Numerical Simulation of Induction Assisted Laser Beam Welding

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The laser beam welding is an efficient industrial process used to join metallic pieces and it is commonly used in many applications. Unfortunately, due to the high values of space and time thermal gradients created by the beam, problems can occur in the metallurgy of the seam that usually affect the joint mechanical properties. One proposed solution is the use of induction heating, placed close to the laser beam, that can smooth out the thermal gradients controlling the metallurgical structure of the welded material. The simulation of this industrial process requires the analysis of both heating sources (laser beam and induction heating) coupling together the electromagnetic and the thermal phenomena. To this aim, a specific analysis tool has been developed that can take into account all the peculiarities of the phenomena. The procedure is based on the Cell Method and its novelty lies in the use of a coupled electromagnetic-thermal procedure taking into account the laser modelling. The description of the procedure together with some obtained results are presented.

***Index Terms*—Coupled problems, Induction Heating, Laser Beam Welding, Cell Method.**

I. INTRODUCTION

THE LASER BEAM WELDING (LBW) process is made by an intense local heating, created by a focused laser beam source, of two workpieces: local fusion of material joins the two parts creating a seam. The process is continuous since the laser source is moving with a speed of some centimetres per seconds. The accurate modelling of the interaction between the laser beam and the material is not an easy task since many phenomena occur at the same time like: thermal conduction, fluid flow in the weld pool, keyhole dynamic, optic effects etc. To overcome this simulation problem, several simplified beam models have been developed, as for instance in [1], [2], [3]. A phenomenological model of the interaction of the laser beam is thus used whose main aim is to compute the thermal power transferred from the beam to the workpiece. The dynamic of the material thermal state is mainly influenced by the power of the beam and by its speed: the larger the speed the lower the energy exchanged with the material. Consequently, a transient thermal analysis of the phenomenon has to be carried out to evaluate the thermal history of the material. The thermal dynamic of the workpiece can be controlled by the addition of other thermal sources that control the heating and cooling of the treated parts. An efficient control of the thermal power can be obtained by electromagnetic induction heating. This process has been used experimentally both in heating up the material before the action of the beam and controlling its cooling down after the welding [4].

A simulation of the LBW process with an induction post-heating has been developed and is here presented. The analysis steps are:

1) laser beam model: a phenomenological model of the beam power has been developed by using few tuning parameters;
2) a nonlinear thermal transient analysis tool has been developed where the movement of the beam is considered;
3) electromagnetic induction heating has been added using a nonlinear first-harmonic analysis of the eddy currents. Nonlinearities in the magnetization curve created both by magnetic and thermal conditions have been taken into account.

Steps 1 and 2 of the procedure have been iterated in order to tune the beam parameters with respect to some experimental data on welded seam.

In the following a brief description of the various steps of the procedure will be highlighted and some results presented.

II. LASER BEAM MODEL

The laser beam is interacting with a plane metal sheet whose depth is extending between the coordinates z_1 and z_2, as shown in Fig. 1. The beam shape is not influenced by the direction of motion, so that a cylindrical frame of reference can be used to describe it. It is assumed that the beam is focused by an external optic system so that its shape is conical with a focus which can assume different depth values inside the metal. The coordinate of the focus is z_0 and the aperture of the beam is θ. In correspondence of the focus the laser spot diameter is d_0. The double conical shape is approximated by the function:

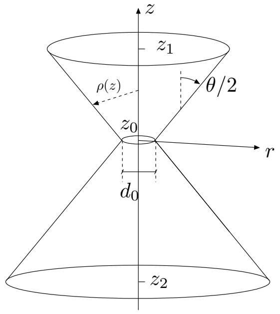


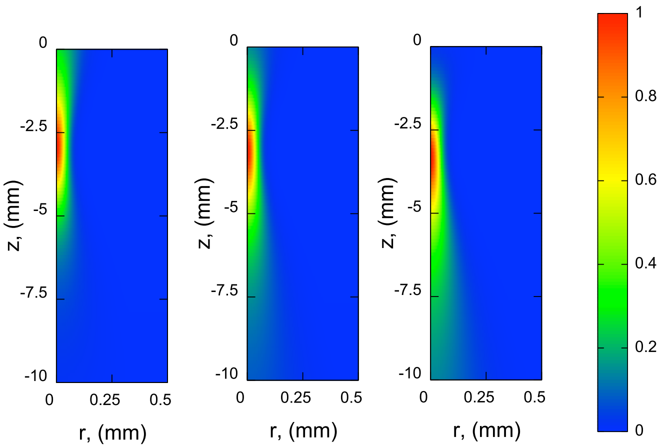
Fig. 1: Shape of the laser beam and frame of reference.

