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Modelling for predicting seam geometry in laser beam welding of stainless steel

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ABSTRACT

A methodological approach for analytical modelling of deep penetration laser beam welding (LBW) of stainless steels and its experimental verification is provided. After an analysis of the problem in general terms and a review of the modelling activity, a particular double source model is proposed and discussed. The model allows the derivation of penetration and width of melting zone caused by moving laser beam. Dependences of penetration length, width of the melting zone and aspect ratio of the zone were derived as a function of welding speed and laser power. The theoretical results obtained using the particular model are discussed and analyzed in comparison with experimental data obtained on a typical test case. Optimal conditions for obtaining a preliminary optimization of the process parameters were derived based on experimental results. The case study in the present paper, referred to the assembly of fuel injectors for automotive industry, demonstrates that when laser welding is performed at high speeds on thin wall components the energy released by the laser per unit of surface (energy density, ED) can be used to describe the heat transfer to the material and to shorten the experimental phase avoiding the dependencies on each single process parameter.

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1. Introduction

Laser beam welding (LBW) has been increasingly used in all industrial areas in which high volume of production, high welding speed and high accuracy are required such as car manufacturing, aircraft industry, ship building, electronic industry, etc. [1–3].

Nowadays, in automotive industries, manufacturing of modern fuel injectors for gasoline, diesel, and gaseous fuels – where tubular parts are joined in butt, fillet or overlap configuration to create a pressure vessel undergoing to a pulsed stress during service life [4] – involves laser welding to improve quality and maximize production throughput. 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 functioning.

Nd:YAG laser performs best for welding small and heat sensitive complex parts of a fuel injector because of its short time cycles and metallurgy of the stainless steels used for this application. In this specific application the conduction welding mode hinders to reach enough resistant length at the interface between the tubes [5]. On the other hand keyhole welding is not recommended because deep penetrations can pierce thin wall tubes and beyond certain energy input resistant length reaches a limiting value [6]. The weld bead has then to be parabolic: this shape can be obtained in an intermediate regime between pure conduction and keyhole.

The proper definition of process parameters is a key-factor in order to achieve high quality junctions with few defects and small heat-affected zones. Understanding the thermal phenomena accompanying LBW process is required for an appropriate use and an optimization of this welding technique.

The shape and size of the melt pool can be derived from either numerical simulation or from theoretical modelling. Mathematical modelling of the laser spot welding process can be considered as an effective and cheaper alternative to experimental studies, allowing appropriate selection of process parameters used to obtain a desired shape and width as well as appropriate mechanical properties of welded joint. A comprehensive analysis of the problem is provided in Ref. [7].

The review of recent developments shows a preference in numerical simulation since it represents the most complete tool to incorporate the whole welding phenomena. Computational fluid dynamic modelling and finite element modelling have been used to understand the formation of net-shape weld geometry [8]. Numerical approaches are also found to be favourable for comprehending how the driving forces affect the flow characteristics of a molten pool [9].

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Nomenclature

c_p	Mass specific heat [J/kg K]
D	probing depth [m]
ED	energy density [J/m^2]
Ei	exponential integral function
erfc	complementary error function
F_0	power density at $z = 0$ [W/m^2]
H	heat generation per unit volume [J/m^3]
ierfc	integral of the complementary error function
k	thermal conductivity [W/m K]
$K_0(x)$	modified bessel function of second kind and zero order
L	wire length [m]
p	penetration depth [m]
P	input power supply furnished with the DC power supply [W]
Q'	heat transfer rate per unit area and unit time [W/m^2]
Q_l	heat rate per unit length [W/m]
Q_p	intensity of the point source (released power) [W]
Q	input energy [J]
r	radial distance from a heat source $r = \sqrt{x^2+y^2+z^2}$ [m]
R	reflectivity
R_0	*circular* radius of the source $R_0 = \sqrt{x^2+y^2}$ [m]
R_i	internal radius of the valve body [m]
R_e	external radius of the valve body [m]
s	resistance length [m]
t	time [s]
T	temperature [K]
T_0	room temperature [K]
T_m	melting point [K]
v	laser beam speed [m/s]
w	weld width [m]
x	travelled distance in the fixed frame [m]
X	distance from the source in the moving frame [m]
y, Y	transversal position [m]
z, Z	depth [m]
z_2	position of the second source
α	thermal diffusivity [m^2/s]
γ	power balance
ρ	density [kg/m^3]
ϕ_s	focal spot diameter (fibre diameter) [m]
ΔT	temperature difference [K]
Δz	element size [m]
Δt	time interval [s]

