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Comprehensive model of thermal phenomena and phase transformations in laser welding process

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ABSTRACT

This paper concerns computational modelling of thermal phenomena and phase transformations in solid state in laser welding process. The analysis is performed on the basis of numerical solution into continuum mechanics governing equations as well as classic Johnson–Mehl–Avrami (JMA) and Koistinen–Marburger (KM) kinetics models with continuous heating transformation (CHT) and continuous cooling transformation (CCT) diagrams of S460 steel. The influence of latent heats on temperature distributions is analysed. Obtained results include temperature field, melted material velocity field in the fusion zone and structure composition of welded joint. Calculations are partially verified by experimental data.

1. Introduction

Welding process using a laser beam as the heat source allows joining materials previously regarded as a non-weldable or difficultly weldable [1]. Recently, this welding method is intensively developed, examined and implemented in a wide range of industrial applications and successfully displaces conventional welding methods [2,3]. A high welding speed used in the process and a good quality of the weld as well as a small heat affected zone are major advantages of this joining technology. However, laser welding of steel is accompanied by many phenomena previously not found in conventional welding methods [4,5]. The interaction of concentrated heat source on the material is responsible for generating high temperature gradients and high cooling rates appearing in the joint. The laser power is absorbed in the ionised vapour and transferred to the walls of the "keyhole" forming the weld pool [5,6]. One of difficulties during welding is the formation of hardening structures even good weldable steels due to the high concentration of heat energy on a small area of the workpiece resulting in high cooling rates. Changes in the microstructure of welded joint occurring during phase transformations in solid state are the cause of significant changes in the properties of heat affected zone (HAZ) in comparison to base material [7–11].

The quality of welded joint is determined by different process parameters, such as: laser mode, beam radius, laser power and welding speed. Therefore, the knowledge about temperature profile, including: heating rate, maximal heating temperature and cooling rate, is crucial in determining technological parameters of this process to ensure desired geometry of the joint and appropriate mechanical properties in the field of static and dynamic loads [11,12].

Laser-material interaction is a very complex issue, covering interplay between many phenomena like evaporation, melting, solidification, phase transformations in solid state, thermal and structural stress etc. [4–14]. The computational complexity of this issue forces researches to use simplified mathematical and numerical models describing chosen phenomena. On one hand, the study is focused on weld pool dynamics and plasma formation [5,6], on the other hand on microstructural and mechanical phenomena in welded material [9–12]. One of usually ignored phenomena in the numerical analysis of welding processes is the motion of liquid material in the welding pool and the latent heat generated during phase transformations in solid state, which influence temperature distribution and has a significant effect on numerically predicted microstructure composition [14–17]. The resulting microstructure in welded steel highly depends on thermal cycle parameters. In the analysis of phase transformations during welding the attention is mainly focused on phase transformations during cooling process [18,19]. The analysis of phase transformations in the heating process in most cases is carried out for constant austenitization temperatures (Ac_1 and Ac_3), whereas the effect heating rate on austenitization temperatures is substantially omitted [20–22]. This is not acceptable in the case of advanced welding methods using

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high power and high intensity laser beam heat source (where high heating rates as well as very high and various maximum heating temperatures of steel are present).

A very important issue in the modelling of laser beam welding is an appropriate selection of heat source power distribution in order to reflect the real process conditions as much as it is possible. New mathematical models describing the distribution of the energy flux are constantly looked for through theoretical study on laser induced plasma formation [5] or assuming Gaussian-like simplified volumetric heat source model [9,13,14]. A major problem is the determination of the geometry of the keyhole corresponding to the experimental data with appropriate accuracy. From the research on laser welding process it is observed that heat source power decreases with increasing depth of penetration in the relation with welding speed [4,7,23–25]. Proposed by Ranatowski [23] universal heat source model allows for modelling of variety concentrated heat source shapes form parabola to a point, assuming Gaussian distribution in the radial direction with exponential decrease of heat source power input with material penetration depth.

This paper presents a three-dimensional model of thermal phenomena and phase transformations in solid state occurring during laser butt-welding of sheets made of S460 steel. Temperature field and liquid steel velocity field are obtained by the solution of continuum mechanics differential equations using projection method and finite volume method (FVM) [26]. Effective heat capacity model is assumed in solution algorithms where latent heat of fusion is considered with linear approximation of solid fraction in solid–liquid region [4,9,27,28], latent heat of evaporation in temperatures exceeding the boiling point of steel assuming linear approximation of liquid fraction in liquid–gas region [6,14], whereas latent heat of phase transformations in solid state with the increase of each volumetric fraction of phases in the weld and HAZ. Liquid material motion is assumed as a laminar flow of incompressible, viscous fluid. Fuzzy solidification front is assumed in calculations where solid–liquid zone is treated as a porous medium. Laser beam heat source power distribution is modelled using CIN model [23]. The kinetics of phase transformations in solid state and volumetric fractions of arising phases are obtained using Johnson–Mehl–Avrami and Koistinen–Marburger equations. Reflected in CHT diagram austenitization temperatures (A_{c1} and A_{c3}) changing with heating rates is used in the model of phase transformations during heating. The case of incomplete austenitization is considered if maximum thermal cycle is fount between A_{c1} and A_{c3} temperatures. CCT diagram for welded S460 steel is used in the modelling of phase transformation during cooling.

