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Numerical optimization approaches of single-pulse conduction laser welding by beam shape tailoring

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ABSTRACT

While circular laser beams are usually applied in laser welding, for certain applications tailoring of the laser beam shape, e.g. by diffractive optical elements, can optimize the process. A case where overlap conduction mode welding should be used to produce a C-shaped joint was studied. For the dimensions studied in this paper, the weld joint deviated significantly from the C-shape of the single-pulse laser beam. Because of the complex heat flow interactions, the process requires optimization. Three approaches for extracting quantitative indicators for understanding the essential heat flow contributions process and for optimizing the C-shape of the weld and of the laser beam were studied and compared. While integral energy properties through a control volume and temperature gradients at key locations only partially describe the heat flow behaviour, the geometrical properties of the melt pool isotherm proved to be the most reliable method for optimization. While pronouncing the C-ends was not sufficient, an additional enlargement of the laser beam produced the desired C-shaped weld joint. The approach is analysed and the potential for generalization is discussed.

1. Introduction

Laser beam welding is a suitable technique for joining thin sheets in industrial applications because of its low heat input, high precision, high controllability and repeatability. This is especially true for electrical applications where sufficient joint strength and electrical conductivity are usually the two main criteria for a successful weld. Joint strength and electrical conductivity can be translated into the design parameters joint geometry and contact area which is controlled by the heat transfer between the work-pieces. Conduction-mode welding is often preferred for these applications because of the larger weld area compared to key-hole welding.

Traditionally, rotationally symmetric laser beams with Gaussian-like or top hat-like profiles are used for welding since these are the beam-intensity profiles often generated by high power laser sources, particularly when the beam is guided by an optical fibre to the work-piece. The laser light is delivered from the fibre end and projected to the work-piece through a collimator and a focusing lens. The ratio of their focal lengths determines the magnification of the fibre diameter. Accordingly, in the focal plane a top-hat like power density distribution is achieved. However, not too far from the focal plane the beam profile changes to a cone-like shape and finally to a Gaussian-like shape, even for fibre-guided laser beams, as was described by a mathematical model [1]. In contrast, free-running Gaussian-like beams keep their Gaussian profile along the entire optical path. Numerical models have shown that there even can be a significant difference in temperature distribution between an ideal Gaussian beam and a measured Gaussian-like beam profile [2].

Gaussian-like and top-hat like profiles are however not suitable for all applications, hence Diffractive Optical Elements (DOE) have been developed to tailor the beam shape irradiance profile in order to achieve a better joint design and to improve productivity. DOEs can be used to produce tailored beam irradiance profiles which are robust and repeatable [3]. Designing a suitable beam irradiance profile for the DOE to achieve the desired results is, however, complex and today expensive trial-and-error approaches are often used.

The two main modes of laser welding are keyhole mode and conduction mode. In conduction mode laser welding, which was

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studied in this paper, no keyhole is formed and the absorbed beam profile directly determines the boundary condition in form of the temperature gradient. Depending on the joint design, tailored beam shape profiles can then have benefits compared to the above standard beam shapes to optimize the weld shape, particularly for pulsed conduction mode laser welding when the work-piece and laser beam is are fixed relative to each other. For example, Funck et al. [4] have shown experimentally that a ring-shaped beam generates favourable temperature distribution and convection behaviour. A tailored beam can be produced by several different tools, for example by a beam scanner, by the combination of beams or by a DOE, which the present study is dedicated to. DOEs can be designed to create almost any beam shape irradiance profile, which makes them promising for a number of applications. Hammond et al. [5] showed that a DOE is suitable to optimize dissimilar welding of copper and aluminium with good results. Kell et al. [6] used a DOE to control the melt pool in conduction mode limited welding. Dual laser beam welding is a well-established technique option [7]. Tseng and Aoh [8] used a tailored beam for laser cladding. The above mentioned papers show that there are clear benefits of non-standard beam shapes for potentially a broad range of applications. Still they are rarely used in industry. The main technical barrier for DOEs is the complexity of predicting a beam shape irradiance profile to obtain a desired joint geometry. The iterative trial-and-error approach used today to optimize the design of a DOE for a specific application is expensive and time-consuming.

The investigation in this paper is based on an industrial electrical application where a C-shaped joint is desired for joining two 0.3 mm thick discs of 7 mm diameter in an overlap configuration. Earlier results revealed a sensitivity and mismatch between beam and joint shape [9]. Several different beam intensity profiles are designed and the resulting joints are compared to a weld joint from the logical initial C-shape for the beam profile. The obtained results can serve as guidelines on how the heat transfer when using DOE for single-pulse laser welding can be optimized and to enable a better understanding and consequently greater control over complex heat transfer phenomena in other contexts.

