Optics and Lasers in Engineering 50 (2012) 823–828

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Interaction time and beam diameter effects on the conduction mode limit

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ARTICLE INFO

Article history:
Received 12 November 2011
Received in revised form
29 January 2012
Accepted 1 February 2012
Available online 19 February 2012

Keywords:
Laser welding
Keyhole mode
Conduction mode

ABSTRACT

Laser welding has two distinctive modes: keyhole and conduction mode. Keyhole mode is characterized by deep penetration and high welding speeds, while conduction mode has higher quality welds with no defects or spatter. This study focuses on the transition from conduction to keyhole mode by increasing power density and using different beam diameters and interaction times. Based upon the results it was possible to evaluate that there is a transition mode between conduction and keyhole mode. The results show that the transition between conduction and keyhole mode is not defined by a single power density value. This transition has a range of power densities that depend on the beam diameter and on the interaction time. This study allows the identification of the power density that limits conduction mode, based on parameters such as beam diameter and interaction time instead of a single power density value independent of these parameters.

1. Introduction

There are two main modes of laser welding: conduction and keyhole [1] with many example applications of these. However the number of applications that use the keyhole mode [2–4] is considerably higher than the number of applications where conduction mode is used [5,6]. The advantages that conduction mode presents such as no porosity, cracks and undercut in the welds along with the fact that there is no spatter during welding makes this a useful mode [7]. The main difference between conduction and keyhole mode welding is the power density applied to the welding area. In conduction mode the power density applied is insufficient to cause significant vaporization [1,8,9]. While in keyhole mode the power density is high enough not only to vaporize material but also to open a hole in the melt pool. Despite many studies on these two welding modes the boundaries between them are not clear in terms of processing parameters. For example, sometimes the separation between conduction and keyhole welding is described as follows: if the power density is lower than 10^6 W/cm^2 the weld is in conduction mode, if it is higher than this it occurs in keyhole mode [5,8–10]. Other definitions based on the power are also used, e.g. if the weld takes place with a laser power, of the order of 1kW; it is considered that the weld is in conduction mode [8]. These definitions only rely on the power density or laser power used during the process, completely neglecting other parameters such as the welding speed or the beam diameter used. These definitions also assume that there is a sharp transition between conduction and keyhole mode [1,5,8–10], meaning that there is no transition regime in them. The number of studies focused on the transition between conduction mode and keyhole mode is very limited. An example is the study done by Sibillano where he was able to determine the welding mode by studying the plasma/plume emission during welding based on the spectroscopy data [11]. However this study does not relate the welding parameters to the welding mode and is relied on the fact that there is a single power density separating conduction mode and keyhole mode. Another study that focused on the transition between conduction and keyhole mode laser welding was carried out by Zhang et al. [12]. In his work he studied the transition between the different welding modes using laser power, focal position and travel speed as his process parameters. During this study he identified three welding mode regimes: heat conduction welding, stable deep penetration welding and unstable mode welding. The unstable mode welding had been previously identified by Chen et al. [13] and Zhang et al. [14] and it was attributed to thermal focusing [15,16], to an incorrect selection of welding parameters or to welding mode fluctuation. More studies have shown the presence of a regime between conduction mode and keyhole mode [1,17–20], while other studies just take into account two welding modes [21,22]. The transition between conduction mode and keyhole mode is somewhat unclear, not only in terms of which and how the different process parameters will influence this transition but also related to the presence of a transition mode or not.

The depth-to-width ratio or aspect ratio is also used to distinguish between conduction and keyhole mode. It is assumed that over a certain ratio value the weld will be in keyhole mode and below it will be in conduction mode [23].

In this paper, the fundamental material interaction parameters of power density and interaction time [1,9] are used. The specific

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doi:10.1016/j.optlaseng.2012.02.001

point energy parameter is also used. The power density is calculated using the following equation:

$$\text{Power density} = \frac{P}{A_{(Beam)}}, \tag{1}$$

where P is the power and $A_{(Beam)}$ is the area of the laser beam. Interaction time is calculated based on the following equation:

$$t_i = \frac{d_b}{V}, \tag{2}$$

where d_b is the beam diameter and V is the welding speed. The interaction time can be interpreted as the heating time of the process on the centreline of the weld [9].

The specific point energy is calculated based on the following equation:

$$\text{Specific point energy} = \text{power density} \times A_{(Beam)} \times t_i. \tag{3}$$

The use of these parameters allows a like for like comparison between different beam diameters.

The objective of this paper is to investigate the current definition of conduction and keyhole mode and to see if the transition between conduction and keyhole mode is a sharp transition. The evaluation of the beam diameter and interaction time effect on the upper limit of power density for conduction mode is also made. Understanding the effect of these parameters on this limit is important while choosing to use one mode or the other.

