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Numerical assessment and experimental verification of the influence of the Hartmann effect in laser beam welding processes by steady magnetic fields

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A B S T R A C T

Controlling the dynamics in the weld pool is a highly demanding challenge in deep-penetration laser beam welding with modern high power laser systems in the multi kilowatt range. An approach to insert braking forces in the melt which is successfully used in large-scaled industrial applications like casting is the so-called Hartmann effect due to externally applied magnetic fields. Therefore, this study deals with its adaptation to a laser beam welding process of much smaller geometric and time scale. In this paper, the contactless mitigation of fluid dynamic processes in the melt by steady magnetic fields was investigated by numerical simulation for partial penetration welding of aluminium. Three-dimensional heat transfer, fluid dynamics including phase transition and electromagnetic field partial differential equations were solved based on temperature-dependent material properties up to evaporation temperature for two different penetration depths of the laser beam. The Marangoni convection in the surface region of the weld pool and the natural convection due to the gravitational forces were identified as main driving forces in the weld pool. Furthermore, the latent heat of solid–liquid phase transition was taken into account and the solidification was modelled by the Carman–Kozeny equation for porous medium morphology.

The results show that a characteristic change of the flow pattern in the melt can be achieved by the applied steady magnetic fields depending on the ratio of magnetic induced and viscous drag. Consequently, the weld bead geometry was significantly influenced by the developing Lorentz forces. Welding experiments with a 16 kW disc laser with an applied magnetic flux density of around 500 mT support the numerical results by showing a dissipating effect on the weld pool dynamics.

1. Introduction

The availability of modern high power laser systems paved the way for a variety of different welding applications into the industrial praxis, e.g. in the automotive and naval industry as well as for large-scaled constructions, power plants, reactor vessels or pipelines. In former times, thick section welding of metal parts was a classical application for the electron beam (EB) welding technology [1]. Electron beam sources of more than 100 kW power were developed and used in the industrial production chain. The improvement of the laser beam (LB) sources over the years made the laser beam welding to an attractive alternative due to its efficiency, flexibility and the possibility to weld under atmospheric conditions.

Due to the development of the metal vapour plasma, the classical CO_2 laser with a wavelength of 10.6 μm is applicable for welded layers of up to 20 mm thickness [2]. A further increase of laser power does not lead to an increase in laser penetration depth. Modern disc and fibre laser deliver output powers of up to 100 kW (cw) with a wavelength of around 1 μm [3]. Those types of lasers allow for the welding of thicknesses of more than 20 mm per welded layer [4]. A further advantage of the laser beam welding technology in contrast to EB welding is that electromagnetic methods can be exploited to improve the welding process and the weld quality [4,5].

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A common issue when joining large structures are the welding distortions depending on the heat input during the processing. When the distortions are larger than the tolerable tolerances, time-consuming and expensive steps of mechanical post-treatment can become necessary. This is especially important for classical arc welding applications but also for multi-layer welding with high accumulated energy input. The bending and angular distortions can be limited by a homogeneous solidification of the weld bead when the side walls of the molten pool are nearly parallel. Thus, the shrinkage associated to the cooling after the welding procedure mainly causes longitudinal and transversal stresses instead.

Characteristically associated to the welding of aluminium alloys is the very high heat conductivity in their liquid state. Thus, the weld beads are very large especially near the surfaces. There, the thermocapillary (Marangoni) convection [7] is the dominating driving mechanism leading to a typical wineglass-shape of the weld cross sections. The strong curvature of the weld bead causes inhomogeneous solidification fronts and promotes bending and buckling distortions after cooling down. For the welding with high laser powers, this is especially important in deep penetration welding.

Another issue when welding thick structures is the development of spattering and blow-outs of liquid metal which are caused by very high local melt velocities [8,9]. When the surface tension cannot hold the melt, welding defects, e.g. a lack of fusion can occur. This can be avoided by a reduction of the influence of the melt dynamics. Hence, this paper deals with the electromagnetic deceleration of the melt during laser welding processes and its influence on the resulting solidification behaviour (see Fig. 1) which is called Hartmann effect.

