Temperature spread modeling of electron beam heating process

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Abstract. The research and creation of the mathematical model of temperature distribution in the electron beam heating, depending on the technological parameters are considered in this paper. A feature of this mathematical model is used by the process of producing welds of parts from aluminum alloys. Aluminum alloys are of great interest for various industries, such as aerospace, aviation, automotive, oil and gas, chemical industry and others, because the aluminum alloys has low weight. However, when welding aluminum alloys, various defects can occur, such as porosity or hot cracks, which limit it uses. One of the main problems is connected with the welding of aluminum alloys this is a problem of determining the causes of porosity during the design and technological preparation and production of products prototypes from the new alloys, also the recommendations preparation for the welding technology of these products.

1. Introduction

The electron beam welding is widely used by the process of production of details for the rocket-space industry, which permits to obtain the high-quality welded joints of materials of large thickness. However, there remains a probability of porosity of the welded joints obtained by this method.

There are many causes of porosity. The study of the porosity of welded joints obtained by electron-beam welding is devoted to the work of such famous scientists as P-A Legait, J.L. Murphy, O.K. Nazarenko, V.V. Bashenko, A.G. Grigoryants, T.V. Olshanskaya, R.V. Egorova and etc. The scientific field of the works of these authors is mainly related to the study of the mechanisms of formation of porosity in aluminum and steel alloys.

In modern time a mathematical model of the dependence of the shape of pores formed in the welded joints produced by electron beam welding has not been obtained. The importance and relevance of this topic for practical application is determined by the goal of developing technological recommendations for the welding parts from aluminum alloys at industrial enterprises, there the radial welding technologies are applied.

2. Simulation of electron beam welding

Some results, techniques and methods of mathematical modeling of the electron beam, the channel of penetration and heat transfer during electron beam welding are widely described by the scientific sources [1–3]. These are models developed by Sudnik V.A. in the LASIM program [4], imitations based on the SYSWELD program [5], and etc.

The impact of a powerful electron beam causes phase transformations in a thin surface layer of a substance, occurring in extreme conditions. Various thermal processes arise, one of the variants of the description of which is the mathematical problem of Stefan [6]. The solution of such problems is found by numerical methods. Methods for solving the tasks of Stefan are divided into two classes with explicit and implicit selection of boundaries. The explicit methods use moving difference grids that monitor the movement of phase fronts. In turn the implicit methods use fixed difference grids.

The enthalpy formulation of the task with a fixed difference grid [7] makes it possible to simultaneously take into account thermal processes and phase transformations.

The mathematical model, built on this method, permits calculating the boundaries of the heating and melting zones η at any time and evaporation zone boundariesξ. The error in the calculation of these limits is 30÷50%. This is explained by the fact that a number of factors influencing the process are not taken into account, such as electron beam scattering on evaporation products, hydrodynamic processes. The main advantage of this method is the ability to analyze the dynamics of the initial phase. Due to the complexity and bulkiness of the mathematical apparatus, it is not possible to calculate the heating parameters in real time. Therefore, for practical purposes, the method under consideration is not used with the current level of technology. The practical application can find methods for calculating the relatively simple formulas using microprocessor means [8].

3. Calculation of the temperature field

At low power values, when the material is not destroyed, the only consequence of the action of the electron beam on the material is heating. If the parameters of the electron-beam heat source are known, the temperature field in the material being processed is determined by solving the problem of thermal conductivity. In particular, for an axisymmetric electron beam incident normally to the surface of a semiinfinite solid, the heating problem has the form [6]:

$$\frac{1}{a}\frac{\partial T(r,z,t)}{\partial t} - \Delta T(r,z,t) = \frac{q(r,z,t)}{\lambda}$$

There is a problem of the temperature field of a semibounded solid heated by a volume source to estimate the critical parameters of a heat source [6].

The volumetric heat source can be described by the following equation:

$$q(x', y', z') = q_0 \exp\left[-(x'^2 + y'^2)\, k_1 - (z' - h)^2 k_2\right].$$

To determine the temperature of the heated metal at an arbitrary point A *(x, z),* it is necessary to know the nature of its distribution over the thickness of the interlayer in the cross section passing through this point.

The heating temperature is unevenly distributed, especially in a thickness. It was found that the average heating temperature is practically independent of the process mode and varies over a wide range.

The calculation of the temperature field is simplified, if conditions of tasks with sufficient accuracy for practice, that is possible to take the thermal conductivity coefficient λ and volume specific heat constant $c\rho$. Then the differential heat equation becomes linear and takes the form

$$\frac{\partial T}{\partial t} = \frac{\lambda}{c\rho}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{q_3}{c\rho} = a\nabla^2 T + \frac{q_3}{c\rho},$$

where $a = \dfrac{\lambda}{c\rho}$ is a thermal conductivity coefficient, cm^2/sec and

$$\nabla^2 = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right);\ \nabla^2 T = \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right).$$

When heated “per pass”, i.e. when the metal in the zone of the heating source is heated to the full thickness, the temperature through the thickness of the metal $T(z)$ can be considered constant.

