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Simulation Of Thermal Processes At Electron-Beam Welding With Beam Splitting

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Abstract

The mathematical model describing distribution of temperatures at electron-beam welding with beam splitting on three is presented. Let's consider strangers of the mathematical model describing distribution of temperatures at electron beam welding with beam splitting on three. The proximity of steam-gas channels results to the change of temperature-time modes of the welding which differ from a thermal cycle at one-beam welding. This directly influences on the structure of a weld and heat-affected zones. Besides, the proximity of steam-gas channels influences on hydrodynamic processes in a welding pool. Also an additional remelt of the metal in a weld by the following beam can take place. To forecast the processes occurring in a welding pool and forming structure it is necessary to know the character of temperature distribution, the shape and the dimensions of a welding pool. The given model can be used for the exposition of the final sizes of a weld pool, on a crystallization isotherm, for different materials. Results of calculations for experimental samples from an aluminium alloy, steels, and as from heterogeneous materials: a steel-bronze, are presented.

Keywords: electron-beam welding, beam splitting, pool welding, welds, heat conduction equation, distribution of temperatures, crystallization isotherm.

Introduction

The electron beam is practically without a slugged source of thermal energy, that allows to realize fast roadability a current, an aberration and position of focus of a beam. With development of new control systems by an electron beam and programming of conditions of welding there were possibilities of perfecting of processing methods EBW, ensuring almost unrestricted variety of conditions of effect of a beam on a work piece surface (oscillation a beam on various aspects of trajectories, multifocal welding (fig. 1), dynamic positioning of a beam, etc.) [1]

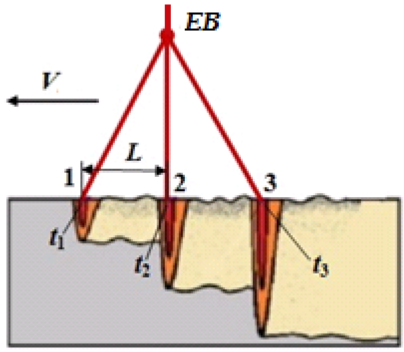

Fig.1. Circuit EBW 3-pool welding: V-speed of welding; EB-an electron beam; 1, 2, 3-points of effect of an electronic beam on a worked surface; t_1, t_2, t_3-time of effect of an electron beam in each point; L-distance between points [4].

Last year's electron-beam welding with dynamic positioning of a beam (beam splitting) is widely applied. At such welding the formation of several thermal sources occurs which provides simultaneous introduction of heat into workpiece in the sites located on some distance from each other. Electron-beam splitting allows to carry out welding with different variations, for example: welding in several zones at the same time; welding with the formation of several welding baths (multi-pool welding), or combination of welding and hardening [2, 3].

The technique of beam splitting on the concentrated thermal sources, along with increase productivity of the process, allows quality of welded joints, such of difficult-to-weld materials, as cast irons, titanium alloys [4-6], and as heterogeneous materials, for example at bronze and steel welding [7, 8]. Application of the given technique leads to decrease of porosity in welds, to minimization of cracking probability in welded joints, to production of more homogeneous mixed structure of welds from heterogeneous materials.

Construction of a mathematical model:

Let's consider strangers of the mathematical model describing distribution of temperatures at electron beam welding with beam splitting on three.

At splitting the electron beam scans on the workpiece surface on three points from one to another and backwards with a high frequency (~ 5 кHz and higher). In each point the power of an electron beam has a fixed value ($q = U \cdot I/W$), the time of its interaction t_i changes. Thereby, steam-gas channel and welding pool are formed in each point. When the beam is absent the penetration channel is not destroyed due to a scanning high frequency. Thus, the effect of simultaneous three beam welding is generated.