It is well-known that applied constant or oscillating magnetic fields can effectively decelerate the fluid flow in metal melts [10] and reduce the convective heat transfer consequently [11,12]. The movement of an electrically conducting medium perpendicular to an applied magnetic field **B** induces an electric current density:

$$\mathbf{j_u} \sim \sigma \mathbf{u} \times \mathbf{B}, \tag{1}$$

where σ and $\mathbf{u}$ are the electric conductivity and the melt velocity, respectively. The interaction of the resulting electric currents with the externally applied magnetic field leads to a Lorentz force distribution being partially directed against the melt velocity. Hence, the corresponding Lorentz force acts like an additional viscous force that dampens the flow velocities. The electromagnetic contribution to the dynamic viscosity of the melt is:

$$\eta_{\mathrm{EM}} = \sigma B^2 L^2, \tag{2}$$

with the weld bead half width L. A measure for the relative importance of magnetically induced drag and viscous forces is the Hartmann number [13]:

$$\mathrm{Ha}^2 = \frac{\eta_{\mathrm{EM}}}{\eta} = \frac{\sigma B^2 L^2}{\eta}. \tag{3}$$

To clarify the relative influence of the induced braking forces on the resulting flow field, their ratio to the flow inertia is decisive. This relation is described by the interaction parameter [13]:

$$\mathrm{N} = \frac{\mathrm{Ha}^2}{\mathrm{Re}} = \frac{\sigma B^2 L}{\rho U} \tag{4}$$

with Re being the Reynolds number and U the velocity magnitude. An estimation of the interaction parameter can be seen in Fig. 2.

It shows, that the effect of an applied magnetic field is larger for wider weld beads as well as for smaller melt velocities, where the flow inertia is lower.

In many industrial processes like continuous casting or crystal growth, steady, travelling and oscillatory magnetic fields are widely used to achieve widespread goals, e.g. a grain refinement, surface stabilization or a flow deceleration in electrically conducting liquids. Reviews on the use of magnetohydrodynamics in materials processing are given in Refs. [14,15]. Especially the Hartmann effect was also used in crystal growth [16], surface alloying [17] and continuous casting [18] reporting a distinct flow deceleration and a reduction of turbulence levels. Welding-related examples of the application of Lorentz forces in the weld bead are given in Ref. [19].

First experimental results of an investigation of the Hartmann effect due to stationary magnetic fields in CO_2 laser beam welding were presented in Ref. [20]. The half width of the weld bead was around 1 mm and the magnetic flux density was 40 mT leading to Hartmann numbers Ha^2 around 100. A smoothing of the weld seam and humping prevention was observed in dependence of the polarity of the applied DC fields, which was related to thermoelectric currents between material of different temperatures. These currents were independent of the direction of the applied magnetic fields. In a later publication [21], the observed phenomena were explained by an interaction of the CO_2 laser plasma with the welded specimen and related to the wavelength of the laser radiation. A more recent work reports on thermoelectric currents during laser beam welding including sheath effects as well as a potential drop within the laser-induced plasma [22]. In conclusion, the scientific importance of the investigation presented in this paper is based on the isolated evaluation of the

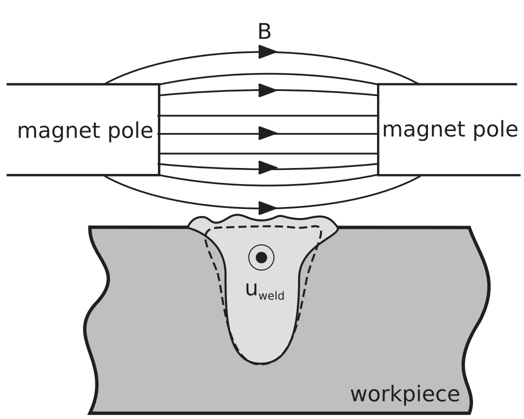

Fig. 1. Influence of the applied magnetic field on the weld pool geometry.

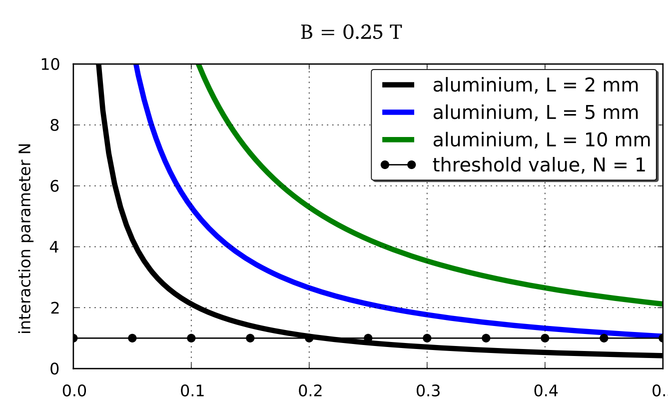

Fig. 2. Influence of an applied steady magnetic field of 0.25 T on the flow field.