$$\rho(z) = \sqrt{\left(\frac{d_0}{2}\right)^2 + \left[\frac{\theta}{2}(z - z_0)\right]^2} \tag{1}$$

It is considered that the volume power density transferred by the beam is inversely proportional to its aperture and that it has a gaussian distribution along the radius. As described in [3], the interaction with material alters the shape of power distribution, so that a linear modification of the power with respect to the depth of the steel is introduced. The resulting power distribution is given by:

$$p = p(r,z) = K\frac{(d_0/2)^2}{\rho(z)^2} e^{-\alpha\left(\frac{r}{\rho(z)}\right)^2}\left[m_0(z-z_0)+1\right] \tag{2}$$

The constant K is used to normalise the volume integral of p to the total laser power, gaussian constant α is taken by literature values to be equal to 3 and m_0, that is the slope of a linear factor deemed to be one at the focus position, is the only tuning parameter. The effects of the m_0 parameter on the power distribution for a beam interacting with a sheet where $z_1 = 0$ and $z_2 = -10\ mm$ and $z_0 = -3\ mm$, can be seen in Fig. 2. The value of m_0 has been used to fit the experimental temperature profiles measured in a ten mm thick steel sheet welded by a 8.5 kW beam moving with a speed of 3.3 cm/s. A value of $m_0 = 100\ m^{-1}$ was found to be optimal.



(a) $m_0 = -100\ m^{-1}$ (b) $m_0 = 100\ m^{-1}$ (c) $m_0 = 300\ m^{-1}$

Fig. 2: Volume power density distribution on the (r, z) section, per unit value, changing the m_0 parameter. Scale on the horizontal axis is twenty times the vertical one.

III. INDUCTION HEATING

The induction heating can assist the process by heating the material prior to the welding, in order to increase the power exchanged by the beam and/or after the beam welding to decrease the cooling rate of the material avoiding the formation of hard metallurgic structure [4]. In the present study, the second case has been considered with a structure sketched in Fig. 3, where the laser beam is moving in the x direction and some inductors are trailing behind it heating the welded region. The nonlinear eddy current problem is solved by means of a first harmonic approximation, using an equivalent material characteristic, as proposed in [5]. The magnetic nonlinearity takes into account also the thermal dependence by the material temperature. A complete formulation of the nonlinear eddy current problem can be found in [6].

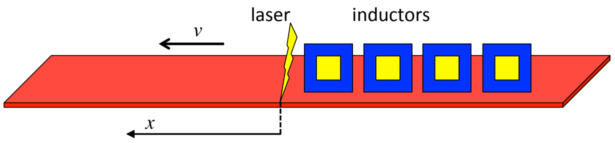


Fig. 3: Sketch of the induction heating applied after the welding.

IV. RESULTS

The analysis of the coupled thermo-electromagnetic problem gives the dynamic of the material temperature after the welding and allows the design of the induction system able to cool it down with prescribed cooling rate preventing the formation of undesired steel structures. This is particularly important in the $250 \div 550\ ^{\circ}C$ temperature interval, where different structures can be formed depending on the cooling rate. As it can be seen in Fig. 4, a suited heating contribute is able to force the cooling profile to stay almost completely within the austenite-bainite formation, without passing through the formation of martensite which is undesired in the present case.

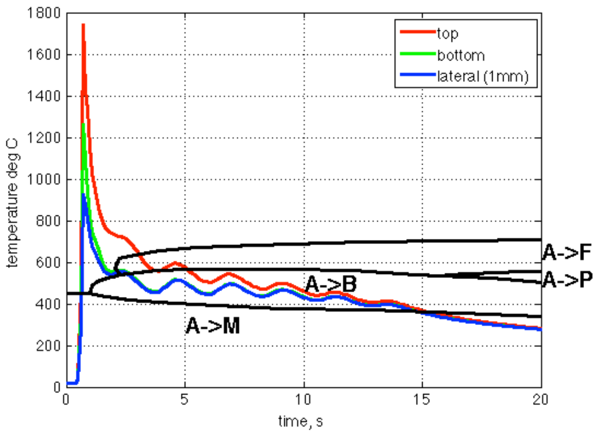


Fig. 4: Temperature profile vs. time of different points on the steel sheet and diagram of ironcarbon alloy phase formation: $A \rightarrow M$ austenite to martensite, $A \rightarrow B$ austenite to bainite.

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