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The influence of distance between heat sources in hybrid welded plate on fusion zone geometry

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Abstract

Results of numerical analysis into temperature field in hybrid laser-arc welding process with motion of liquid material taken into account are presented in this study. On the basis of obtained results the influence of the distance between the arc foot point and the laser beam focal point on the shape and size of fusion zone in hybrid butt welded plate. Temperature field was calculated on the basis of solution of transient heat transfer equation. The solution of Navier-Stokes equation allowed for simulation of fluid flow in the fusion zone. Fuzzy solidification front was assumed in calculations with linear approximation of solid fraction in solid-liquid region where liquid material flow through porous medium is taken into consideration. Numerical solution algorithms were developed for three-dimensional problem. Established numerical model of hybrid welding process takes into account different electric arc and laser beam heat sources power distributions.

Keywords: Hybrid Heat Source, Temperature Field, Fluid Flow, Numerical Analysis

1. Introduction

Laser beam welding is well known and involved in a growing number of industrial applications. However due to the economic and technical advantages of using two different heat sources: laser beam and electric arc cooperating in a single process, this technology is often replacing laser beam welding [1].

However, laser-arc hybrid technique involves a large number of parameters that should be correctly set to achieve improvements, because those parameters have major influence on fusion zone shape and size, thus quality of welded joint [1, 2]

Relative arrangement of the laser and the arc has an important influence on the process. Preceding electric arc in the geometrical set-up allows obtaining narrower fusion zone and proper penetration of material. The laser beam efficiency in this set-up increases due to lower heat loss coming from laser beam reflection at welded element glossy surface. Depending on the energy ratio of the two heat sources, the character of the fusion zone may be either more arc-like or laser-like.

The distance between the arc foot point and the laser beam is one of the most important parameters, which has a significant influence on the process performance. Generally, the best result is achieved when two heat sources are co-operating in one welding pool, because of the synergistic effect between electric arc and laser beam [1].

Experimental determination of an appropriate set of welding processes parameters is expensive and time consuming, therefore the research is also focused on numerical analysis [2, 3, 4], which allows for understand a complicated and coupled physical phenomena accruing during this welding process and estimation of appropriate technological parameters that can be used in practice.

In this paper, an influence of laser-to-arc distance on the fusion zone shape and size is analyzed in laser-arc hybrid welding process. The temperature and velocity fields were calculated on the basis of transient heat transfer equation with activity of internal heat sources and Navier–Stokes equation with natural convection of liquid material in the fusion zone as well as fluid flow through porous medium in the mushy zone. Different laser beam and electric arc heat sources models were used in numerical analysis. Latent heat of fusion and latent heat of evaporation were assumed in the solution algorithm. The scheme of considered system is illustrated in figure 1. Calculated temperature field and liquid material velocity field in the fusion zone were compared for assumed different laser-to-arc distance.

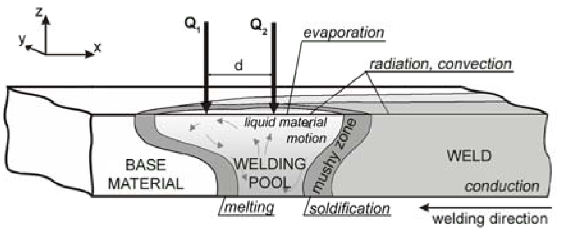

Fig. 1. Scheme of considered system

2. Theoretical formulation

Temperature field was obtained by the solution of transient heat transfer equation given by the following expression

$$\nabla \cdot (\lambda \nabla T) = C_{ef}\left(\frac{\partial T}{\partial t} + \nabla T \cdot \mathbf{v}\right) - Q \qquad (1)$$

where $\lambda=\lambda\ (T)$ is a thermal conductivity, $C_{ef}=C_{ef}(T)$ is an effective heat capacity which includes latent heat of fusion assuming linear approximation of the solid fraction in the mushy zone [5] and latent heat of evaporation assuming linear decrease of liquid fraction in temperatures exceeding boiling point of steel up to maximum temperatures in the process [3], $Q=Q_1+Q_2$ is laser-arc hybrid heating source, $\mathbf{v} = \mathbf{v}(\mathbf{x},t)$ is a velocity vector, $T = T(\mathbf{x},t)$ is a temperature, $\mathbf{x} = \mathbf{x}(x_\alpha)$ is a vector of a material point coordinates.

