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Numerical simulation of electron beam welding with beam oscillations

D N Trushnikov and G L Permyakov

The department for Welding Production and Technology of Constructional Materials, Perm National Research Polytechnic University, 29 Komsomolsky ave., Perm, 614990, Russia

E-mail: gleb.permyakov@yandex.ru

Abstract: This research examines the process of electron-beam welding in a keyhole mode with the use of beam oscillations. We study the impact of various beam oscillations and their parameters on the shape of the keyhole, the flow of heat and mass transfer processes and weld parameters to develop methodological recommendations. A numerical three-dimensional mathematical model of electron beam welding is presented. The model was developed on the basis of a heat conduction equation and a Navier-Stokes equation taking into account phase transitions at the interface of a solid and liquid phase and thermocapillary convection (Marangoni effect). The shape of the keyhole is determined based on experimental data on the parameters of the secondary signal by using the method of a synchronous accumulation. Calculations of thermal and hydrodynamic processes were carried out based on a computer cluster, using a simulation package COMSOL Multiphysics.

1. Introduction

Currently, there have been widely known advances in the numerical simulation of electron-beam welding (EBW) and laser welding [1-3]. However, all results are related to modeling of welding without beam oscillations. A complete dynamic welding model, including beam oscillations, is still missing. The complex character, high speed of processes, high temperature gradients and multifactorial nature of the process make the direct numerical simulation of the conditions of periodic actions extremely difficult, even for modern computing resources. The main difficulty in modeling is determining the shape of the keyhole.

To solve this problem, a method for experimental determination of the keyhole shape using the parameters of the secondary signal in EBW with beam oscillation has been proposed [4]. Apart from the keyhole shape, this method provides additional information about the processes in the channel. In particular, this technique can be used to determine the distribution of the beam energy on the channel walls [5]. This approach eliminates the need to take into account all the complex factors that affect the formation of the keyhole.

The purpose of this study is to use these parameters as inputs to calculations to determine the effect of different beam oscillations and their parameters on the keyhole shape, the heat and mass transfer and the weld parameters, in the development of methodological recommendations. The calculations for the thermal and hydrodynamic processes were carried out based on a computer cluster, using a simulation package COMSOL Multiphysics. The calculations gave the geometry of the welds, the temperature fields and the flow velocity of the melt.

2. A mathematical model

Figure 1 shows a schematic of the welding model. The process parameters and physical parameters of steel are presented in Tables 1 and 2, respectively.

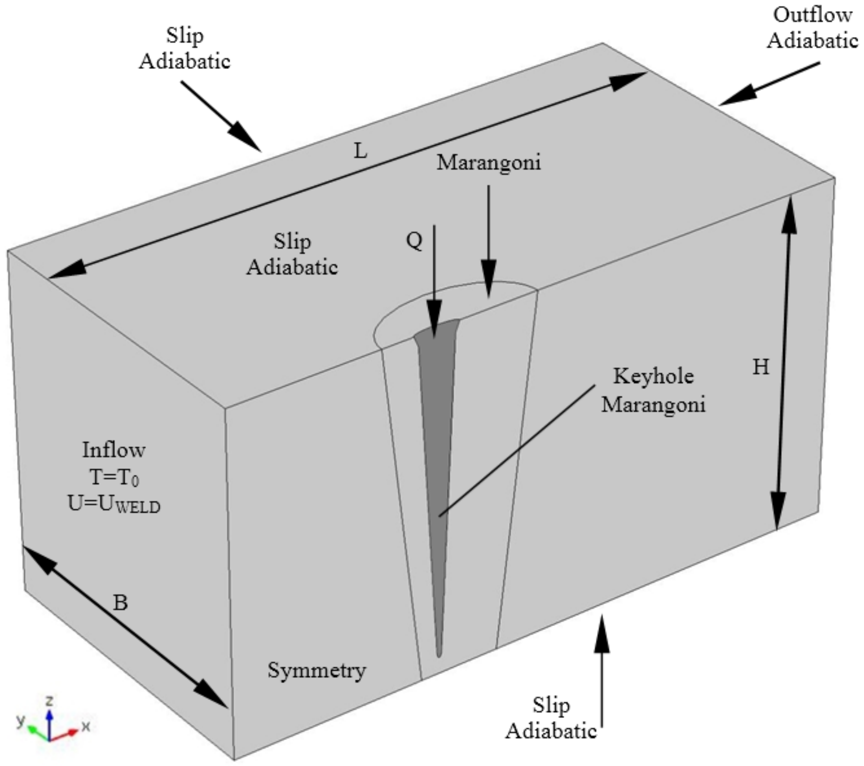


Figure 1. The schematic of the geometry of the model, initial and boundary conditions

Table 1. Process parameters.