In this case, the aluminum plate of thermal scheme is realized and the temperature field is two-dimensional (flat) $T = T\ (x, y, t)$. In the linear element of the heat-conducting body, which owns an infinitely long prism form with a small *dxdy* base, at the initial moment of time $t = 0$ we input a heat distributed uniformly along the length of this prism with intensity Q_1 J/cm.

The temperature field resulting from the action of an instantaneous linear source, by virtue of the linearity of the problem, can be obtained by superposing the temperature fields of an infinite number of instantaneous point sources uniformly distributed along the axis *z*, coinciding with the prism axis, and introducing heat into the element of length $dz\ dQ = Q_1\ dz$. At the same time for the temperature of any point of the solid

$$T(x,y,t)=\frac{Q_1\exp\left(-\dfrac{x^2+y^2}{4at}\right)}{c\rho(4\pi at)^{3/2}}\int\limits_{-\infty}^{\infty}\exp\left(-\frac{z^2}{4at}\right)dz\,.$$

The fundamental heat equation for this case

$$T(x,y,t)=\frac{Q}{c\rho s(4\pi at)}\exp\left(-\frac{r^2}{4at}\right).$$

The temperature field of the instantaneous linear source at a given time depends only on the flat radius vector $r=\sqrt{x^2+y^2}$, and its isothermal surfaces are circular cylinders whose axis coincides with the axis of the source. In this case, the isothermal lines in the y_z plane are straight lines, and in the *xy* plane is a circles.

The study of temperature in the heating zone was carried out by numerical simulation in the “Comsol Multiphisics”. This software package provides all the stages of the simulation. The applied computational grid is more detailed in the vicinity of the beam in order to adequately solve the modeling problem. The investigated medium is considered to be isotropic linear, and the thermal field of the welding process is quasi-stationary.

The solution of the corresponding boundary-value problem is carried out on the basis of its finite-element approximation with the subsequent application of the iterative method. The source model (electron beam) is shown in Figure 1.

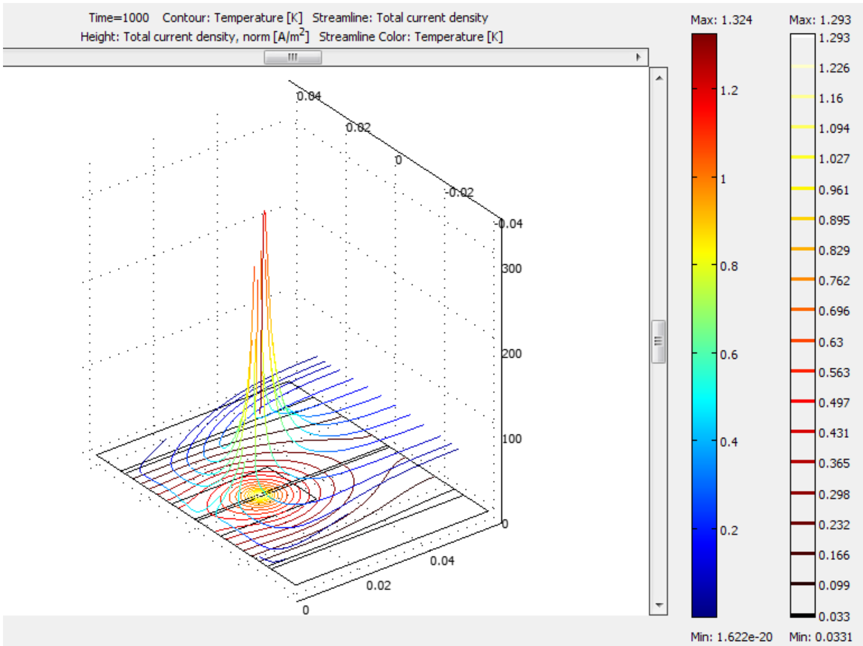
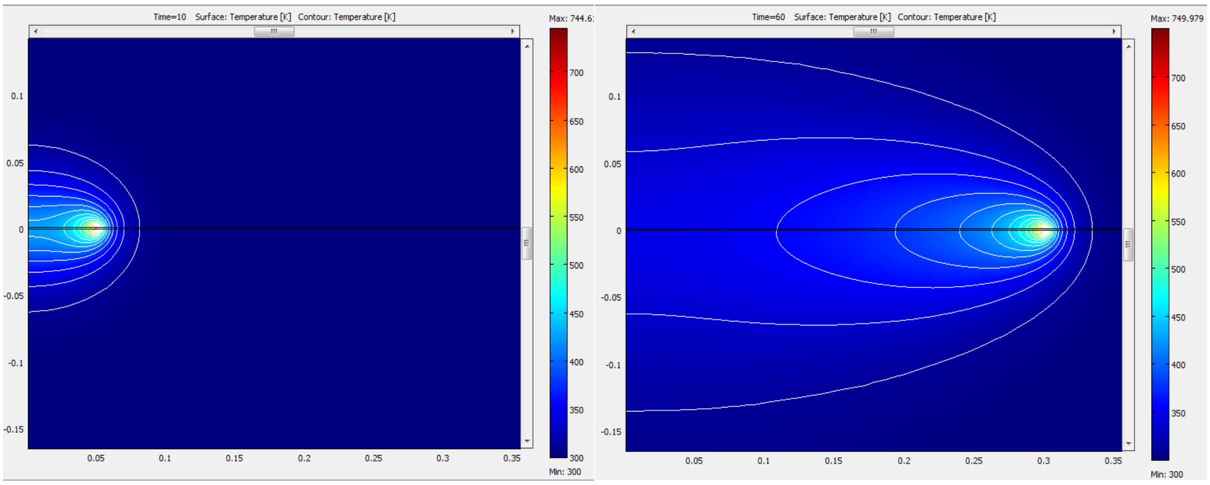