Elaborated mathematical and numerical models are implemented into computer solver in Object Pascal programming language. Obtained results of performed computer simulations are verified by experimental data. The influence of latent heats generated during phase transformations in solid state on thermal cycles is analysed.

2. Thermal phenomena

Schematic sketch of considered system is illustrated in Fig. 1. Temperature field in analysed laser welding process depends mostly on the power distribution of the laser beam heat source (Q) and welding speed. Phase transformations due to materials' state changes are considered between solidus and liquidus temperatures and in temperatures exceeding boiling point of steel. Latent heats generated during phase transformations in solid state are also taken into account in the weld and heat affected zone (HAZ). Liquid material flow in the welding pool is mostly driven by the buoyancy. In the mushy zone (between solidus and liquidus temperatures) flow of liquid metal is assumed as a flow through porous medium.

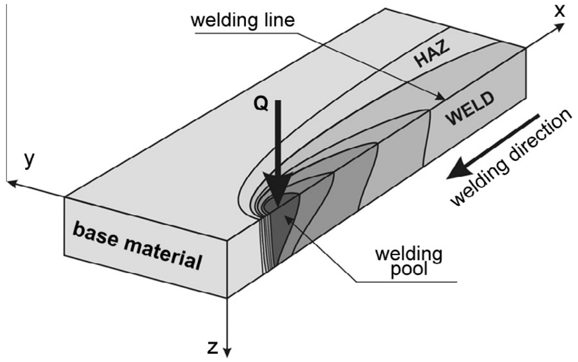

Fig. 1. Schematic sketch of considered system.

2.1. Governing equations

Based on the continuum formulation differential governing equations consist of mass, momentum and energy conservation, expressed in general:

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0 \tag{1}$$

$$\frac{\partial(\rho\mathbf{v})}{\partial t} + \nabla\cdot(\rho\mathbf{vv}) = -\nabla p + \nabla\cdot(\mu\nabla\mathbf{v}) + \rho\mathbf{g}\beta_T(T - T_S) - \frac{\mu}{K}\mathbf{v} \tag{2}$$

$$\nabla\cdot(\lambda\nabla T) = C\left(\frac{\partial T}{\partial t} + \nabla T\cdot\mathbf{v}\right) - \widetilde{Q} \tag{3}$$

where ρ is a density [kg/m^3], $\mathbf{g}$ is acceleration of gravity, β_T is a volume expansion coefficient due to heating [1/K], T_{ref} is a reference temperature [K], μ is a dynamic viscosity [kg/ms], K is porous medium permeability, $T = T(x_i,t)$ is temperature [K], $\mathbf{v} = \mathbf{v}(\mathbf{x},t)$ is a velocity vector and $\mathbf{x} = \mathbf{x}(x_\alpha)$ is a vector of a material point coordinates, $\lambda = \lambda(T)$ is a thermal conductivity, $C = C(T)$ is an effective heat capacity with latent heat of fusion, evaporation and latent heat of phase transformations in solid state taken into account, $\widetilde{Q}$ are volumetric heat sources [W/m^3].

In momentum conservation Eq. (2) a convective motion is considered according to Boussinesq's model as well as fluid flow through porous medium formulated in Darcy's model [13,14]. Assuming, that the mushy zone is composed of regular matrix of spherical grains submerged in liquid material, the porous medium permeability can be expressed by Carman–Kozeny equation [14,29]:

$$K = K_0\frac{(1-f_S)^3}{f_S^2};\quad K_0 = \frac{d_0^2}{180} \tag{4}$$

where f_S is a solid fraction, d_0 is an average solid particle diameter [m].

Solid fraction f_S in Eq. (4) is assumed with linear approximation between solidus and liquidus temperatures

$$f_S = \begin{cases} 1 & \text{for} \quad T < T_S \\ \frac{T_L - T}{T_L - T_S} & \text{for} \quad T_S \leqslant T \leqslant T_L \\ 0 & \text{for} \quad T > T_L \end{cases} \tag{5}$$

where T_S and T_L are solidus and liquidus temperatures respectively [K].

Eq. (2) is completed by initial condition $t = 0 : \mathbf{v} = 0$ and boundary conditions implemented at the welding pool boundary determined by solidus temperature ($T_{ref} = T_S$) [29,30]: