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A double-point moving source model for predicting seam geometry in laser welding

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ABSTRACT

A theoretical double moving point source model, based on the superposition principle, is proposed for predicting the weld seam geometry produced by a CW Nd:YAG laser in a constrained overlap configuration on a martensitic stainless steel in a transitional regime between pure conduction and keyhole welding. This intermediate regime is modelled by varying the power balance between the two point sources along with their relative distance. Tests show that the main geometrical features of the weld bead (penetration depth and resistance length) are comparable to the predicted values (error less than 5%). Finally the model can be also profitably used in order to predict the temperature field around the molten pool.

1. Introduction

Laser beam welding (LBW) is a well-established production technology for joining 3D structures, complex assemblies, high precision components and very thin materials including metals and polymers. LBW in the automotive sector includes the assembly of fuel injectors where tubular parts are joined in butt, fillet or overlap configuration to create a pressure vessel undergoing to a pulsed stress (0–40 MPa) during service life [1]. The weld seam has to be homogeneous over the 360° to guarantee at the same time tightness to the fuel and strength to the stresses generated by the intermittent functioning. In this specific application the conduction limited mode hinders to reach enough resistant length at the interface between the tubes with a consequent drastic reduction of the joint mechanical properties [2]. On the other side keyhole welding is not recommended since beyond certain energy input resistant length reaches a limiting value [3] and deep penetrations can pierce thin wall tubes causing internal leakage. The correct weld bead has then a parabolic shape which represents an intermediate regime between pure conduction and keyhole, and is less studied in the literature.

1.1. Research objectives

Understanding the transition between pure conduction and keyhole represents a process keyfactor since it allows a proper selection of working parameters along with a robust control during production.

Assumed that environmental conditions (e.g. the miniaturized emitting area) limit the availability of precise information directly from the melt pool, its shape and size can be derived from either numerical simulation or from theoretical modelling. The review of recent developments shows a preference in numerical simulation since it represents the most complete tool to incorporate the whole welding phenomena including heat transfer but also diffusion and electromagnetism, as well as solid, liquid, gas, and plasma phases. Computational fluid dynamic modelling and finite element modelling have been used to understand the formation of net-shape weld geometry [4]. Numerical approaches are also found to be favourable for comprehending how the driving forces affect the flow characteristics of a molten pool [5]. Its characterizing features are studied as a function of the geometry of 3D heat source used to describe the heat input into the material. Among all, the double ellipsoid model [6], representing a volumetric heat input generated by a moving source, can be retained the most comprehensive one.

Though calculation capabilities increase using FEM methods, simulations are influenced by the meshing net adopted to describe the heat exchange phenomena. This is a critical point in the welding of components whose thickness has the same order of magnitude of the spot diameter, since numerical results might vary at different scales. On the other hand theoretical solutions based on the Rosenthal equation [7] are not enough to describe the intermediate regime which bridges the gap between pure conduction and keyhole regimes and relate a hypothetic thermal field to process parameters.

In order to overcome the abovementioned drawbacks and analyze the geometrical features of the melt pool from the perspective of the process parameters, the main objective of the present research is to develop a theoretical model for predicting the thermal field which produces the peculiar parabolic profile in laser welding. The analytical model will be validated with experimental observation.

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2. Experimental problem

The material used in experiments is AISI 416 since fuel injector production commonly makes large use of martensitic stainless steel when high mechanical properties are required together with a good resistance to corrosion. Geometrical characteristics of the examined weld in overlap configuration are shown in Fig. 1. The inside diameter of outer shell and the outside diameter of inner shell are ground to Ø7.500 ± 0.025 mm and Ø7.556 ± 0.015 mm while thicknesses are 0.5 mm and 1.5 mm, respectively. A standard washing procedure practised in the automotive industries is followed to clean, cool and dry the shells. Tubular parts are then press fit one into the other to ensure close contact (zero clearance) at the interface surfaces during welding. This step is done as a replication of the actual fabrication process.

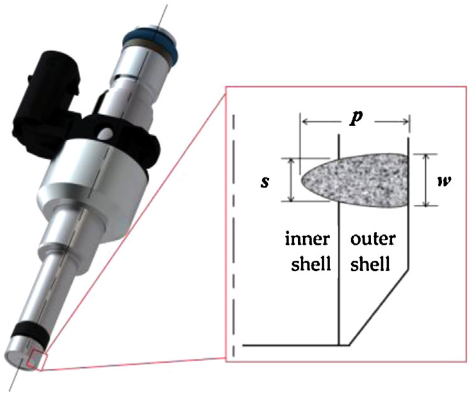

Fig. 1. 3D view of a fuel injector and weld characteristics: *w*, width; *p*, penetration depth; *s*, resistance length.

