Numerical and Experimental Study of the Weld Joints Formation in Welding Foam Materials

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Abstract. A numerical analysis of fusion welding of steel- and aluminum-based foam materials is carried out. The schemes of the structured and stochastic pore distribution are considered. The research results were used to conduct the experiments which confirmed the reliability of the numerical calculations.

Keywords: foam materials, heat source, welding, joint, pore mesostructure

INTRODUCTION

In the last two decades the production of aluminum foam, foam steel and other metal-based foam materials in the metallurgy industry has been growing through out the world. The density of the produced foam materials can be 2–10 times lower than of solid metals and alloys. The pore mesostructure of these materials is well pronounced. The linear dimensions of the pores may vary from fractions of a micron to several millimeters. The internal structure of the base material depends on the total porosity of foam materials and the production technology. These ultralight foam materials are promising to be used in such industries as construction, aircraft manufacturing, land and water transport, machine-tool manufacture and others.

Currently, the factor that prevents widespread use of metal foams is the problem of the joint of the materials. The conventional technologies of fusion welding to joint porous details are considered to be hardly suitable. The experience shows that the choice of rational modes to make a quality welded joint by fusion welding is restrained [1, 2]. Therefore, more detailed study is required.

MODEL EQUATIONS

One of the methods to find a rational mode of quality welding is a mathematical model of heating structurally inhomogeneous material by the moving arc source [3]. The form of the model is as follows:
heat equation

$$\rho(T)C_p(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right), \tag{1}$$

the equation of phase transformations:

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$$L_k V_k = \lambda_s \frac{\partial T}{\partial n_{+0}} - \lambda_l \frac{\partial T}{\partial n_{-0}}, \tag{2}$$

energy flux density distribution over the surface of the material in the area of the source action:

$$q(r) = \frac{IU\eta}{\pi e^{-k \cdot r^2}}, \tag{3}$$

the initial and boundary conditions:

$$T(x, y, z, 0) = T_0, \tag{4}$$

$$\lambda_1(T)\frac{\partial T_1}{\partial n} = \lambda_2(T)\frac{\partial T_2}{\partial n}, \ x, y, z \in S_{12}, \tag{5}$$

$$\lambda_1(T)\frac{\partial T_1}{\partial n} = \lambda_3(T)\frac{\partial T_3}{\partial n}, \ x, y, z \in S_{R-r}, \tag{6}$$

$$\lambda_1(T)\frac{\partial T}{\partial n} = q, \ x, y, z \in S_r, \tag{7}$$

$$\lambda_1(T)\frac{\partial T_1}{\partial n} = \lambda_4(T)\frac{\partial T_4}{\partial n}, \ x, y, z \in \Gamma_1, \tag{8}$$

$$\lambda_2(T)\frac{\partial T_2}{\partial n} = \lambda_4(T)\frac{\partial T_4}{\partial n}, \ x, y, z \in \Gamma_2. \tag{9}$$

The designations used in equations (1)–(9) are as follows: $\rho(T)$ is density; $C_p(T)$ is heat capacity; T is temperature; t is time; x, y, z are spatial coordinates; $\lambda(T)$ is the dependence of the thermal conductivity on temperature; L_k is the heat of phase transition (including melting, evaporation and crystallization); V_k is speed of the phase transition front; n is the vector of normal to the interface (subscripts $\pm$ indicate different sides of the interface); λ_s, λ_l are the coefficients of thermal conductivity in the state of phase transition (e.g., the solid and liquid phases, respectively); q is the amount of the heat absorbed in the surface layer; r is the radius of the heat spot from the heat source; η, k, I and U are the parameters controlling the power of the heat source; S_{12} is the contact area of the heated sample matrix containing inclusions; S_{R-r} is the area of contact of the sample with a protective gas; S_r is the area of the contact with the heat source (heat spot area); Γ_1 is the free surface of the heated sample; Γ_2 the inclusion of the free surface. In the notations for the physical parameters, index 1 refers to the base material of the heated sample, index 2 refers to the inclusion material, index 3 refers to protective gas, and index «4» refers to the gas-environment. The heat source rectilinearly moves along the surface. The system of equations (1)–(9) is solved numerically by the finite difference method.