The proximity of steam-gas channels results to the change of temperature-time modes of the welding which differ from a thermal cycle at one-beam welding. This directly influences on the structure of a weld and heat-affected zones. Besides, the proximity of steam-gas channels influences on hydrodynamic processes in a welding pool. Also an additional remelt of the metal in a weld by the following beam can take place. To forecast the processes occurring in a welding pool and forming structure it is necessary to know the character of temperature distribution, the shape and the dimensions of a welding pool.

Thermal processes at welding are convenient for describing by means of a differential heat conduction equation in a mobile coordinate system with a fixed heat source:

$$\frac{\partial T}{\partial t} = a \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + V \frac{\partial T}{\partial x} + \frac{1}{c\rho} \cdot F(x,y,z,t) , \quad (1)$$

where $F(x,y,z,\tau)$-a function heat source.

One way for solving of a heat conduction problem is the method of sources (the method of Green functions). This method allows to receive analytical solutions depending on different boundary value problems and the character of a welding power source. An instant point source which is described with the use of delta in Dirac $\delta(x)$ function is applied for Green function definition. Integral solution of heat conduction problem goes like this:

$$T(x,y,z,\tau) = \int_\tau \int_z \int_y \int_x G(x,x',y,y',z,z',\tau) \cdot F(x,y,z,\tau) \partial x' \partial y' \partial z' \partial \tau , \quad (2)$$

where $G(x,x',y,y',z,z',\tau)$-a Green function.

The Green function supposes a deficient separation of variables (it is disjointed on space variables x, y, z, but it is not disjointed on time τ), i.e. can be presented in the form of product of the one-dimensional Green functions selected proceeding from edge conditions:

$$G(x,x',y,y',z,z',\tau) = G_x(x,x',\tau) \cdot G_y(y,y',\tau) \cdot G_z(z,z',\tau) . \quad (3)$$

For an estimation of character of distribution of temperature fields at EBW often use mathematical models in which thermal effect of an electron beam is considered as effect of continuously operating combined source [9,10,11]. In works [11] the models of distribution of temperature fields in an infinite plate for the combined source of heat consisting from normally arranged on surface and linear on depth is offered. In this case function of sources of heat we are described as:

$$F(x,y,z,\tau)=\frac{q\eta}{c\rho}\cdot\left(k1\cdot\delta(x')\delta(y')\delta(z')E(\tau)+\frac{k2}{h}\cdot\delta(x')\delta(y')E(z')E(\tau)\right)$$

$$E(z')=\begin{cases}1\,at\;0\le z'\le h\\0\;at\;h<z'<0\end{cases};\quad E(\tau)=\begin{cases}1\,at\;t0\le\tau\le t\\0\;at\;\tau>t\end{cases};\quad t0=\frac{1}{4aK};\quad K=\frac{12}{d^2} \qquad (4)$$

where q-power of an electron beam, η-efficiency, c-a specific thermal capacity, ρ-tightness of metal, *k1* and *k2*-the factors considering distribution of power of a beam between sources, h-depth of a linear source, E*(z')* and $E(\tau)$-unit functions, *t0*-time of operation of the dummy source imitating effect of an is normal-circular source, K-factor of a concentration for the set diameter electronic beam d.

Integral solution of a heat conduction problem for EBW with the use of a stationary beam for an endless plate is described in the following way:

$$T(x,y,z,\tau)=\frac{k1\cdot q\eta}{4c\rho\cdot\left(\sqrt{\pi a}\right)^3}\cdot\int_{t0}^{t}\frac{1}{\left(\sqrt{\tau}\right)^3}\cdot\exp\left(-\frac{(x+V\cdot\tau)^2-(y)^2}{4a\tau}\right)\cdot\sum_{n=-\infty}^{\infty}\left(\exp\left(-\frac{(z+2n\delta)^2}{4a\tau}\right)\right)d\tau+$$

$$+\frac{k2\cdot q\eta}{8h\pi\lambda}\cdot\int_{t0}^{t}\frac{1}{\tau}\cdot\exp\left(-\frac{(x+V\cdot\tau)^2-(y)^2}{4a\tau}\right)\cdot\sum_{n=-\infty}^{\infty}\left(erf\left(\frac{z+h+2n\delta}{2\cdot\sqrt{a\tau}}\right)-erf\left(\frac{z-h+2n\delta}{2\cdot\sqrt{a\tau}}\right)\right)d\tau \qquad (5)$$

