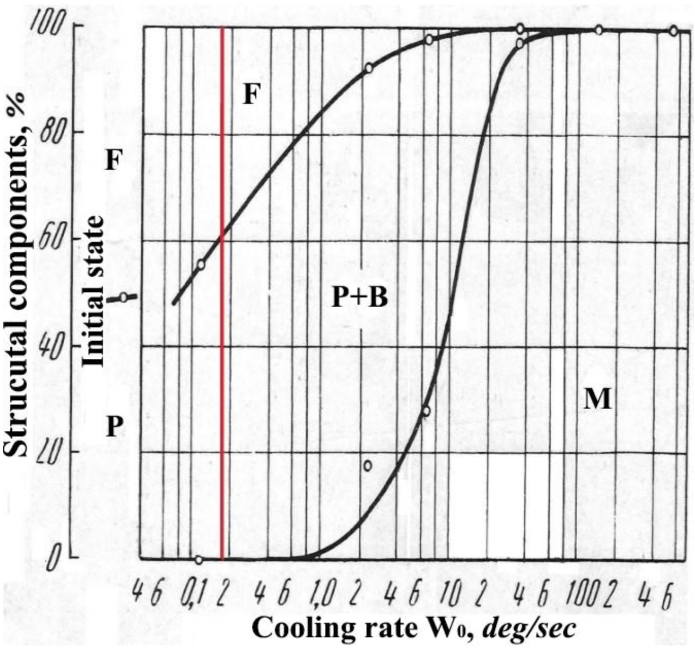


Fig. 4. *Diagram of anisothermal transformation of austenite in the steel 35*

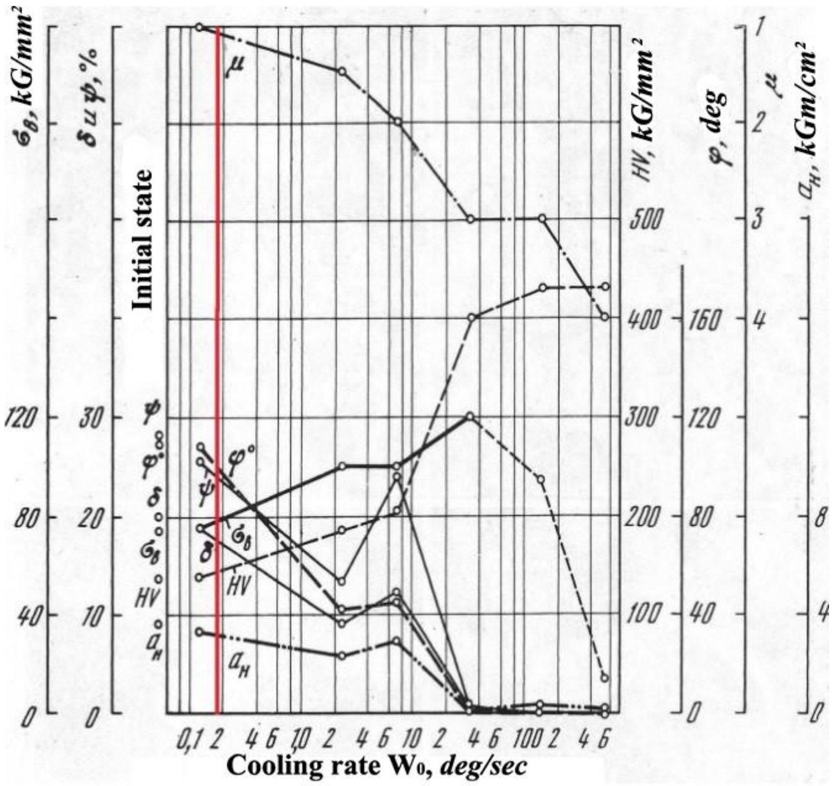


Fig. 5. *Dependence of mechanical properties of the steel 35 on the cooling rate*

Conclusions

Therefore, the obtained results show that on the basis of generalized data of usage of combined techniques of parameters determination of electroslag welding conditions (nomogram, graphical dependence and empirical formulas) it is possible to define their optimal values. The proposed in the paper technique of usage of specialized nomograms allows to determine the cooling rate of the areas around the weld during the electroslag welding. When carrying out the welding according to the proposed conditions, the satisfactory structure and phase content and mechanical characteristics of material of the zone of heat (thermal) influence of the weld may be reached.

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