Initial condition $t=0: T=T_0$ and boundary conditions of Dirichlet and Neumann, and Newton's condition, which takes into account the convection heat loss, radiation emission heat loss and evaporation heat loss [5], complete equation (1).

Velocity field of melted material in the fusion zone was obtained by the solution of Navier – Stokes equation for laminar flow of incompressible, viscous fluids with assumption of material natural convection (Boussinesq's model) and fluid flow through porous medium in the mushy zone (Darcy's model) [2].

$$\frac{\partial(\rho\mathbf{v})}{\partial t} + \nabla \cdot (\rho\mathbf{v}\mathbf{v}) = -\nabla p + \mu\nabla^2\mathbf{v} + \rho\mathbf{g}\beta_T\left(T - T_{ref}\right) - \frac{\mu}{K}\mathbf{v} \qquad (2)$$

where ρ is density, g is gravity acceleration, β_T is thermal expansion coefficient, μ dynamic viscosity, K is porous medium permeability.

Equation (2), fulfilling mass conservation equation $\frac{\partial\rho}{\partial t} + \nabla \cdot (\rho\mathbf{v}) = 0$, is completed by initial condition t=0: $\mathbf{v}$=0 and boundary condition of Dirichlet type Γ: $\mathbf{v}$=0, implemented at the fusion zone boundary.

Porous medium permeability coefficient in the mushy zone (Darcy's model) is described according to Carman–Kozeny formula [2].

Hybrid heat source model was used in calculation with electric arc heat source power distribution described by the Goldak's model [4] and laser beam heat source model defined by cylindrical-involution-normal model [6]. Exemplary heat source power distribution is shown in figure 2, in geometrical set-up with leading arc in the tandem.

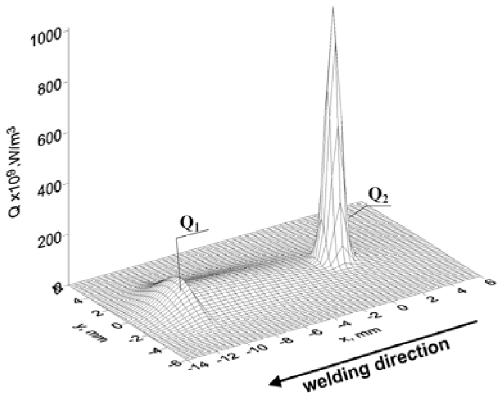

Fig. 2. Exemplary hybrid heat source power distribution at the top surface of welded element

3. Results of calculations

Governing differential equations were numerically solved using projection method with finite volume method [7]. Three hybrid welding simulations were performed for butt welded plates with dimensions 150x30x4mm made of steel. The same material properties as well as heat sources parameters were assumed in calculations and three different laser-to arc distances. Process parameters used in calculations are described in table 1.

Table 1.
Hybrid welding process parameters

Welding speed	v=2.6 m/min		
Laser beam	Q_L=3800 W, r_0=1 mm		
Electric arc	I=310 A, U=31.8 V		
Laser-to-arc distance	d=3 mm	d=5 mm	d=10 mm

Figures 3÷5 presents calculated temperature field and liquid steel velocity field in longitudinal section of welded plate, in the middle of heat sources activity zone (y=0) where black solid line determines boundary of the fusion zone (T=1750K). Temperature field and velocity field of liquid steel in the welding pool at cross sectional area of the joint are presented in figures 6÷8 where solid line determines fusion zone boundary (geometry of the weld after solidification).

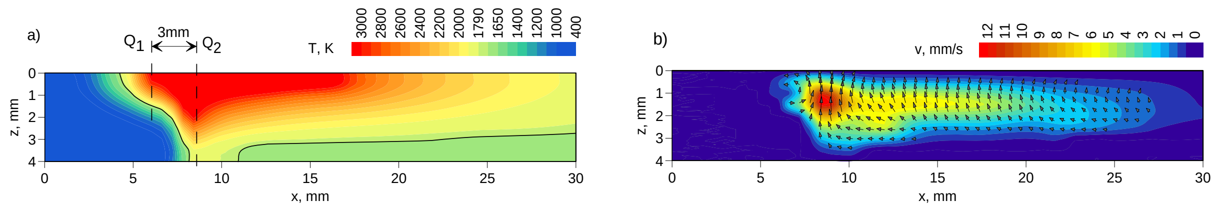

Fig. 3. Results of calculations into a) temperature field and b) velocity field in the fusion one, in longitudinal section of welded plate (in the middle of heat sources activity zone y=0). Laser-to-arc distance equals d=3mm