Type of oscillations	Beam's parameters		Oscillation's parameters		Welding speed, U[mm/s]
	Power [kW]	Min radius [mm]	Amplitude [mm]	Frequency [Hz]	
Lengthwise	3	0.25	0.75	645	5

Table 2. Physical parameters of steel (0.15 wt. % C, 5 wt. % Cr and around 1 wt. % Mo).

Parameters	Symbol [Unit]	Value
Ambient temperature	T_0 [K]	293.15
Liquidus	T_L [K]	1730
Solidus	T_S [K]	1700
Fusion latent heat	L_f [J·kg^{-1}]	700
Dynamic viscosity	μ [Pa·s]	0.007
Density	ρ [kg·m^{-3}]	7750
Heat capacity	c [J·kg^{-1}·K^{-1}]	483
Thermal conductivity	λ [W·m^{-1}·K^{-1}]	37

The following simplifying assumptions were made when mathematically modeling the welding process:

- Flow is laminar in the weld pool.
- The power distribution in the beam is Gaussian.
- The heat source is linear along the x axis.

- The solid–liquid phase change is modeled by a jump in viscosity and the introduction of the latent heat of the phase transition.
- The shape and dimensions of the keyhole were determined from experimental data. The keyhole was approximated by an oblique elliptical cone with a spherical apex.

2.1 Reconstruction of a keyhole shape

The keyhole's shape is determined by the method of synchronous accumulation. The data of the reconstruction of the keyhole shape in EBW with oscillation along the joint [3, 4] were used for further calculations. These data are presented in Figure 2.

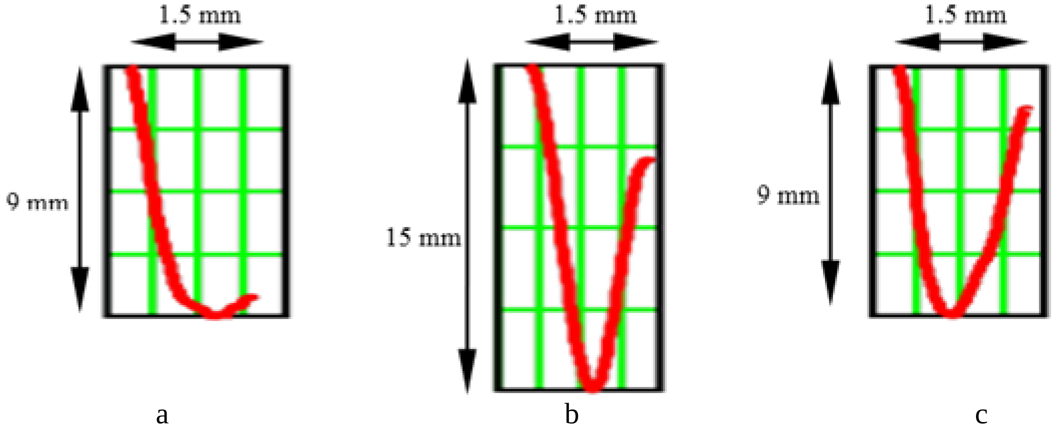


Figure 2. The result of synchronous accumulation for steel welding with oscillation along the joint for different focus regimes (longitudinal projection): a – under-focused; b – sharp focus; c – over-focused modes

2.2 Governing equations

The governing equations for the calculations are as follows [1, 6].

Mass Conservation:

$$\nabla \vec{u} = 0 \tag{1}$$

The equation of motion for an incompressible fluid:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u}\nabla)\vec{u} = \mu \cdot \nabla^2 \vec{u} - \nabla P + F \ , \tag{2}$$

where ρ is density, $\vec{u}$ is the melt flow rate vector, μ is dynamic viscosity, P is pressure, F is force term.

Force term:

$$F = \rho g a(T - T_{ref}) - C\left(\frac{1 - f_L}{f_L^3 + B}\right)\vec{u} + \rho U \frac{\partial \vec{u}}{\partial x} \tag{3}$$

where g is gravitational acceleration, α is thermal expansion coefficient, T the absolute temperature, T_{ref} is reference temperature, taken as a solidus temperature (T_S), U is welding speed.

