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[INVITED] An overview of the state of art in laser welding simulation

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ABSTRACT

The work presented in this paper deals with the laser welding simulation. Due to the rise of laser processing in industry, its simulation takes also more and more place. Nevertheless, the physical phenomena occurring are quite complex and, above all, very coupled. Thus, a state of art is necessary to summarize phenomena that have to be considered. Indeed, the electro-magnetic wave interacts with the material surface, heating the piece until the fusion and the vaporization. The vaporization induces a recoil pressure and deforms the liquid/vapor interface creating a vapor capillary. The heat diffused in the material produces thermal dilatation leading to mechanical stress and strain.

As a complete simulation is too large to be computed with one model, the literature is composed by two kinds of models, the thermo-mechanical simulations and the multi-physical simulations. The first aims to find the mechanical stress and strain due to the welding. The model is usually simplified in order to reduce the simulation size. The second, compute the more accurately the thermal and the velocity fields. In that case authors usually search also the size of the weld bead and want to be totally self consistent.

In this review, the major part of equations and assumptions needed to simulate laser welding are shown. Their effects on simulation results are illustrated for each simulation type. The paper aims to give sufficient knowledge and tools to allow a simulation of laser welding.

1. Introduction

The laser welding is an increasing process in the whole international industry, for micro-welding as well as deep welding. As other welding processes (with fusion), the assembly of two pieces is obtained by a local fusion and solidification, forming the "welding joint" or "weld bead". The particularity of laser welding is based on the way used to deposit the thermal energy to the piece surface. If with other processes, the heat is transmitted to the piece mainly by conduction and convection (in arc welding, for example). The principle here is to heat the material by the interaction of a light radiation (laser) beam with the material. The energy input responds to the well known optical laws, which means a high temporal stability and a flexibility in terms of spatial distribution. Indeed, the beam shape depends directly on the optical path (fiber, lens, mirror, …). Thus, it is quite easy to set and change the beam concentration, which leads to a large range of laser intensities and allows a quite large weld penetration scale.

Of course, the research in laser technologies remains more newsworthy than ever and lasers are nowadays more and more efficient in terms of time stability, spatial distribution and energy consumption. Technologies used for welding applications were mainly CO_2 lasers and solid state lasers like Nd:YAG or fiber laser. The CO_2 technology was the first able to deliver a power higher than 10 kW but its wavelength (10.6 μm) leads to the incapacity to be transported by classical optical fibers, to be focused by lens and tends to be absorbed by the keyhole plasma. Solid state lasers have a more useful wavelength (1.06 μm for Nd:YAG and 1.03 μm for Yb:YAG), for which the silica fibers or lenses are nearly transparent. Nevertheless, a third category of laser is now able to produce a sufficient power for welding applications (between 5 kW and 15 kW): the laser diodes, which also tend to have better optical properties.

As the beam can be shaped quite easily by users, the laser welding can be realized by two main ways: *conduction* type or *keyhole* type. The first produces a weakly penetrated weld bead similar to other processes (arc, for instance). The energy is deposited to the component surface and the beam distribution is shaped to produce low power density only able to fuse the material. The second is obtained from a more dense power distribution, which is sufficient to increase locally the material temperature above to the vaporization one. Due to the recoil pressure (vaporization pressure) a narrow keyhole is created. Depending on the laser wavelength, the beam is more or less well deposited inside this cavity. Thus, the energy is distributed in the material thickness leading to a deep weld penetration (several millimeters to centimeters).

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The consequences of this specific welding case are very interesting in the actual industrial context. First of all, the heat generated by laser can be highly localized (several micrometers) and allows the welding of very small components. Conversely, the very high intensity (power density) generates a keyhole and permit the welding of thick materials. The energy given to the metal is highly concentrated producing very large gradient and thus a small volume thermally affected. Thus, the major effects are few weld distortions associate to large mechanical residual strains. Moreover, the high power density allows very fast welding (until a meter per second) producing in many cases hot cracking.

As the computing hardware is more and more efficient, the numerical simulation is growing in all industrial fields. The welding and more particularly laser welding are also concerned by this fast evolution. The first industrial objective is the design and the optimization of manufacturing processes and components. The simulation is also useful to improve the production sequences and to minimize production problems. That is why a huge amount of model tries to calculate the mechanical effects of welding as residual strains and distortions. Nevertheless, a complete (multi-physical) simulation can also help manufacturers to better understand and to master their processes.