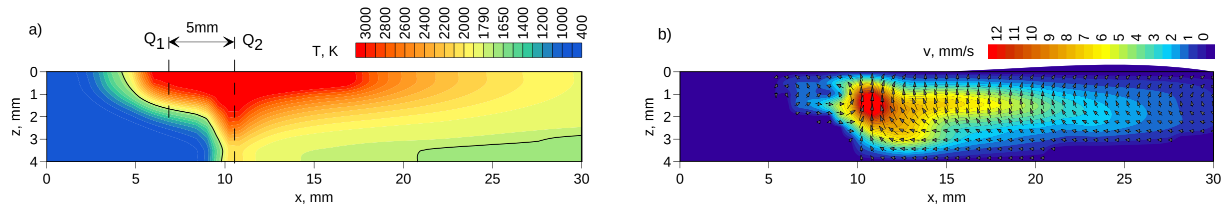

Fig. 4. Results of calculations into a) temperature field and b) velocity field in the fusion one, in longitudinal section of welded plate (in the middle of heat sources activity zone y=0). Laser-to-arc distance equals d=5mm

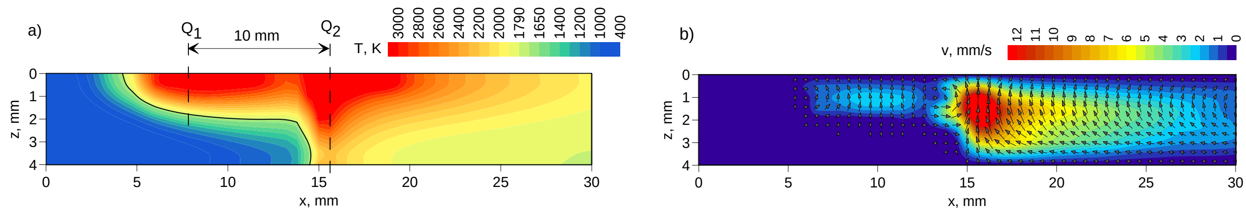

Fig. 5. Results of calculations into a) temperature field and b) velocity field in the fusion one, in longitudinal section of welded plate (in the middle of heat sources activity zone y=0). Laser-to-arc distance equals d=10mm

It can be observed that increasing the distance between heat sources expand heat sources activity zone (fig. 3÷5). Using distance between heat sources set to d=3mm results in a higher temperatures in the welding pool and a smaller fusion zone (fig. 3 and fig. 6). The distance d=5mm contributes to enhancing effect of material melting (fig. 4 and fig. 7). Heat sources are cooperating in a single welding pool, but heat source influence zone is drawn apart. The arc melts upper parts of the workpiece and laser beam fully penetrate the plate, pre-melted previously by the arc. In the third simulation (d=10mm) a significant enlargement of heat sources activity zone is observed (fig. 5 and fig. 8). Further, increasing the distance between heat sources will undoubtedly cause a separation of melting zones produced by laser beam and electric arc and will cause fading of the synergy effect in laser-arc hybrid welding process.

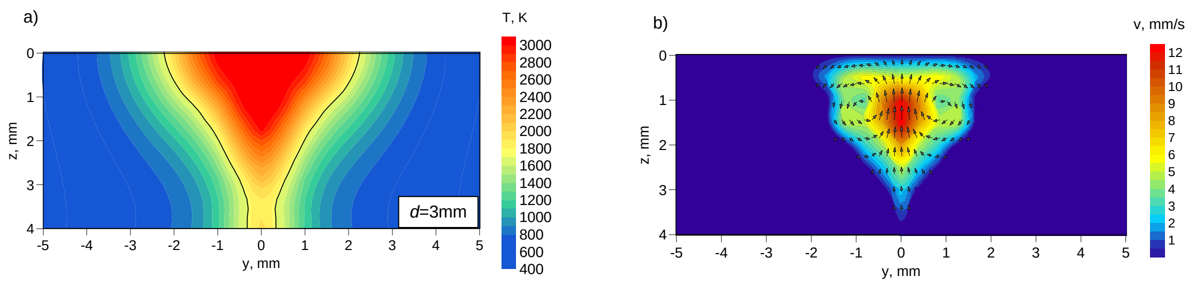

Fig. 6. Results of calculations into a) temperature field and b) velocity field in the fusion one, in cross section of the weld. Laser-to-arc distance equals d=3mm