For three-pool electron beam welding it is possible to present the temperature distribution as superposition of temperature fields from simultaneously acting three beams with the power $q_{i,}$ described by the equation (5).

$$T(x,y,z,\tau)=T_1(x,y,z,\tau)+T_2(x,y,z,\tau)+T_3(x,y,z,\tau). \qquad (6)$$

Thus power of each electronic beam q_i will vary in time with definite periodicity:

$$q_i(\tau)=\begin{cases}q\;at\;0\le\tau\le t_s\\0\;at\;t_s<\tau<T\end{cases};\quad q_i(\tau)=q_i(\tau+kT), \qquad (7)$$

where q-power of not split electron beam, t_s-time of activity of a beam in a point, T-the period of repetition of a signal, k-amount of cycles, an integer.

Such periodic activity of a beam power in time represents a rectangular signal (fig. 2), which can be described as Fourier series:

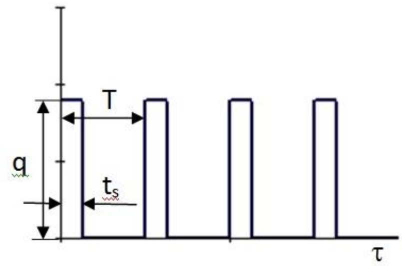

Fig 2. The circuit change of a beam power in time

$$q_i(\tau)=\frac{a_0}{2}+\sum_{k=1}^{\infty}a_k\cos\frac{2k\pi\tau}{T}+b_k\sin\frac{2k\pi\tau}{T}, \qquad (8)$$

where a_0, $a_k b_k$-Fourier series factors defined as:

$$a_0 = \frac{2}{T}\cdot\int_0^T q_i(\tau)d\tau;\quad a_k = \frac{2}{T}\cdot\int_0^T q_i(\tau)\cos\frac{2k\pi\tau}{T}d\tau;\quad b_k = \frac{2}{T}\cdot\int_0^T q_i(\tau)\sin\frac{2k\pi\tau}{T}d\tau$$

After transformation factors of a Fourier series for (7) and function of change of beam power from time in everyone steam-gas channel the port (8) look like:

$$a_0 = \frac{2qt_s}{T};\quad a_k = \frac{q}{k\pi}\cdot\sin\frac{2k\pi t_s}{T};\quad b_k = \frac{2q}{k\pi}\cdot\sin\left(\frac{2k\pi t_s}{T}\right)^2 \tag{9}$$

$$q_i(\tau) = q\frac{t_s}{T} + \frac{t_s}{T}\cdot\sum_{k=1}^{\infty}\frac{1}{k}\cdot\left(\sin\frac{2k\pi\tau}{T} + \sin\frac{2k\pi(t_s-\tau)}{T}\right) \tag{10}$$

The first member of the equation (10) represents average value of the beam power and the second member of the equation takes into account the influence of power harmonic oscillations.

It is known as also other introducing of a Fourier series which powers up performances of a spectral analysis of periodic series:

$$q_i(\tau) = A_0 + \sum_{k=1}^{\infty} A_k\cdot\left(\cos\frac{2k\pi\tau}{T} + \varphi_k\right) \tag{11}$$

where $A_0 = \frac{a_0}{2T}$ -average value of amplitude of harmonics, $A_k = \sqrt{a_k^2 + b_k^2}$ - amplitude k harmonics (amplitude-frequency characteristic), $\varphi_k = -arctg\frac{b_k}{a_k}$ -phase k harmonics.