NUMERICAL AND EXPERIMENTAL RESULTS

The macrostructure of the foam (porous) material was calculated layer-by-layer with respect to both stochastic and uniform pore distribution. The size of the pores in the layer was not changed (Fig. 1). The minimum linear pore size was 0.4×0.4×0.4 mm and the maximum pore size was 10×10×10 mm. The lower limit is due to the fact that the welding heat source does not virtually react to a single pore with a size of 0.2×0.2×0.2 mm or less [4, 5]. Increase in the number of small pores changes the thermal properties of the material as a whole, but not locally. The upper limit of the pore size is due to the technology of foam material production.

The above scheme was used to design foam materials of different porosity with pores of various forms. The calculations were carried out for St3 steel-based foam materials and technically pure aluminum. The pores under consideration were filled with air or vacuum. In accordance with the recommendations in [5] we investigated closed cell foam materials only (porous surface was covered with a thin layer of solid metal).
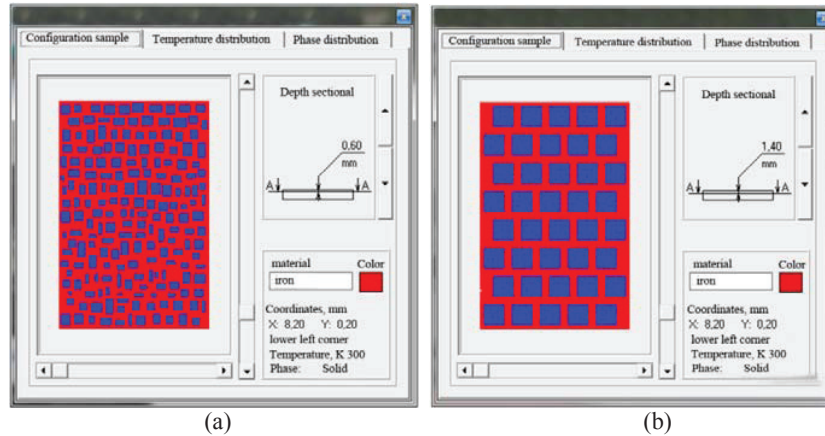
FIGURE 1. Examples of constructing foam materials by stochastic (a) and structured (b) filling the layer with pores

It was found in the calculations that filling pores with air or vacuum insignificantly affects the overall picture of the process of weld formation. The presence of large pores in the weld area is of particular significance. In this case, the temperature of the melt increases dramatically. The weld pool material intensively evaporates in the local areas and this may cause thermal deformation of the metal frame and deformation of the shape of the welded sample. This can be seen in Figure 2 which shows one of the inner layers of the porous steel (Fig. 2(a)) and calculated curves (Fig. 2(b)), which demonstrate the change in temperature along the centerline in welding a five-layer composite material. The upper and lower layers are made of solid steel sheet St3 and the three inner layers are made of the same steel by applying a structured arrangement of holes of the same diameter. For each of the layers the scheme of pore distribution is different. All the layers are of the same thickness of 0.8 mm and the total thickness of the welded samples is 4 mm. The experimental model was designed and the numerical calculations were performed.

The upper curve (Fig. 2(b)) shows the change in temperature on the surface of the molten pool. A sufficiently unstable pattern of metal evaporation can be observed throughout the upper layer with a thickness of 0.4 mm. Along the next layer of 0.4 mm thickness (the third curve from the top), we can detect the emergence of a stable state of the melt (within the intervals of 15 and 25 mm, 60 and 70 mm, 90 and 95 mm). At a depth of 1.2 mm and less the fluctuations of temperature become less pronounced and they occur at each depth about its equilibrium position.

