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MODEL OF CONVECTIVE HEAT TRANSFER IN KEYHOLE MODE LASER WELDING

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Abstract

Article applies a model of welding with high-power laser beam. As a result of heating the material in the area of a laser beam creates a narrow and deep keyhole. Welding in such conditions favors the formation of pores in the weld. In the presented model takes into account double curvature of the keyhole. Surface tension acting on the convex and concave part of the liquid surface, accordingly seeks to opening and closing keyhole. Intense evaporation in the area of a laser beam causes appearance of recoil force whose value increases with the surface temperature of liquid steel. It was found the temperature limit, above which the recoil is greater than the force originating from the surface tension. In such welding conditions, keyhole is deeper. Presented two-dimensional model of the process take into account the dependence of thermophysical material properties and characteristics of the laser beam. It was found a little influence of the sulfur content on the weld pool shape. The keyhole formed during the welding becomes asymmetric. The rear part of the keyhole moves away from the front and faults appear on the solid-liquid border. As the keyhole becomes deeper faults are becoming more numerous.

Key words: laser welding, welding pool, keyhole, recoil pressure, free surface, VOF, CFD

1. INTRODUCTION

Laser beam welding for the last twenty years is improved materials joining technology. Laser welding can be applied both to join metallic and nonmetallic components. Laser welding, depending on the amount of evaporated material, can proceed in two modes. Intense superficial vaporization of a material occurs when the density of laser beam power exceeds the critical value, 10^{10} W/m^2. This phenomenon occurs during cutting and welding. Vaporization leads to creation of a hollow on the surface of welding pool or even formation of the keyhole in the case of higher density power (Kou, 2003). Shapes of the keyhole and the welding pool have an effect on the quality of weld joint. The quality of a weldment can be assured by identification of welding parameters controlling shape of the keyhole to provide the optimal ratio of the width of a welding pool to its depth.

It is well known that the appropriate weld shape can reduce chemical inhomogeneity of a joint and also can prevent a weld against the intercrystalline fracture. The fundamental issue for the optimal selection of welding parameters providing good quality of weld is to investigate physical parameters that control a shape of the keyhole.

Energy of laser beam in contact with metal is consumed mostly on vaporization of metal and its minor part is transferred inside welded of cut material. A material from the region of laser beam is ejected by the recoil force produced by material vaporization (Chen & Wang, 2001). It is the principal mechanisms responsible for shifting of the melt-

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ing front inside a material. When the temperature of the melting front reaches a value close to the boiling point, the recoil pressure according the Anisimov's calculations can be equal or even may exceed the value $0.55p_s$, where p_s stands for the pressure of saturated vapor (Semak & Matsunawa, 1997). The recoil pressure exceeds significantly the pressure related to a surface tension. Experimental measurements indicate that the laser beam in the front of the welding pool produce high velocity of melted metal. These measurements confirm that in this region the recoil force dominates and exceeds other forces produced by the surface tension and hydrostatic pressure (He et al., 2006).

The surface temperature for a high power laser is close to the boiling point and the energy absorbed by solid material is balanced by heat conduction, vaporization and the energy of liquid metal flux ejected through the keyhole. The surface temperature relatively to the absorbed energy can slightly exceed the boiling point or it can be much higher for a high power laser beam. The temperature growth increase vaporization intensity and ejection of a liquid metal. The recoil pressure acting perpendicularly to the keyhole surface pushes the solid-liquid boundary and the liquid-gas boundary further to the welding direction and to the interior of solid. The front of the keyhole surface can move faster than a laser beam and this could be the reason for the keyhole instability.

Interactions described above are included in the model of welding developed here. The model can be used for evaluation of temperature, the recoil force, and velocity of gas and liquid metal ejected from the zone of interaction between the laser beam and a welding pool. All material characteristics are temperature dependent.