Figure 1. Electron beam heating model

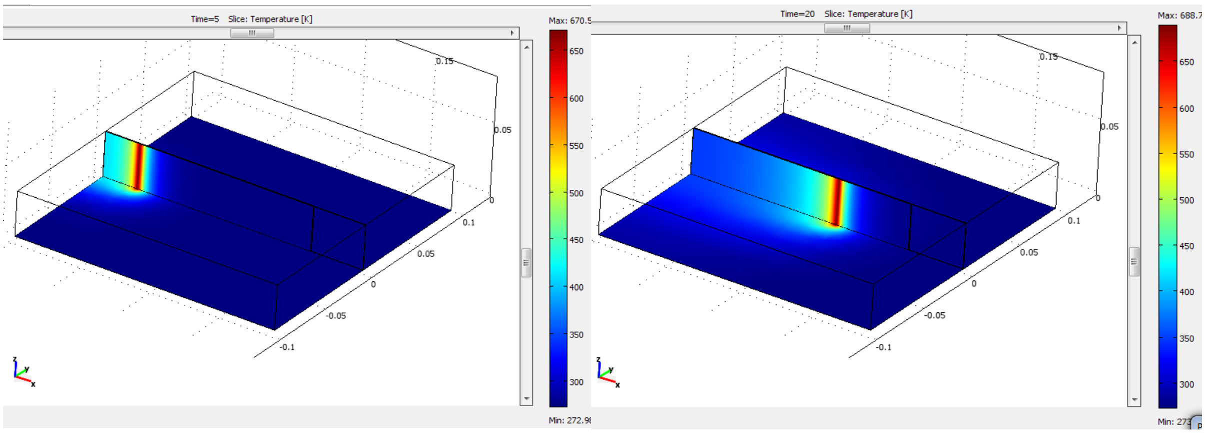
For solving the system of linear equations that are formed when solving partial differential equations, the specialized library UMFPACK (the library includes direct and iterative algorithms) is used.



a b

Figure 2. Simulation of a temperature field in the electron beam heating at time t =: a - 10, b - 60 second

Figures 2 and 3 show the results of temperature simulation in a heated product at different points in time.



a b

Figure 3. Three-dimensional simulation of the temperature field with an electron beam heating at time t =: a - 5, b - 20 seconds

The presence of a sharp temperature gradient changes the movement of gas bubbles in a liquid, i.e. the velocity component appears in the direction of increasing temperature.

The finite element grid for performing calculations on the three-dimensional model used in the work is presented in Figure 4. In the heating area, the grid is made denser to improve the accuracy of the calculations performed by software.

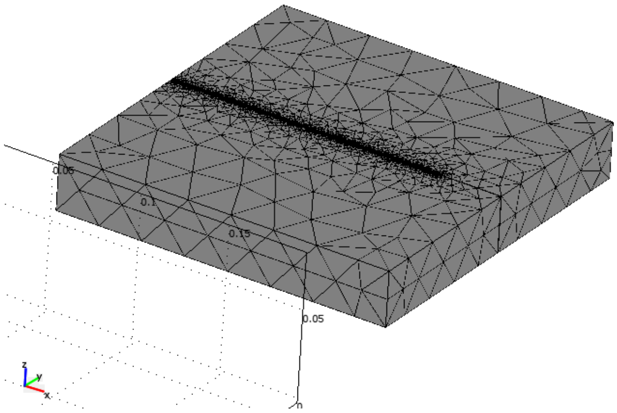


Figure 4. Modeling grid

4. Conclusion

The developed mathematical model of the temperature distribution in electron beam heating allows evaluating the influence of various process parameters on the degree of heating and, as a consequence, the appearance of various structures in the processed metal. On the basis of the obtained results, technological recommendations were developed aimed at obtaining certain properties of the metal processed by electron beam heating.

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