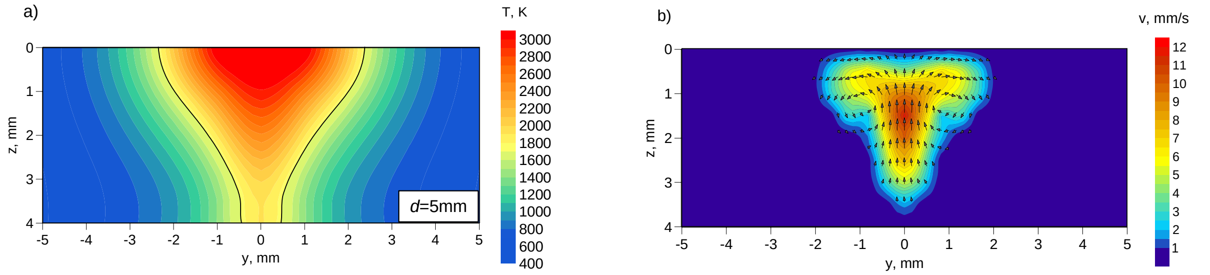

Fig. 7. Results of calculations into a) temperature field and b) velocity field in the fusion one, in cross section of the weld. Laser-to-arc distance equals *d*=5mm

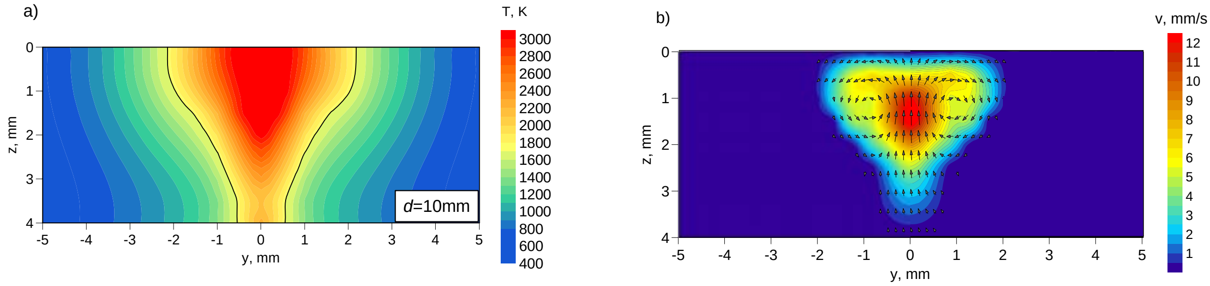

Fig. 8. Results of calculations into a) temperature field and b) velocity field in the fusion one, in cross section of the weld. Laser-to-arc distance equals *d*=10mm

4. Conclusions

Developed numerical model allows for estimation of the influence of chosen hybrid welding process parameters on the shape and size of the weld.

Laser-to-arc distance has a significant impact on temperature distribution in welded workpiece and should be set precisely to obtain the most efficient interaction between heat sources and appropriate geometry of the weld.

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Wpływ odległości źródeł ciepła w płaskowniku spawanym hybrydowo na geometrię strefy przetopionej

Streszczenie

W pracy przedstawiono wyniki numerycznej analizy pola temperatury w procesie spawania hybrydowego laser-łuk elektryczny z uwzględnieniem ruchu ciekłego metalu w strefie przetopienia. Na podstawie otrzymanych wyników oszacowano wpływ odległości elektrody od punktu skupienia wiązki laserowej na kształt strefy przetopionej płaskownika spawanego doczołowo. Pole temperatury otrzymano z rozwiązania równania nieustalonego przewodzenia. Rozwiązanie równania Naviera – Stokesa pozwoliło na symulację ruch cieczy w strefie przetopienia. Przyjęto łagodny front krzepnięcia z liniową aproksymacją udziału fazy stałej w obszarze dwufazowym, w którym uwzględniono ruch cieczy przez medium porowate. Opracowano algorytm numeryczny dla zagadnienia trójwymiarowego. W modelu numerycznym procesu spawania hybrydowym źródłem ciepła uwzględniono różne rozkłady mocy źródeł ciepła łuku elektrycznego i wiązki laserowej.