As in each penetration channel an electron beam performs high-frequency oscillations (~ 5 кHz and higher), and time of its activity reaches tens microseconds it is possible to assume that the beam acts with some fixed average power, which is lower than the power of unsplit beam. In the first approximation we may accept A_0 average value of amplitude of harmonics from the equation (11) for such power. However, the influence of high-frequency harmonics will not be taken to consideration. The spectral analysis of an amplitude-frequency characteristic for rectangular periodic oscillations has shown that the amplitude got the maximum value in the first harmonic (fig. 3), and its value would depend on oscillations ratio (T/t_s).

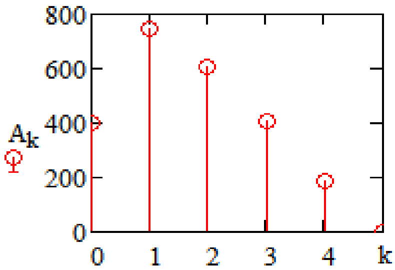

Fig 3. Spectrum of amplitudes for periodic oscillations of power at q-2000 W, t_s-40 μs, T-200 μs, f-5 кHz

Proceeding from this, we will accept that average power in each penetration channel will be defined as amplitude of the first harmonic:

$$q_i = A_1 = \sqrt{a_1^2 + b_1^2} = \frac{2q}{\pi} \cdot \sin\frac{\pi t_s}{T}. \qquad (12)$$

Having meant $q_i = m_i \cdot q$, and having substituted in the equation (12), we receive:

$m_i = \frac{2}{\pi} \cdot \sin\frac{\pi t_s}{T}$ - the factor considering a fraction of power from not split beam.

Having substituted in the equation (5) instead of q (powers of an electron beam) $m_i \cdot q$, we receive the equation for calculation of temperatures for each split beam.

Thus, the mathematical model distribution of temperatures for three-pool electron beam welding is reduced to the equations (5, 6). Realization of the received model has been carried out in mathematical package Mathcad.

Application of mathematical model for experimental samples

With the use of the given model the calculations for experimentally welded samples from aluminium alloy, austenitic steel and heterogeneous steel-bronze joint have been carried out.

Figure 4 shows distribution of temperatures in longitudinal-section (a) and cross-section (b) for alloy AlMg6, welded three-pool electron beam welding under the circuit of split **1-2-2** (t_1-40 μs; t_2, t_3-80 μs; T-200 μs; f-5 кHz,), q-2400 W, V-10 mm/s, L-2 mm. The white line shows the crystallization temperature of alloy defining the sizes of a weld pool. The cross-section is constructed in the field of the maximum sizes of a weld pool and corresponds to a weld cross-section (fig. 4, c).

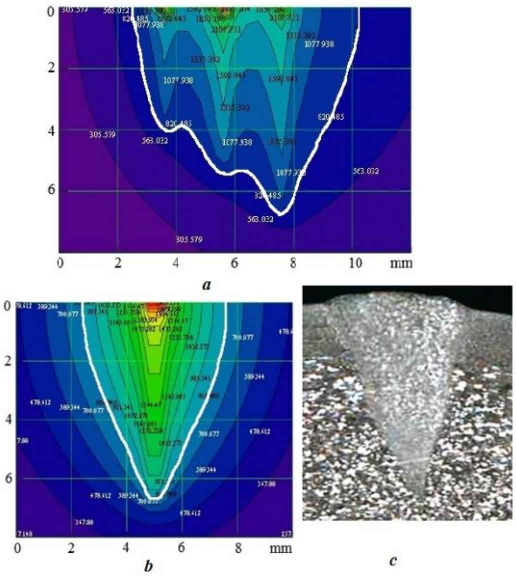

Fig. 4. Distribution of temperatures in longitudinal (a) and cross (b) section for alloy AlMg6, c-weld macrostructure in a cross-section

On figure 5 are presented the calculated sizes of a weld pool in longitudinal-section and a cross-section for a steel 12Cr18Ni10Ti, welded under the circuit of split 1-2-2, *q*-2400 W, *V*-5 mm/s, *L*-2,5 mm are presented. Dotted lines on fig. 5 correspond to isotherms of crystallization caused by the interaction of three split beams, and the points correspond to the experimental size of a weld.