Specimens are welded circularly using a 2 kW continuous wave disk laser. Radiation conveyed in a 300 μm fibre is collimated by a 200 mm focal lens to a minimum spot diameter of 300 μm with a top flat energy distribution. The beam is focused normally onto the outer shell surface and no shielding gas is used.

Being the laser welding extremely fast (from 230 ms to 630 ms) in the tested range of welding speed v (60–200 mm/s), it is possible to adopt the concept of energy density as in many Rapid Manufacturing (RM) techniques [8]. Energy density (ED hereinafter) expresses the energy input per unit area (J/mm^2)

$$\mathrm{ED} = \frac{P}{\upsilon \phi_s} \tag{1}$$

This single parameter provides the effects of three-factor interactions on geometry and mechanical properties of the weld. Laser power P (W) describes the thermal source capability, welding speed v (mm/s) determines the interaction time, and spot diameter ϕ_s (mm) defines the area through which energy flows into the material. During experimentation, energy density inputs on the focused area are derived from process parameters (P, v) and varied in the range of 12–50 J/mm^2.

After welding, specimens are sectioned axially to obtain transverse sections of the weld bead under various welding conditions and finally prepared for metallographic analyses following the standard procedure recommended for martensitic stainless steel. Examples of the experimental results can be found in Fig. 2. For low values of ED heat is conducted in isotropic way giving a semicircular weld profile, which is generally not enough to melt both components. In the intermediate regime a deeper penetration is reached due to the motion of melt inside the pool (Marangoni flows), giving a parabolic profile which ensures a required resistance length. An increase in ED input results in the classic deep and narrow shape which characterizes the formation of keyhole. ED can be then considered as an index of the heat exchange regime.

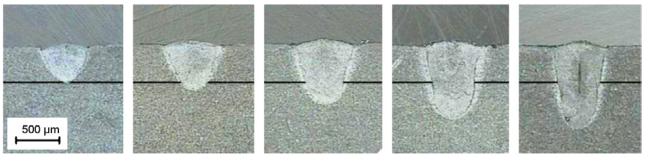

Fig. 2. Weld profiles at increasing ED: (a) ED = 20 J/mm^2, (b) ED = 25 J/mm^2, (c) ED = 31 J/mm^2, (d) ED = 36 J/mm^2, (e) ED = 49 J/mm^2.

3. Weld profile modelling

In order to analytically describe the welding process in overlap configuration and to find an analytical solution for the Fourier's equation the following assumptions are made:

- the maximum temperature $T_{\max}$, reached at the workpiece surface, is lower than the vaporization point.
- Heat transfer is mainly governed by conduction. Convection and radiation are neglected due to extremely small exchange area.
- The internal heat generation term in Fourier's equation is set at zero. This leads to define the power of heat sources in terms of boundary conditions.
- Energy absorption by the material is considered complete because of the multiple reflections in the molten pool once it reaches the steady state [9].

Among simple theoretical solutions collected in [7], the moving point source model and the moving line source model are found to be the most reliable in respecting the first assumption, being the calculated $T_{\max}$ of the same order of magnitude of the vaporization point for the selected steel. The first model is commonly used in order to predict the temperature field in pure conduction welding processes while the latter is well representative of deep penetration welding. Anyhow both these models are not suitable for describing such a complex phenomena in which a typical boundary exchange due to laser/surface interaction is joined with the activation of heat and mass transport in the domain.

Modelling the intermediate regime where the weld seam acquires the parabolic shape can follow up the superposition principle, as firstly proposed in [10]. A double moving point source model–whose parameters are functions of energy density – can be hypothesized in order to cover this gap. Considering a moving frame (X, Y, Z) one point source is set at the free surface to simulate the interaction with the laser beam. A second point source is located inside the material, at depth z_2, to simulate heat transfer phenomena not related to isotropic conduction from the free surface (Fig. 3).

Taking into account the Rosenthal's solution for the temperature field generated by a single moving point source [7] and applying the superposition principle, it is possible to find the analytical solution for a double moving point source. The temperature under the workpiece surface can be found using the following equation:

$$T(r_1, r_2, X, \upsilon) = T_0 + \frac{Q_{\mathrm{p1}}}{2\pi k r_1} e^{(-\upsilon/2\alpha)(r_1+X)} + \frac{Q_{\mathrm{p2}}}{4\pi k r_2} e^{(-\upsilon/2\alpha)(r_2+X)} \tag{2}$$

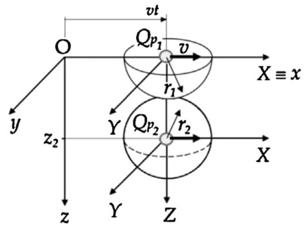

Fig. 3. Position of point sources in a semi-infinite medium respect to the fixed frame O(*x*,*y*,*z*). Isotherms are referred to the moving frame *X*,*Y*,*Z*.