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Research paper

Minimization of the thermal material effects on pulsed dynamic laser welding

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A B S T R A C T

Achieving a uniform welding seam with minimum overheating is crucial to obtain high quality joints in laser welding. The classical formula of the overlapping factor for laser pulsed welding was modified by the introduction of empirical corrections from the application of static pulses involving constant energy combinations of laser power and pulse duration. The energy re-allocation in the case of dynamic pulses was studied as a function of the laser displacement speed. Energy optimization criteria aiming the minimization of the energy per length unit or surface unit were introduced. An optimized uniform welding seam with minimum thermal affectation was obtained by means of dynamic pulses.

1. Introduction

Laser welding technology is capable of achieving high quality seams through the correct allocation of the energy supplied to the process, as is illustratively detailed for several practical cases in Katayama's handbook (2013). That work highlights the importance of the welding technique to control the energy effectively introduced into the material.

Laser pulsed welding allows the energy introduced into the process to be controlled by adjusting several variables. According to Tzeng (2000), the energy transmitted into the material in pulsed welding depends mainly on the following set of variables: laser peak power, pulse time, process speed and the superposition of consecutive pulses, known as overlapping factor. This last one is calculated considering the process speed and the frequency of the pulses, synthesizing, representatively, the effect of a particular combination of process parameters.

The work of Tadamalle et al. (2013) shows that the fused area in the material may not coincide with the theoretical laser beam diameter. This difference leads to unexpected results if the overlapping factor formula uses the theoretical beam diameter without any empirical correction representing the energy supply on the treated surface. Particularly, it could result in the selection of parameters leading to an overheating of the surface, associated to quality problems.

Several works deal with the problem of an excess of energy introduced into the material. For example, Vesel et al. (2008) show how at prolonged high temperatures in stainless steels there is a growth of iron oxide that can harm the protective passive layer. Roberge (2008) explains how a weakened passive layer will be more prone to be affected by other kinds of corrosion such as galvanic corrosion, found in dissimilar joints of two different metals. Also, overheating of the liquid metal can lead to spattering and irregularities in the welding which may cause corrosion in the crevices and constitute the origin of cracks. Considering metallurgical aspects, Alizadeh-Sh et al. (2014) show that an oversized heat affected zone (HAZ) promotes changes in the microstructure and grain size that reduce the mechanical strength of the welded joint.

All of these difficulties justify a methodology to extend the capabilities of the formula of the overlapping factor in order to take into account the influence of the process parameters on the real affected area in the material, which, in turn, must determine the effective distance between consecutive pulses. While some studies use statistical approaches, such as Masoumi and Shahriari (2010), by means of the Taguchi method in order to select the correct set of parameters during the laser welding, the current study focus on the phenomena which characterize the laser-material interaction, offering a practical approach to the problem. In the review by Mackwood and Crafer (2005), it can be seen how the heat absorption changes between the different welding techniques through three different physical mechanisms of interaction, con-

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Table 1
Composition and physical properties of the AISI 430 ferritic stainless steel.

C	Si	Mn	P	S	Cr	N
≤0.080	≤1.00	≤1.00	≤0.040	≤0.015	16.00-18.00	≤0.045

Property (at different Temperatures)	20 °C	100 °C	200 °C	300 °C	400 °C	500 °C
Elasticity Modulus (GPa)	220	215	210	205	195	195
Coefficient of Thermal Expansion (10^{-6} K^{-1})	10	10	10	10.5	10.5	11
Thermal Conductivity (W/m·K)	25	25.8	31	32	33	34

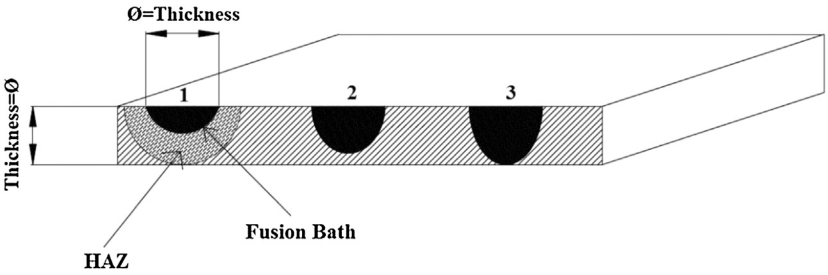

Fig. 1. Interaction modes for a beam diameter matching the thickness of the plate 1. Conduction mode. 2. Conduction-keyhole. 3 Keyhole mode.

