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Power factor model for selection of welding parameters in CW laser welding

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ABSTRACT

Laser welding offers enormous flexibility in terms of delivered energy. It does however, require a vast amount of parameters and phenomena to be monitored in order to control the process and to ensure high quality processing. In laser welding the same depth of penetration can be achieved using different combinations of parameters, such as laser power, travel speed. The problem is further complicated by the effect of beam diameter, which may vary significantly between different laser systems. In this work an empirical model, which enables achievement of a particular depth of penetration independent of the beam diameter is presented. First, the user selects a weld shape which meets a certain quality requirements and depth of penetration that have to be accommodated and then the model will specify how to achieve this weld using a particular laser system with a particular beam diameter.

1. Introduction

Depth of penetration is one of the most critical parameters in laser welding, which users usually need to adjust for the material being welded. For a given beam diameter a range of combinations of laser power and travel speed can be used to achieve a desired depth of penetration. Alternatively, for a given combination of power and travel speed, different depths of penetration occur, if different beam diameters are used. Beam diameter is controlled by the laser properties and optical system and these may vary between laser systems. This causes difficulties in both, selecting the optimum laser parameters for a particular application and in transferring parameters between laser systems. The difficult and unclear character of different phenomena affecting depth of penetration in laser welding has encouraged laser practitioners to use a much simpler approach. Very often parameters are developed individually based on the trial and error approach. In most experimental works using CW lasers depth of penetration is studied using system parameters, such as the laser output power and travel speed. The use of these makes the process dependent on the particular laser system, due to the unique character of beam diameter.

There are many different ways to study and optimise laser welding. Some authors tried to identify parameters that would define depth of penetration of laser welds independently of the laser system, based on the energy absorbed. The first approach included characterisation of the process by the heat input [1,2]. However, for the same heat input various welds can be achieved if different beam diameters are used. Mannik and Brown [3] collected available laser data and developed a graph showing the energy required per unit of thickness of a workpiece. Swift-Hook and Gick [4] derived normalised parameters that control depth of penetration in laser and electron beam welding. Leong et al. [5] attempted to derive an equation for the threshold irradiance required for melting. However, the predicted values of the threshold irradiance were much lower than those required in real welding conditions. Laser welding can be also studied by using dimensionless numbers, such as Péclet or Reynolds number, as reported in the literature [6,7]. However all these methods can only be used to estimate general trends in laser welding, rather than to optimise a particular welding process in practice.

On the other hand, numerical modelling provided insight into different phenomena and interactions occurring between laser and matter and contributed to the understanding of the process. It has been shown that the laser welding conditions are dependent on many factors, such as absorption of laser by workpiece [8–10], formation of keyhole [11–13], melt flow around keyhole [14–16], interaction of laser beam with the vapour plume [17–19]. All these findings have led to the evolution of complex models of laser welding in recent years [20–22]. Such complex models enabled researchers to study welding process in great detail, but they require a lot of computational capacity and therefore are inefficient to be used for optimisation of welding process in real applications.

A lot of effort has been made on improvement of the computational efficiency of numerical modelling and on development of

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simplified process models, which could be used for on-site process optimisation [23–25]. Another tool used for optimisation of laser welding is statistical analysis and neural networks [26–29]. However despite good predictability, the outcome of such optimisations is usually limited to the particular case, from which the input data were taken.

Frequently laser processing has to be carried out on different laser systems with different optical set-ups. Thus it would be useful to have a system of parameters which would specify given welding conditions uniquely and independently of a laser system. This work investigates if it is possible to find a phenomenological model of parameters, which would specify depth and width of fusion zone in laser welding, independently of the beam diameter. This would allow a potential user to select a suitable weld with a desired depth of penetration and width, required in a particular case. Then the concept would identify which phenomenological parameters should be used in order to achieve this weld. These phenomenological parameters could be transferred to the system parameters and applied to different laser systems with different beam diameters.