2. MODEL OF LASER WELDING PROCESS

The proposed welding model is two-dimensional. As the benchmark problem we are going to consider the sample, which is 10 mm long and 2 mm thick, heated by the laser beam mode TEM_{10}. The laser beam moves along a fixed sample of welded part made of steel as can be seen in figure 1. The welding process is specified by the following assumptions:

- The initial temperature is 300 K,
- The heat source moves with constant velocity along x axis but with the negative sense,
- The iron evaporation rate is evaluated from the Langmuir equation when the temperature of metal reaches the solidus level (Dasgupta &Mazumder, 2007). The evaluated value is assumed as the upper limit of the evaporation rate,
- The shape of the liquid-gas boundary depends on the equilibrium of the recoil pressure, surface tension, hydrostatic and hydrodynamic pressure (Aalderink et al., 2007). This boundary surface is not flat.
- Material characteristics such as: the specific heat, the coefficient of thermal conduction, density, viscosity, the heat transfer coefficient, are temperature dependent,
- The liquid flow is described by the k-ε turbulent flow model.
- The buoyant force is evaluated by using the Bousinesq approximation.

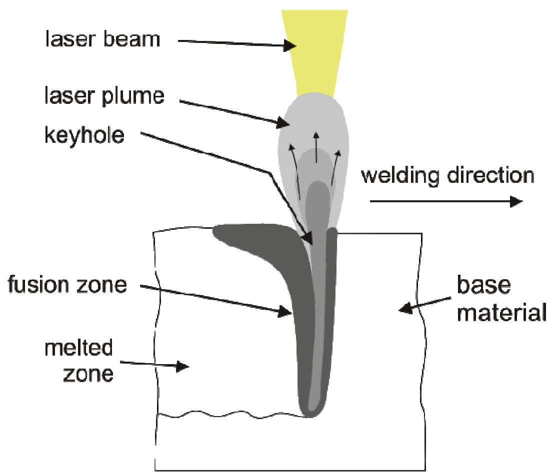

Fig. 1. *Scheme of the steel sample remelted by the laser beam moving along the upper surface with constant velocity.*

A free surface is traced by using VOF (volume of fluid) algorithm. In spite of shortcomings of this method such as blurred surfaces and improperly evaluated velocity of flow in the vicinity of surfaces, this method can be sufficient for two- and three-dimensional flow problems. During laser welding, flow of liquid metal is produced by the recoil force, surface tension and the thermocapillary forces. The evaluation of the normal vector and both the shape and curvature of free liquid surface is required for determination of boundary conditions. The surface shape is defined by the function $F(x,y,t)$, which decreases during solidification. The region including cells with assigned values between zero and one is called as the semi liquid region and is treated as pseudo-porous region. The liquid fraction in each cell is evaluated iteratively from the balance of enthalpy. When temperature of a cell is less than the temperature of melting ($T < T_m$), the enthalpy can be calculated from the relation (Han & Liou, 2004)

$$h(T)=\int_0^T \rho(T)c_p(T)dT \tag{1}$$

where density is marked by ρ and c_p stands for the specific heat.

The enthalpy for the liquid phase, when $T>T_m$ is given by

$$h(T)=\int_0^T \rho(T)c_p(T)dT + L_m \tag{2}$$

where L_{m} is the latent heat for melting.

For temperature between solidus and liquidus, i.e. $T_{liq} < T < T_{sol}$, the liquid fraction in the element of mesh β is defined by

$$\beta=(T-T_{solid})/(T_{liq}-T_{sol}) \tag{3}$$

Then, the latent heat of melting can be defined as follows

$$\Delta H=\beta L_m \tag{4}$$

The function $F(x,y,t)$ for surface tracing fulfills the following condition

$$\frac{dF}{dt}\equiv\frac{\partial F}{\partial t}+(\mathrm{V}\cdot\nabla)F=0 \tag{5}$$

where **V** is the velocity vector. The sample free surface is loaded by the normal and tangential forces. The equilibrium equation for dynamic forces and tangent tension is expressed by

$$\mu\left(\frac{\partial u_s}{\partial n}+\frac{\partial v_n}{\partial s}\right)=\frac{\partial\gamma}{\partial T}\frac{\partial T}{\partial s} \tag{5}$$

where u and v are velocity components in the direction of x and y axes, γ is the surface tension coefficient, T is temperature and subscripts n and s stand for the normal and tangent directions.

The pressure p inside the keyhole and normal to the free surface is defined by

$$p=p_\sigma+p_r \tag{6}$$

where p_σ is the pressure produced by the surface tension and p_{r} is the recoil pressure.