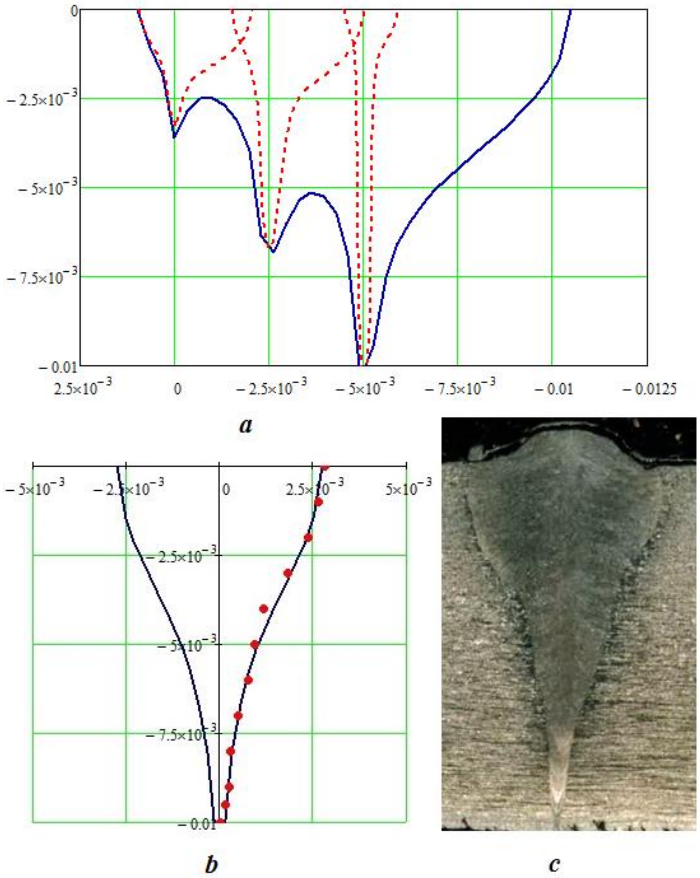

Fig. 5. The shape of a welding pool (a crystallization isotherm) in longitudinal (a) and cross (b) section for a steel 12Cr18Ni10Ti, c-a weld macrostructure in a cross-section

The presented mathematical model has been used for the assaying of the reasons of formation of structure of metal of a weld at welding of the heterogeneous joint, consisting their noncorrosive austenitic-ferrite steel 12Cr21Ni5Ti and a chromium copper of BrCr-08. In figure 6 the macrostructure of a welded connection and a microstructure in various parts of a weld from a steel 12Cr21Ni5Ti – bronze BrCr-08 are presented. These are results of the researches spent by us earlier, and presented in work [8].