The liquid fraction:

$$f_L = \begin{cases} 1 & T > T_L \\ (T - T_S)/(T_L - T_S) & T_S \le T \le T_L \\ 0 & T < T_S \end{cases} \tag{4}$$

where T_L is liquidus, T_S is solidus.

The differential equation of energy transfer:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+\upsilon\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=a\cdot\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{Q}{c\rho} \quad (5)$$

where $a = \lambda / C_{eff} \cdot \rho$ is the thermal diffusivity, u, v, w are velocity components along the axes, c is heat capacity, ρ is density, Q is input heat.

The latent heat of melting and solidification was taken into account by introducing effective heat capacity

$$C_{eff} = C_0 + \frac{\exp[-((T-T_{melt})/(T_L-T_S))^2]}{\sqrt{\pi}(T_L-T_S)}H_f, \quad (6)$$

where C_0 is heat capacity depending on temperature, H_f is latent heat, T_{melt} is melting temperature.
The Maramgoni effect:

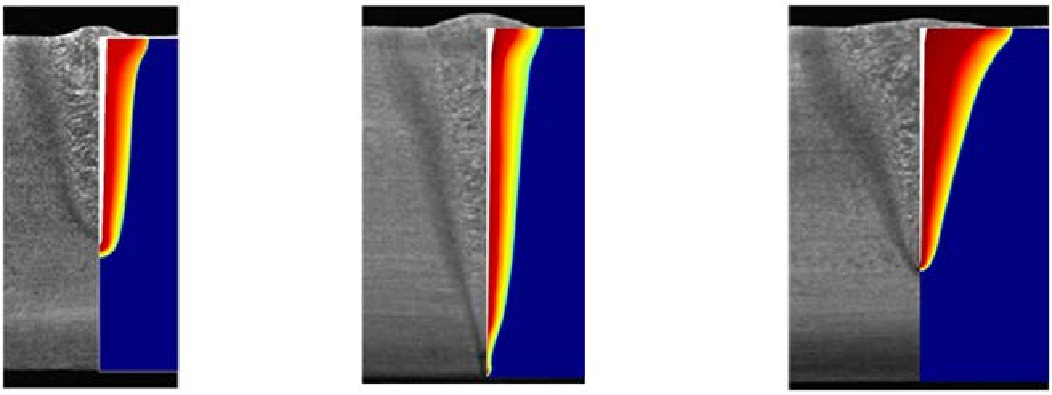
$$\mu\frac{\partial u}{\partial z}=f_L\frac{d\gamma}{dT}\frac{\partial T}{\partial x};\quad \mu\frac{\partial v}{\partial z}=f_L\frac{d\gamma}{dT}\frac{\partial T}{\partial y};\quad \mu\frac{\partial w}{\partial z}=f_L\frac{d\gamma}{dT}\frac{\partial T}{\partial z} \quad (7)$$

where u, v, w are velocity components along axes X, Y and Z, μ is dynamic viscosity, f_L is liquid fraction, $d\gamma/dT$ is temperature coefficient of surface tension, T is the absolute temperature.

This effect is applied to the model as a boundary condition at the top surface of the weld pool and walls of the keyhole. Initial and boundary conditions are presented in Figure 1.

3. Results and Discussion

Figure 3 presents the experimental and calculated cross sections of weld joints for different focus regimes.



a b c

Figure 3 Experimental and calculated cross sections of weld joints for different focus regimes: a – under-focused; b – sharp focus; c – over-focused modes

The calculated and experimental data for sharp and over-focused modes are well correlated. Differences between simulation and experiment for the under-focused mode are caused by errors in determining the depth of the channel.

The analysis of the influence of various factors on the weld's geometry formation and on the probability of defects formation during electron beam welding with oscillation was carried out. Convective phenomena in the liquid phase are one of the reasons of a specific form of welds with the broadening upper part (the characteristic values of the Marangoni and Rayleigh numbers were $5\cdot10^3$

and $2\cdot10^3$ respectively). The intensity of these effects depends on the input energy distribution and on the focusing mode.

4. Conclusions

It is possible to analyze the effect of the oscillation parameters through studying the effect of channel geometry on heat and mass transfer in a liquid bath. The methodology proposed in [4, 5] can be used to determine the geometry of the keyhole. It was found that the intensity of convection caused by the Marangoni effect increases during the transition from the over-focused to the under-focused mode. The intensity of thermogravitational convection in this case is decreased.

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