Mathematical modelling can be applied to predict, understand and optimize the laser welding process, in turn enabling a significant reduction of the number of experimental iterations. Numerical models of laser welding have been used for a long time, starting with Steen and Mazumders work [10] by the Finite Differences Method for the heat flow followed by Paul and DebRoy [11] who presented a Finite Differences scheme incorporating fluid flow in conduction mode welding. The literature review by Mackwood and Crafer [12] gives a good overview on the field of thermal modelling of laser processes until 2002. Advances in computational power and software have since then allowed models to become even more sophisticated [13–15].

Studies of pulsed conduction-mode welding also exists, the model of He et al. [16,17] provides a comprehensive study of the heat transfer and fluid flow for short pulses. They use the models for calculating the power needed to reach the boiling point and to estimate the weld pool size. The weld pool size has been accurately modelled by using an adaptive Gaussian heat source [18], the same approach was also used to model residual stress after welding [19]. Parameter assumption must always be done during modelling of welding, especially for high temperature data. Uncertainties in final result due to assumptions will always exist even though they can be reduced by optimization [20].

A few studies have also been made on more unusual beam shapes. Han and Liou modelled resulting melt pool shapes for four different laser beam modes [21]. An analytical modelling approach based on concentric superposition of heat conduction solutions by an instantaneous ring source [22] was used to model a Gaussian beam, however, multiplied with the temperature dependent absorptivity (for Au-coated copper) as a function of time, i.e. enabling in principle to model any rotationally symmetric beam profile, as well as time dependent variations and finite disc thickness. The model was applied to analyse and optimize the sensitivity of the melting process.

Almost all of the above mentioned studies are concerned with standard beam shapes. This paper will present a simplified numerical process model with emphasis on a tailored non-standard beam irradiance profile. The model only concerns heat conduction and not convection through fluid flow. It is used in a comparative manner to illustrate and optimize heat transfer mechanisms which, in turn, can provide general knowledge and guidelines for DOE design, lowering the barrier for industrial use. Different indicators of the heat flow contributions will be discussed, to identify trends and support guidelines. The results obtained will later be incorporated in a computer design tool for DOEs.

2. Methodology

For the selected laser welding case, the heat flow mechanisms were studied by numerical simulation with the commercial Finite Element Analysis (FEA) software COMSOL Multiphysics 4.3b. A desired joint geometry from an industrial application was translated to a corresponding beam irradiance profile. The result from this beam irradiance profile did not match the desired joint. To improve the weld shape via the beam shape, the thermodynamic conditions were then analysed using three different approaches. As a first order optimization step, the calculated temperature field for three more promising beam shapes [9] was studied and compared (denominated Cases 2, 3, 4 respectively). Drawing on the additional insights gained from these case studies, a fifth beam profile, Case 5, was developed which produced a weld joint that fulfils all criteria and matches the desired shape sufficiently. The three different approaches for analysis and for optimizing the heat flow and beam shape are presented and discussed, with the aim of developing guidelines for future studies.

2.1. Case studies

The application addressed in the case studies presented in this paper consists of two circular steel discs with a thickness of $d=0.3$ mm each and a diameter of $2r_D=7$ mm, see Fig. 1(b). The concentric discs shall be joined in an overlap configuration by single pulse conduction mode laser welding. The desired joint geometry (the melting isotherm at the interface $z=d$), was initially set to equal the laser beam shape (denominated Reference Case 1). It is C-shaped with a radius of $r_L=2.5$ mm, a width of $w_L=0.3$ mm and an angle of $\varphi_L=270°$, see Fig. 1(c). As an additional criterion, the maximum weld width was set at 0.45 mm, i.e. defining an envelope domain for the target weld shape.

The incident laser beam profile $I(r,\varphi,z)$ was initially modelled using a lateral Gaussian distribution along the C-shape $f(\varphi)$, see also Fig. 1(a)

$$I(r,\varphi)=I_0\exp\left(-2\frac{(r-r_L)^2}{w_L^2/4}\right)f(\varphi) \tag{1}$$

(Central peak power density I_0 corresponding to the chosen laser beam power $P_L=550$ W, or a pulse energy of 110 J). The function $f(\varphi)=1$ for $-\varphi_L\le\varphi\le\varphi_L$, while having a Gaussian φ-decay outside this range.

During the improvement steps, beam profile enhancements were made by superimposing secondary rotationally symmetric