2. Experimental procedure

The welds were produced using an IPGYLR-8000 fiber laser with a maximum power of 8000 W and a wavelength of 1070 nm. The delivery system consisted of a fiber with a diameter of 300 μm, a 125 mm collimating lens and five different focal length lenses. The focusing lenses used and the respective beam diameters in focal position are shown in Table 1. Using different focusing lenses several beam diameters were obtained without defocusing and without altering the laser beam profile.

The focal position and the beam diameter for the different lenses used were determined using a Primes GmbH Focus monitor system. A typical beam profile is shown in Fig. 1, indicating that the beam had a ‘top-hat’ profile. The laser power was calibrated using an Ophir Laser Meter; model 20 kW.

The experiments were carried out by increasing the laser power and maintaining a constant beam diameter. This increased the power density while maintaining a constant interaction time. For different interaction times the beam diameter was also maintained constant and the travel speed was changed in order to obtain the values required.

The material used was S355 mild steel 12 mm thick. The plates were cleaned using a wire brush and then with acetone in order to avoid organic contamination of the welds. The chemical composition of the S355 mild steel is presented in Table 2. For the metallographic preparation all the samples were mounted, polished and etched using Nital 2%.

Table 1
List of focusing lens used and respective beam diameters in the focal position.

Focusing lens (mm)	Beam diameter in the focal position (mm)
f_f=300	0.74
f_f=400	0.95
f_f=500	1.18
f_f=680	1.61
f_f=1000	2.35

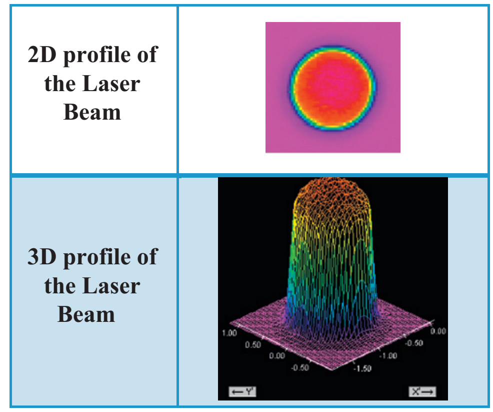

Fig. 1. 2D and 3D profile of the laser beam of the cw laser with a focusing lens of f_f=500 mm.

Table 2
Chemical composition of the S355 mild steel.

Element (wt%) S355 mild steel					
C	Si	Mn	Cr	Ni	Cu
Max 0.15	0.25/0.55	1.00/1.65	Max 0.25	Max 0.45	Max 0.3

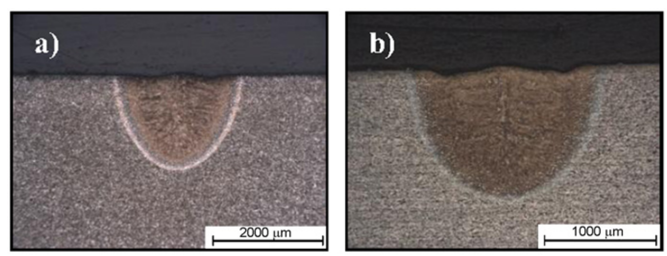

Fig. 2. (a) Macrographs of a weld produced with interaction time=40 ms, beam diameter=0.95 mm and power density=0.277 MW/cm^2. (b) Macrograph of a weld produced with interaction time=32 ms, beam diameter=0.95 mm and power density=0.265 MW/cm^2.

3. Results

The current definition of conduction and keyhole mode based on a single power density value, independent of beam diameter or interaction time was tested. Fig. 2 shows an example of welds made at a lower power density than the 1 MW/cm^2 but they have a keyhole weld profile, due to the high aspect ratio of the welds and the presence of undercut [7,24,25].

The influence of increasing the power density with a constant interaction time and beam diameter was analyzed. Fig. 3 shows how the penetration depth changes with the power density for a constant beam diameter of 0.95 mm and a constant interaction time of 10 ms. For each interaction time and beam diameter it was possible to fit a fourth order equation, with an R^2 of 0.99, and to identify two inflection points. Combining the evaluation of the first inflection point with a visual analysis of the weld profiles it was possible to identify the power density that separates the conduction mode regime from the transition regime. This power density represents the upper limit of conduction mode, Pd_{CML}. An evaluation of the power density influence on penetration depth for different interaction times and different beam diameters allowed for the identification of the Pd_{CML}, i.e. the maximum power density allowed to do a conduction weld for a certain interaction time and beam diameter. Based on this three different