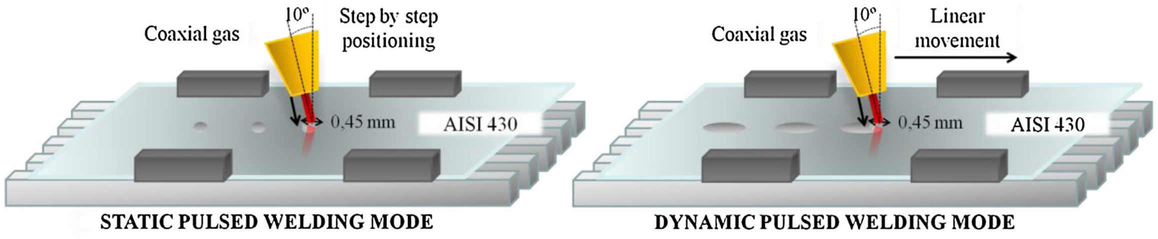

Fig. 2. Scheme of the process for static and dynamic pulses, representing the clamping system and the incidence angle.

duction welding, keyhole welding, whose governing equations are thoroughly developed by Zhou et al. (2006), and the inverse Bremsstrahlung shielding. The energy efficiency of these mechanisms changes depending on the flow dynamics and reaches its peak in the keyhole phase as explained by Eriksson et al. (2013). A procedure which is able to select the appropriate mechanism, and make a suitable use of it through the overlapping factor formula is proposed, considering, innovatively, the welding regime, conduction or keyhole, and its consequences in the context of the of the process, static or dynamic, showing important phenomena that must be controlled.

In the first place, a static and dynamic set of test has been carried out to characterize the laser-material interaction. The observation of single static pulses is used to reduce the range of interest of the parameters which will be tested dynamically. A comprehensive energy characterization of the empirical results is carried out to determine the conditions to obtain a certain affected area in the material with the minimum waste of energy. Then, the reproduction of static parameters in dynamic conditions at different speeds provides understanding of the energy re-allocation as a consequence of the dynamic transition. Finally, by selecting the most energy efficient results and introducing them in the modified overlapping formula the desired pulsed welding seam is obtained. In this way, the proposed methodology offers a novel way of reducing the uncertainty in the selection of the process parameters, by the introduction of empirical corrections and criteria to optimize the energy supply.

The design of welding seams using the formula of the overlapping factor with dynamic laser pulses has demonstrated its capabilities to obtain uniform welding seams with a minimum overheating of the material. It has led to high quality results, measured in terms of absence of corrosion and mechanical resistance of the joint, in comparison with continuous welding, for similar process parameters.

2. Material and experimental setup

Without any lack of generality, the AISI 430 steel (1.4016 or X6Cr17 according to EN designation) has been selected as working material. It is one of the most common ferritic stainless steels in engineering with important applications in consumer goods and food industry. Table 1 synthesizes the chemical composition and physical properties of the AISI 430 steel.

The welding equipment is a Rofin Sinar Nd:YAG laser releasing radiation at a wavelength $\lambda = 1064$ nm, with a maximum output power $P = 3{,}3$ kW. The laser radiation is transported through optical fiber to a welding nozzle installed in an industrial robot ABB IRB 4400. The head of the welding equipment is prepared for autogenous welding with the option of using coaxial gas in a controlled way. The clamping system combines mechanical clamps and magnets to guarantee similar positions in different welding samples.

An important characteristic of the process arrangement is the coincidence between the diameter of laser beam, Ø, and the thickness of the plates that were irradiated in the experimental tests. For the case of the present study a value of 0.4 mm has been selected for both magnitudes. On the one hand, this value constitutes a typical diameter size to get a suitable energy density in laser welding, keeping, at the same time, the thickness of the plates within a value where it is possible to evaluate accurately the effect of the laser in both sides, the irradiated face and the opposite one. On the other hand, the diameter of the laser beam is strongly related with the depth and size of the fusion bath. It implies that, if the thickness of the plate is smaller than the laser beam diameter, it melts before