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Experimental and numerical investigation of an electromagnetic weld pool control for laser beam welding

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- Invited Paper -

Abstract

The objective of this study was to investigate the influence of externally applied magnetic fields on the weld quality in laser beam welding. The optimization of the process parameters was performed using the results of computer simulations. Welding tests were performed with up to 20 kW laser beam power. It was shown that the AC magnet with 3 kW power supply allows for a prevention of the gravity drop-out for full penetration welding of 20 mm thick stainless steel plates. For partial penetration welding it was shown that an 0.5 T DC magnetic field is enough for a suppression of convective flows in the weld pool. Partial penetration welding tests with 4 kW beam power showed that the application of AC magnetic fields can reduce weld porosity by a factor of 10 compared to the reference joints. The weld surface roughness was improved by 50 %.

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1. Introduction

The advantages of keyhole mode laser beam welding, such as high welding speed and low heat input, are well known. An especially high weld quality is achieved in PA position full penetration keyhole laser beam welding. The

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laser beam forms a narrow weld pool with nearly parallel side walls. During solidification of the weld pool, the longitudinal and transversal shrinkage stress variations along the keyhole axis are much lower than in most other welding technologies. This results in very low buckling and bending of the workpiece (Ready et al. (2001)). Moreover, full penetration welding can suppress the development of the so-called process porosity due to the keyhole instability near its bottom tip, see Seto et al. (2001). However, for full penetration welding of thick metal parts the surface tension cannot completely compensate the hydrostatic pressure in the melt. This can result in sagging of the root side of the weld or even a complete drop-out of the melt when the workpiece thickness is above a threshold.

Both AC and DC magnetic fields can be effectively used to control large amounts of molten metal in many industrial processes, e.g. crystal growth and metal casting. The so-called electromagnetic (EM) processing is widely used and well-known to stabilize the surface of solidifying material, to accelerate (EM stirring) or decelerate (the Hartmann effect) the convection in metal flows to refine the melt from oxide particles and gas bubbles (EM rectification), see e. g. the proceedings of the last EPM (Electromagnetic Processing of Materials) conference 2012.

The idea to use this technology to prevent the gravity drop-out in high power laser beam welding of thick stainless steel plates was developed in Jones et al. (2003) and successfully verified in full penetration welding tests of up to 12 mm thick stainless steel (Avilov et al. (2009)) and 30 mm thick Al-alloy plates (Avilov et al. (2012)).

The numerical investigations in this paper were made with the commercial finite element solver COMSOL Multiphysics 4.2 to get insights into the process zone and a detailed description of the underlying effects as well as to analyze the MHD interactions with the fluid flow and subsequent solidification behavior in the weld pool. Moreover, a simulation allows for an optimization of the process parameters including the amplitude and the frequency of the magnetic field.

2. Physical Background

The interaction between the fluid flow during welding and the applied magnetic fields is due to the Lorentz force

$$\mathbf{F_L} = \mathbf{j} \times \mathbf{B}, \tag{1}$$

where $\mathbf{j}$ and $\mathbf{B}$ are the electric current density and the magnetic flux density. When the applied magnetic field is of oscillatory nature, electric eddy currents develop in the workpiece inside the skin depth which depends on the applied oscillation frequency according to the classical skin effect theory, see Landau et al. (1984):

$$\delta = \left(\pi \mu_0 \sigma f\right)^{-1/2}, \tag{2}$$

with the magnetic permeability in vacuum μ_0, the electric conductivity σ and the frequency f. The time-average of the resulting electromagnetic force is directed against the gravity force. Thus, a drop-out of metal can be suppressed. A further component to the electric current density is due to the movement of the electrically conducting material transverse to the magnetic field:

$$\mathbf{j_u} = \mathbf{u} \times \mathbf{B}. \tag{3}$$

The part of the Lorentz force due to this effect is directed against the melt velocity acting as a braking force. That force is also present for the application of time-invariant magnetic fields and is called Hartmann effect. The strength of the electromagnetic deceleration can be expressed in terms of the Hartmann number:

$$\mathrm{Ha}^2 = \sigma\left(|\mathbf{B}|L\right)^2 / \eta, \tag{4}$$

with the half weld bead width L and the dynamic viscosity η. Schematic illustrations of both effects can be seen in Figure 1.