The pressure p_σ depends on the surface curvature κ and the surface tension coefficient γ and can be expressed by the relationship

$$p_\sigma=\kappa\gamma \tag{7}$$

The tangent tension is calculated from the Gibbs and Langmuir relations for adsorption isotherms in the presence of surface-active elements (Sahoo et al., 1988)

$$\gamma=\gamma_m^0-A^0(T-T_m)-RT\Gamma_s\ln\left(1+k_1a_ie^{-\frac{\Delta H^0}{RT}}\right) \tag{8}$$

where $\gamma_m{}^0$ is the surface tension coefficient of a pure metal in melting point, A^0 is the negative coefficient of $d\gamma^0/dT$ for a pure metal, T_m is the melting temperature, R is the universal gas constant, T is temperature, Γ_s the surface surplus of a solute in saturated conditions, k_1 is the coefficient of entropy, and ΔH^0 is the enthalpy of segregation.

The normal vector $\vec{n}$ on the free surface of liquid is equal to the gradient of the function, F (∇F) and its curvature κ is defined as

$$\kappa=-\left[\nabla\cdot\left(\frac{\vec{n}}{|\vec{n}|}\right)\right] \tag{9}$$

It is assumed that the heat distribution in the laser beam has cylindrical symmetry for the mode TEM_{10} (Han & Liou, 2004). Energy losses in welded sample are observed due to convection, radiation, and evaporation.

Energy transferred from the laser beam and absorbed by a material heats and subsequently melt a material surface. High rate of temperature growth accelerates evaporation of material and produces the recoil pressure that pushes out liquid from a region of the beam.

Liquid level declines in the direction of greatest gradient of the recoil pressure. The new portion of solid is melted after ejection of a liquid fraction. The solid-liquid boundary penetrates the solid material with constant speed. The penetration is deeper when the power of laser beam is higher. The recoil pressure p_{r} is proportional to the saturation pressure p_{s} and can be evaluated from the relation

$$p_r=Ap_s(T_s)=AB_0T_s^{-\frac{1}{2}}\exp\left(-\frac{U}{T_s}\right) \tag{10}$$

where T_s is the surface temperature of welding pool, A is the coefficient related to pressure, B_0 is the empirical constant, and U is the evaporation energy for a single atom.

The above presented model is used in numerical simulation of laser remelting of steel sample illuminated by the beam of TEM_{10} mode with 4kW power. The beam is focused to a spot of 0.5 mm diameter on the sample upper surface. The sample is fixed and the beam shifts with 0.08 m/s velocity (figure 1). The sample is 10 mm long and 2 mm thick. The initial temperature is 300K. The unsteady Navier–Stokes equations and the energy conservation equation are numerically solved by the finite volume method using the CFD Fluent software. An implicit time integration scheme is used. VOF (Volume-of-Fluid) algorithm and κ-ε turbulence model are used to solve the transport equation with dynamic viscosity (Fluent Inc., 2009). The sample is split into 144000 quadratic elements with a side approximately equal to ~0.017mm. The time step between two iterations is selected as 10^{-7}s. It is assumed, that initially the sample is kept in ambient temperature T_∞ = 300K and ambient pressure p_{atm} = 101325Pa. Thermo physical data for the sample material, HS6-5-2, are given in table 1. The specific heat, c_p, the coefficient of thermal conductivity,λ, density, ρ, viscosity, μ, the convective heat-transfer coefficient, α, are temperature dependent characteristics.

Table 1. *Thermo physical data for steel HS6-5-2 and parameters used in numerical evaluations.*

Property	Symbol	Value
Absorption coefficient	η	0.13
Emissivity	ε	0.4
Heat of fusion	L_m	$2.6\cdot10^5$ [J/kg]
Solidus temperature	T_s	1620 K
Liquidus temperature	T_l	1740 K
Density of liquid steel	ρ	7300 [kg/m^3]
Heat capacity of solid state	c_{ps}	411 [J/kg·K]
Heat capacity of liquid	c_{pl}	612 [J/kg·K]
Thermal conductivity of solid	λ_s	19 [W/m·K]
Thermal conductivity of liquid	λ_l	70 [W/m·K]
Heat coefficient of surface tension	A^0	$-0.43\cdot10^{-3}$ [N/m·K]
Surface tension coefficient	γ_m^0	1.943 [N/m]