Considerable work has been reported in the recent past to numerically simulate the laser beam welding process using both finite difference and finite element methods [10]. Its characterizing features are studied as a function of the type of heat source used to describe the heat input into the material. Among all, the double ellipsoid model [11], representing a volumetric heat input generated by a moving source, can be retained the most comprehensive one.

Anyhow, though calculation capabilities increase using FEM methods, various assumptions on the type of meshing net and its refinement are needed to simplify the complex physical phenomena. Simulation results may then vary as a function of the adopted mesh scale and the relative nodal interconnection with the boundary. Moreover uncertainty of material properties such as effective thermal conductivity and viscosity in the weld pool and concerning the boundary conditions (mainly heat transfer) also made difficult a precise heat and mass transfer analysis. This aspect has a strong influence when welding tubular parts whose thickness has the same order of magnitude of the spot diameter. In this case the sensitivity of results to scale effects makes numerical simulation not beneficial respect to a simpler theoretical model based on approximations derived from experiments.

A simpler and more tractable approach can be to consider phenomenological laws of heat and mass transfer and to resort to a theoretical model of the problem. This model makes it possible to obtain the seam geometry analytically without using numerical analysis methods. Analytical solutions to heat conduction equation offer a quick assessment of temperature field and its dependence on process parameters and are still considered in the recent literature [12]. Among simple theoretical solutions for the Fourier's equation, the single moving point source model, firstly introduced by Rosenthal [13], is commonly used in order to predict the temperature field in pure conduction welding processes. The moving line source model [14] is indicated in case of deep penetration welding on thin sheets, instead. Therefore, there is a lack in analytical modelling for an intermediate regime where the weld seam acquires the typical parabolic shape. It is possible to follow up the superposition principle as in [15], hence to develop different theoretical solutions based on the superposition of moving point and line heat sources in order to cover this gap.

Extensive literature is available on the modelling, both analytical and numerical, of the laser welding process. In case of simple-shaped sources – like point, line or plane sources – it is possible to find an analytical solution for the Fourier's second law. Otherwise, if one uses a source of more complex shape – like, e.g. Gaussian, conical or conical-cylindrical sources – the solution may be only found by numerical integration or using FE-method. The classical heat transfer textbooks by Carslaw and Jaeger [14], Eckert and Drake [16] and Bejan [17] proposed various solutions based on stationary heat sources; this type of modelling does not take into account the beam motion. Lankalapalli et al. [18], Lampa et al. [19] and Hann et al. [20] proposed few models based on moving conical and truncated conical shaped sources considering various power absorption modes. All these models produce excellent results in case of deep penetration welding but they are not suitable in case of parabolic shaped weld. Cline and Anthony [21], Davis et al. [22], Ashby and Shercliff [23] proposed a few solutions for the Fourier's equation based on moving sources but these are only able to predict the penetration depth or the weld width separately. Most of the analytical models based on the theory of heat flow due to a moving source of heat are founded on the Rosenthal's theory. Rosenthal [13] proposed an analytical solution based on a moving line source – suitable for the temperature field prediction in case of keyhole welding on thin sheets – and a moving point source, suitable in case of pure conduction welding.

The basic theory of heat flow developed by Fourier and applied to moving heat sources by Rosenthal is surely one of the most popular analytical method for calculation of thermal history of welds. Even if such a kind of analysis can be subjected to serious errors for temperature near the fusion and heat affected zone – the effect of the various simplification assumptions on the accuracy of temperature distribution from such a kind of analysis has been discussed in detail by Myers et al. in Ref. [24]. The use of hybrid-analytical models joined with experiments, seems to be always an interesting topic.

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