2. Definition of power factor

It has been shown [30] that laser welding can be considered as a periodic process whose period is interaction time. The interaction time was defined as the ratio of the beam diameter d in welding direction to the welding speed v, as given by Eq. (1).

$$\tau_i = d/v[s] \tag{1}$$

Furthermore in the same paper [30] it was demonstrated that constant interaction time and power density (defined as the ratio of the laser power to the beam cross sectional area) did not provide a constant depth of penetration when the beam diameter was varied. For a given interaction time, the depth of penetration was proportional to the product of power density and beam diameter, which is consistent with other works [31,32]. Thus the power factor P_F defined by the product of the power density q_P and the beam diameter d, which also corresponds to the ratio of the laser power P to the beam diameter d, given by Eq. (2) can be used to characterise the depth of penetration in laser welding.

$$P_F = q_P d = P/d[\text{W m}^{-1}] \tag{2}$$

The power factor is not a fundamental laser interaction parameter, but it can be considered as a simplified power density, which in contrast to the power density does not consider the cross sectional area of the beam but only its one dimensional width. The power factor along with the interaction time is used in this work as a parameter selection model.

3. Experimental set-up

The effect of welding parameters was investigated on a set of autogenous bead-on-plate laser welds in 12 mm thick S355 low carbon steel. A CW fibre laser with a maximum output power of 8 kW and a beam parameter product (BPP) of 16 mm.mrad was used. The laser beam was delivered through an optical fibre of 300 μm diameter, collimated with a 125 mm focal length lens and focused using a set of focusing lenses with focal lengths ranging from 150 mm to 300 mm. The set of focusing lenses gave beam diameters at the focal points ranging from 0.38 mm to 0.78 mm, as shown in Table 1. Different focusing lenses were used to ensure a top hat intensity distribution, whilst the beam diameter was varied. The properties of the laser beam, as well as the beam diameters were measured by means of a beam profiler. The second order moment method was used for the beam diameter evaluation. Note that the laser power and beam diameter refer to the power and beam diameter at the workpiece surface, according to the calibration measurements, using a beam diagnostic system.

Table 1
Optical set-ups used in this study.

Ffocusing lens [mm]	150	200	250	300
d [mm]	0.38	0.5	0.63	0.78
Rayleigh l. [mm]	2.1	3.3	5.6	8

All welds were carried out at the focal point, i.e. the laser beam being focused on the surface. Pure shield argon was used as a shielding gas. All welds were sectioned, polished and examined under an optical microscope in order to measure depth of penetration and weld shape. The welding parameters were chosen to ensure the keyhole mode only, to exclude the effect of changing the absorption, which occurs in transition between keyhole and conduction welding.

4. Methodology

4.1. Effect of system parameters on weld bead

To investigate the effect of system parameters on fusion profile of laser welds, a set of bead-on-plate welds with different powers in a range from 2 kW to 8 kW and travel speeds from 0.3 m min^{-1} to 15 m min^{-1} were made. A focussing lens with a focal length of 300 mm, which resulted in a beam diameter of 0.78 mm, was used. The widths of the fusion zones and general quality of the welds were examined.

4.2. Effect of beam diameter

To investigate the effect of beam diameter two focusing lenses with focal length of 150 mm and 300 mm were used. These optical set-ups resulted in two beam diameters, 0.38 mm and 0.78 mm, respectively.

In the first stage the effect of beam diameter on depth of penetration was investigated. A range of bead-on-plate welds was achieved with both beam diameters. The laser power was changed from 2 kW to 8 kW and the travel speed was varied from 0.3 m min^{-1} to 10 m min^{-1}.

In the second set of experiments the effect of beam diameter on weld width was investigated. The data from the previous experiment were used to achieve welds with the same depth of penetration at different travel speeds of 0.5 m min^{-1}, 2 m min^{-1} and 3 m min^{-1}, using two beam diameters of 0.38 mm and 0.78 mm. The laser power was adjusted appropriately for every combination of beam diameter and travel speed to achieve a depth of penetration of 6 mm. Then the macrographs were compared.

4.3. Power factor and interaction time

To validate the model it was necessary to investigate if a given combination of power factor and interaction time results in the same depth of penetration, regardless of the beam diameter. Two different experiments were carried out. In the first experiment, various parameters were used to achieve the same depths of penetration. The laser power was varied from 1 kW to 8 kW and the travel speed was varied from 0.3 m min^{-1} to 10 m min^{-1}. Four different beam diameters were used 0.38 mm, 0.5 mm, 0.63 mm and 0.78 mm. A range of travel speeds and laser powers was used