3. NUMERICAL RESULTS

High temperature in the beam zone produces high equilibrium pressure of metal vapour. The recoil force acting on a surface of the welding pool pushes out liquid metal. The keyhole is surrounded by two surfaces: convex and concave. The surface tension acting on a surface with double curvature produces forces oppositely directed. Therefore, force acting on a concave surface brings the keyhole about to be closed but force acting on a convex surface helps to keep the keyhole open. The direction of surface tension is defined by a surface curvature κ that can be evaluated from formula (9). When temperature on the surface of the welding pool exceeds the critical value, the recoil force in the beam zone exceeds the tension force and liquid is pushed out of the pool. Values of the surface tension and the recoil pressure are shown as welding time functions in figure 2. It is observed during the first period of remelting that the surface tension is higher then the recoil pressure. When temperature grows, the surface tension and the recoil pressure increase but the latter grows faster and after 0.8ms they became approximately equal. Further heating results in faster growth of the recoil pressure. Therefore, liquid metal can be push out from the zone of the laser beam. Temperature in the region of the welding pool stabilizes after 1.3 ms in the range from 4760 to 4980K. This range is higher than the boiling point for HS6-5-2 steel applied in the evaluated benchmark problem. Higher temperature of the welding pool and larger recoil pressure is observed for higher power of the laser beam and longer time of interaction between laser and metal. Numerical results: the recoil pressure measured in Pa and the development of solid-liquid interface, during laser welding are presented in the form of maps in figure 3, where the evolution of weld pool shape can be seen in subsequent figures. Liquid level in the laser beam zone decreases because of high recoil pressure. Displaced liquid metal creates a hump around the keyhole (figure 3 a). A laser beam is incident to the front bank of the keyhole due to laser shift. The hump on the upper surface is higher in this region than behind the beam (figure 3 b-f). The rear bank of the keyhole is indirectly lighted by the beam. The shape of this part depends on the equilibrium between the surface tension and pressure of metal vapour flowing through the keyhole (figure 3 e, f). The curvature of the surface of uplifted liquid is decreasing due to increase of the surface tension and therefore, in the extreme case the keyhole can be even closed. When temperature in the keyhole exceeds the boiling point, the vapour pressure is higher than the ambient pressure. Then the weld pool surface is not flat anymore and this effect can be amplified by the activity of the recoil pressure.

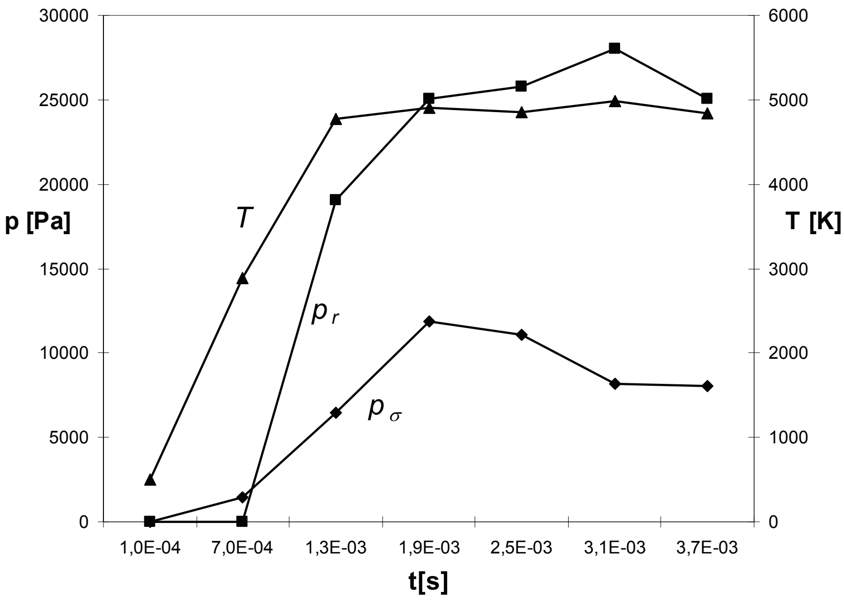

Fig. 2. *Charts of the surface tension p_σ, the recoil pressure p_r and the surface temperature T measured in the axis of the laser beam related to welding time t.*