The difficulty in laser welding simulation is the “multi-physical” aspect of the process. As said previously, mainly phenomena are coupled and different scale of physics interacts (photon–electron interaction versus piece shape distortions for example). In spite of the computer efficiency rises, the complete simulation, starting from the light propagation until the structural distortions, is currently not conceivable. For the moment, numerical codes are constrained to simulate the process scale by scale and to concatenate results. For example, the first step is the laser–material interaction (multiple reflection) which gives the heat input to a heat transfer and fluid flow calculation. Then, having the heat distribution with the time, a metallurgical problem can be solved to obtain the material mechanical properties and leading to the mechanical computation. In the literature, multi-physical simulations are not yet really complete simulations, but mainly heat transfer and fluid flow simulations, coupled to a front (or free surface) tracking method and a multiple reflection consideration. Moreover, it should be noted that the difficulty of considering the whole phenomena leads to reduce the contours of the study, this is the case of energy transfer from the laser beam to the material that is mostly approximated by an absorption coefficient.

This state of art tries to give classical tools to choose a model and assumptions for the numerical simulation of laser welding. This paper is built from three main parts. The first is a recall of generalities of laser processes and technologies. The second is an overview of how thermo-mechanical simulations, assumptions and typical results are made. The third concerns the usual steps of a multi-physical simulation, for example the different ways to simulate the beam reflection of the keyhole deformation. At the end a conclusion will be made on the advantages and drawbacks of each method and the potential food for thought on laser processing simulation.

2. Generalities of laser principle

In order to introduce laser processing, and before the physical models presentation, a very short presentation of laser principle and technologies is made.

Laser is an acronym for “light amplification by stimulated emission of radiation”. As the maser (microwave amplification by stimulated emission of radiation) the laser is based on the stimulated emission founded by Einstein in 1917. The principle is an energy reduction ($-\Delta E$) of an exited electron by the absorption of an electro-magnetic wave (or photon) whose energy is equal to the electronic transition ΔE. During this energy reduction, an electro-magnetic wave (or photon) is produced and this wave is exactly the same as the first (coherence in space and in time). A laser beam is obtained by accumulating these emissions, between two parallel mirrors. Only photons emitted along the resonator axis are efficient, other directions cannot be amplified. As one of the mirrors has a certain transitivity, the system is open and the beam can be extract from the resonator and used for different applications like welding. As this not the object here, the principle described in this section is very summarized and simplified. Nevertheless, more information and details on the stimulated emission and on the laser effect can be found in the Haken's [28], Siegman's [63] books. In these two references, authors give an overview on laser physics and give basic principles and laws to understand well the laser technologies. While these books are quite old, their instructive facets are very interesting (most recent books written by Svelto [64] or Renk [60]). Weber [72] also gives a quite complete and very accurate review of laser technologies, but focusing on lasing media and on the associated wavelength.

Of course, due to the year of publication (1999), the newest lasers are missing, thin disk laser, for example, which was found also in 1999 [15]. However, most recent books are available [34,68].

The laser beam is a light beam highly monochromatic, thus it is an electromagnetic wave with a spectrum centered at a particular wavelength (depending on the lasing medium) starting from the ultraviolet to the far infrared. As the laser beam is a light, its physics is driven by the classical laws of wave optics that can be found in every book dealing with this subject [59,19]. The Dickey's book, written for an engineer or scientist use, gives a broad view of mathematical and physical theory but also many practice examples.

As explained previously, the whole physical phenomena occurring in the workpiece during laser irradiation are highly coupled. While the physic is not easily approachable; the main difficulty remains the numerical computation of this kind of large model. That is why, in the field of welding simulation, some phenomena are commonly brought together and others are uncoupled. For instance, two kinds of model families can be found in the literature: the thermo-mechanical models which aim to compute the effect of welding on the piece mechanical behavior and the so-called “multi-physical” models which try to simulate the process impact on thermal field (weld pool size, thermal gradient) with as much phenomena as possible.

3. Thermo-mechanical simulations

The industry regularly takes part in the thermo-mechanical simulation literature [45,69,70] because the objective is very applied and is about the computation of residual stress and strain induced by laser welding (or other processes). Mainly related to large-sized structures (Fig. 1), this kind of simulation is able to confirm the feasibility of a welding setup. In other words, knowing the material and the process parameters. The model allows to check if residual distortions satisfy the tolerances or if internal strains are coherent with the component use. As the residual distortions are distributed on the whole structure of a component, for very large pieces, numerical methods have been developed but not detailed here, to reduce the size of the numerical problem such as the use of shell elements or local/global approach [21].

As said previously, the simulation of the whole phenomena is not yet possible. Thus, many assumptions have to be made. Firstly, the study contours have to be reduced. That is why the complex interaction of the process with the material is usually reduced to a