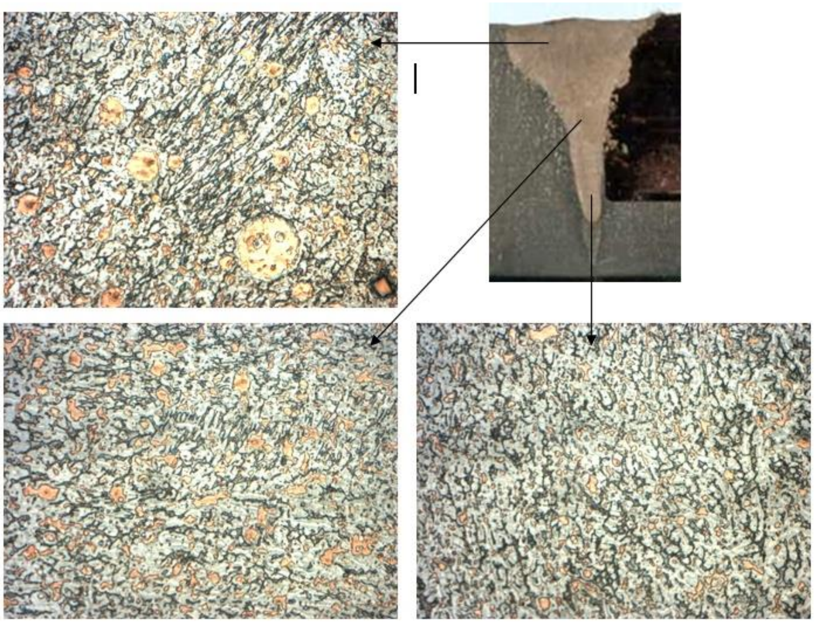

Fig. 6. A macrostructure of a welded joint from a steel 12Cr21Ni5Ti – bronze BrCr-08 and a microscopic structure in various parts of a seam (increase × 600)

Welding was conducted with beam splitting on four ones: three pools and the fourth warming raster from bronze to the temperature up to of 450 °C (fig. 7). A welding regime: *U*-60 kV, *I*-85 mA, *V*-6 mm/s, t_1-45 µs, t_2-60 µs, t_3-40 µs, t_4-65 µs, *T*-65 µs, *L*-5 mm.

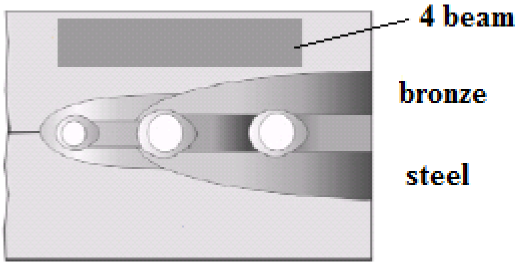

Fig. 7. The circuit design of splitting of an electronic beam at welding

For calculation of temperatures distribution the fourth component has been introduce to the equation (6) a warming up raster which was defined as:

$$T_4(x,y,z,\tau) = \frac{q_4\eta}{16c\rho\sqrt{\pi a}\cdot B\cdot C}\cdot\int_{t0}^{t}\frac{1}{\sqrt{\tau}}\cdot\left(erf\left(\frac{x+B+V\cdot\tau}{2\cdot\sqrt{a\tau}}\right)-erf\left(\frac{x-B+V\cdot\tau}{2\cdot\sqrt{a\tau}}\right)\right)\cdot$$

$$\cdot\left(erf\left(\frac{y+C}{2\cdot\sqrt{a\tau}}\right)-erf\left(\frac{y-C}{2\cdot\sqrt{a\tau}}\right)\right)\cdot\sum_{n=-\infty}^{\infty}\exp\left(-\frac{(z+2n\delta)^2}{4a\tau}\right)d\tau \qquad (13)$$

where *B* =10 mm-length of a raster, *C* = 5 mm-width of a raster.
The equation (13) is obtained by the solution of a problem of heat conductivity a method of functions of Green for a superficial right-angled heat source in an infinite plate.
In figure 8 represented temperature distribution in longitudinal-section, the white line marks out temperature of a weld crystallization. Apparently when affecting by the second and the third beams remelting of the weld obtained by first beam occurs. When affecting by the first beam there is a partial mixing of two heterogeneous materials caused by hydrodynamic processes in the weld pool. The formed weld is exposed to repeated remelting at which hydrodynamic processes from the second and the third beam lead to its additional mixing in the weld pool. As the result the weld with homogeneous structure is formed (fig. 6).