A qualitatively different picture is observed when welding foam aluminum. The calculations have shown that a structured pore distribution scheme causes periodic temperature fluctuations and temperature rise as the welding heat source moves from one end of the sample to the other (Fig. 3). This is due to the fact that the thermal conductivity of solid aluminum is significantly higher than that of the solid steel. Therefore, the heat from the heated area propagates along the sample to the less heated area at high speed. As a result, the arc moves along the more and more heated metal.
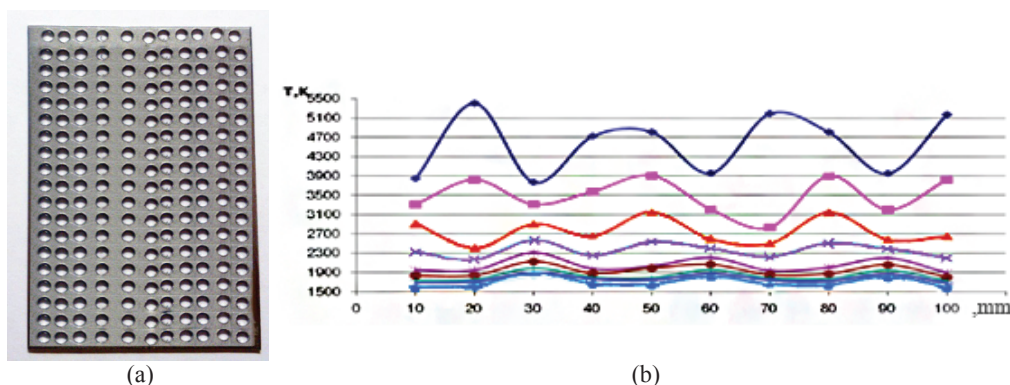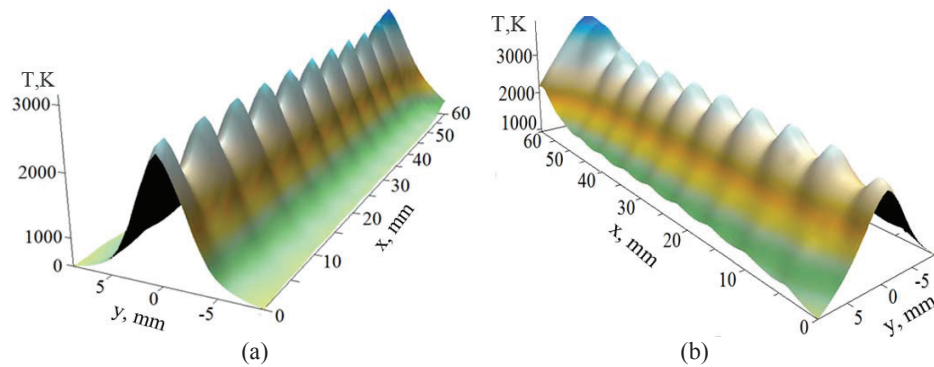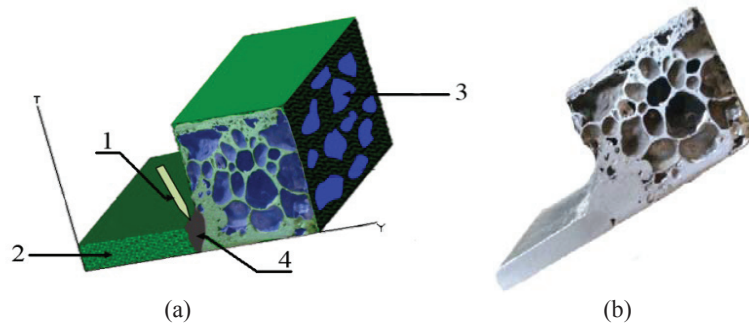

FIGURE 2. Fragment of the porous steel and curves of the change in temperature along the length and through the depth of the sample with 0.4 mm pacing from the top down

FIGURE 3. Temperature distribution along the surface of the aluminum foam:
(a) is a pore size of 4×4×4 mm, (b) is a pore size of 2×2×2 mm

FIGURE 4. Scheme of the computer-assisted experiment (a) and physical analogue (b):
1 is the position of the heat source, *2* is a solid aluminum plate, *3* is aluminum foam and *4* is the weld.

When welding the aluminum foam with a stochastic distribution of pores, no heat accumulation is observed in front of the moving source. It was found as a result of numerical calculations in the real experiment as well. Figure 4 shows a diagram of the computer-assisted experiment and its physical analogue.

It should be noted that in the simulation of aluminum foam welding, the stochastic distribution of the pores within the sample is not known, therefore it was arbitrarily assigned, but so that the weight (total porosity) of the model and that of the real sample were identical.

CONCLUSION

The results of the computer-assisted experiments were used to conduct physical experiments which confirmed the accuracy of the numerical models and allowed substantiation of technological modes to ensure the weld ability of foam materials over a wide range of porosity.

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