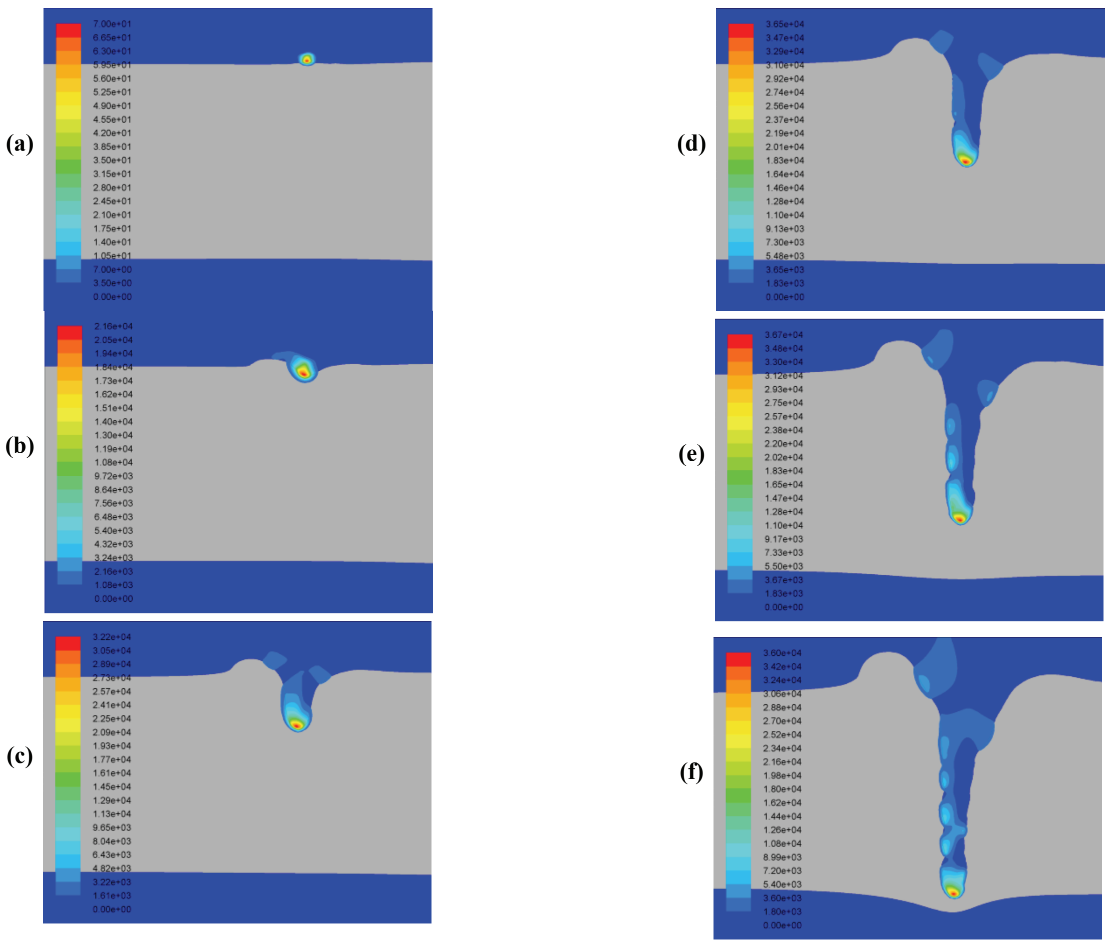

Fig. 3. *The recoil pressure measured in Pa and the development of the solid-liquid interface during laser welding with 0.08 m/s speed for welding periods (a-f):* **t** *= 0.7, 1.3, 1.9, 2.5, 3.1 i 3.7 ms. Laser beam shifts to the left.*

4. CONCLUSIONS AND SUMMARY

Two dimensional model of the weld pool created during the laser welding is proposed by Authors to investigate process parameters controlling shape of the welding pool and identify parameters describing behavior of the keyhole.

Liquid metal in the welding pool is subjected to the ablation pressure and the surface tension. Interaction of these forces can create the keyhole when temperature on a surface of the welding pool reaches the boiling point and the ablation pressure in the keyhole can displace liquid out of the pool.