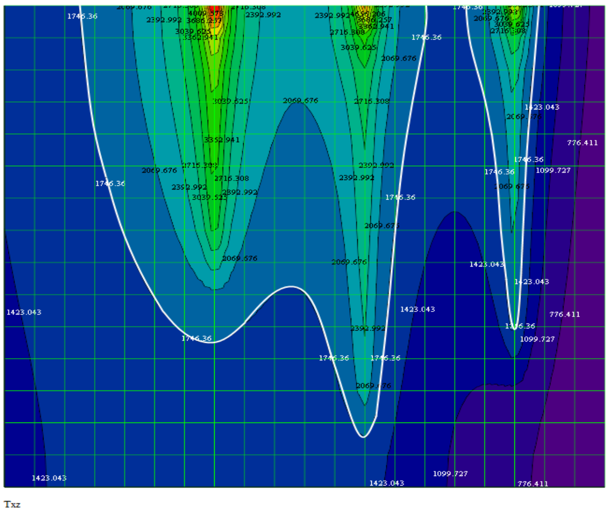

Fig. 8. Distribution of temperatures in an longitudinal-section

Conclusions

The obtained model allows to calculate the temperature distribution and the final size of a weld pool at EBW with splitting beam for various materials. Given results can be used for the analysis of the processes occurring in a weld pool and forming structure, and also for the selection of optimal conditions of welding for the production of the required structure.

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References:

[1] Bashenko V.V, Vihman V.B. Sostojanie and perspective of development of electron beam welding. Techniques and the equipment of electron beam welding//Materials of Sankt-Peterbursky The international scientific and technical conference, on May, 19-22th, 2008 // SPb.: Open Company "Agency" the Vit-print ”», 2008. – With. 5-21.

[2] Masny H. Multi-Beam Technology in Electron Beam Welding – Welding and Joining Institute.-2006.-Vol. 34.-P. 1-4.

[3] Zenker R. Modern thermal electron beam processes-research results and industrial application – La metallurgia italiana.-2009. – Issue 3. – P 1-8.

[4] Rüthrich K., Zenker R., Mangler M. Investigations Relating to Electron Beam Multipool Welding of Metal Welds Based on Cast Iron // 64th Annual Assembly and International Conference of the International Institute of Welding/-Chennai (Indien).-2011.

[5] Rüthrich K., Zenker R., Freiberg D. Characteristics and Prospects of Process Integrated Thermal Field Heat Treatment for Electron Beam Welding of Cast Iron // 2nd Electron beam welding Conference. – DVS BERICHTE. – 2012.

[6] Peng-Fei Fua, Zhi-Yong Mao. Temperature field modeling and microstructure analysis of EBW with multi-beam for near a titanium allos – Huazhong University of Science and Technology. –2013.-Vol.102.-P.54-62.

[7] Belenkiy V.Ya., Krotov L.N., Olshanskaja T.V., Abdullin A.A., Mladenov G. M, Koleva E.G., Bykov S.I. Welding high-strength steels with bronze with use of dynamic positioning of an electronic bundle Welding and diagnostics. – 2014. – № 1. – P. 48-49.

[8] Olshanskaya T.V., Permyakov G.L., Belenkiy V.Y., Trushnikov D.N. The influence of electron beam oscillation on the crystallization and structure of dissimilar steel-bronze welds – modern applied science, 2015, V 9, № 6, P 296-309, ISSN: 1913-1844, DOI: 10.5539/ mas.v9n6p296,http://ccsenet.org/journal/index.php/mas/article/view/49528/26696

[9] Rykalin N. N, Edges And. A, Zuev I.V. Fundamental of electron beam handling of materials. M: Machine industry. 1978.-239 p.

[10] Rykalin N. N, Edges And. A, Zuev I.V., Kokora A. N. Laser and electron beam handling of materials: Directory / M: Machine industry, 1985.-496 p.

[11] Yazovskih V.M. Mathematical simulation and engineering methods of calculation in welding: in 2 p. P. 2. Thermal processes at welding and simulation in bundle MathCad.-Perm: Publishing house PGTU, 2008, 119 p.