It can be seen that during welding a shape of the keyhole become asymmetrical when and the rear part of the keyhole shifts away from the front part and faults appear on the solid-liquid border. A number of faults increases as the keyhole becomes deeper.

It was found close agreement between calculated and encountered in the literature keyhole shapes. Quantitative comparison between the calculated profiles and microstructures requires the preparation of three-dimensional model for welding. Then it will be possible to compare predicted and experimental welding pool profiles in a plane perpendicular to the direction of welding.

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REFERENCES

Aalderink, B.J., Lange, D.F. de, Aarts, R.G.K.M., Meijer, J., 2007, Keyhole shapes during laser welding of thin metal sheets, *J. Phys. D: Appl. Phys.*, 40, DOI:10.1088/0022-3727/40/17/057.

Chen, X., Wang, H.X., 2001, A calculation model for the evaporation recoil pressure in laser material processing, *J. Phys. D: Appl. Phys.*, 34, 2637-2642.

Dasgupta, A.K., Mazumder, J., Li, P., 2007, Physics of zinc vaporization and plasma absorption during CO_2 laser welding, *J. Appl. Phys.*, 102, DOI: 10.1063/1.2777132.

Fluent Inc., 2009, ANSYS FLUENT 12.0 Documentation, www.fluent.com.

Han, L., Liou, F.W., 2004, Numerical investigation of the influence of laser beam mode on melt pool, *Int. J. Heat Mass Transf.*, 47, 4385-4402.

He, X., Norris, J.T., Fuerschbach, P.W., DebRoy, T., 2006, Liquid metal expulsion during laser spot welding of 304 stainless steel, *J. Phys. D: Appl. Phys.*, 39, 525-534.

Kou, S., 2003, *Welding Metallurgy*, John Wiley & Sons, New Jersey.

Sahoo, P., DebRoy, T., McNallan, M.J., 1988, Surface Tension of Binary Metal Surface Active Solute Systems under Conditions Relevant to Welding Metallurgy, *Metall. Trans.*, 19B, 483-491.

Semak, V., Matsunawa, A., 1997, The role of recoil pressure in energy balance during laser materials processing, *J. Phys. D: Appl. Phys.*, 30, 2541-2552.

Wang, Y., Tsai, H.L., 2001, Impingement of filler droplets and weld pool dynamics during gas metal arc welding process, *Int. J. Heat Mass Transf.*, 44, 2067-2080.

MODEL KONWEKCYJNEJ WYMIANY CIEPŁA DLA SPAWANIA LASEROWEGO Z WYTWORZENIEM KANAŁU PAROWEGO

Streszczenie

Artykuł dotyczy modelu spawania stali wiązką laserową o dużej mocy. W wyniku nagrzania materiału, w obszarze działania wiązki lasera tworzy się wąski i głęboki kanał parowy. Spawanie w takich warunkach sprzyja tworzeniu się w spoinie porów. W prezentowanym modelu uwzględniono podwójną krzywiznę kanału parowego. Napięcie powierzchniowe działające na część wypukłą i wklęsłą powierzchni cieczy, dąży odpowiednio do zamknięcia i otwarcia kanału parowego. Intensywne parowanie w obszarze działania wiązki laserowej powoduje powstanie siły odrzutu, której wartość wzrasta z temperaturą powierzchni ciekłej stali. Stwierdzono graniczną temperaturę, powyżej której siła odrzutu jest większa od siły pochodzącej od napięcia powierzchniowego. Przy takich warunkach spawania, kanał parowy staje się coraz głębszy. Zaproponowany w pracy dwuwymiarowy model procesu uwzględnia zależność własności termofizycznych spawanego materiału i charakterystykę wiązki laserowej. W prezentowanym modelu stwierdzono niewielki wpływ zawartości siarki na kształt jeziorka spawalniczego. Kształt tworzącego się w czasie spawania kanału parowego, staje się coraz bardziej asymetryczny. Tylna część kanału parowego odsuwa się od przedniej i tworzą się na niej uskoki. W miarę pogłębiania kanału parowego uskoki stają się coraz liczniejsze.

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