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Numerical Modeling of Laser Transmission Welding: State of the Art

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Abstract. **This work presents the current state of the numerical modeling of laser transmission welding. A review of publications with a similar theme was made and some aspects that remained outside the focus of the authors were highlighted. Laser transmission welding is a technological process, the physical description of which requires the consideration of several physical laws, which are discussed here. Works were reviewed in which the numerical model is based on: the law of conservation of energy, Fourier's law of heat transfer, Lambert-Beer's law of light propagation, Newton's law of convective heat transfer, Stefan-Boltzmann's law of radiant heat transfer, the Navier-Stokes equation for a fluid, the laws of mechanics for a deformable solid along with the criteria for plasticity. Since their joint solution in analytical form is not possible, the authors' approach is to single out one or several of the laws and use numerical methods to solve the differential equations that describe them. In this work, the use of several numerical methods is considered, and the finite element method is most often used for the discretization of space. The programs used by the authors for the numerical modeling of laser transmission welding are mentioned. The results obtained for the temperature field, heat affected zone and weld pool dimensions, voids, material degradation, residual stresses and weld pool flow rate are discussed. Particular attention is paid to the issues of calibration, verification and validation of numerical models. Some conclusions and directions are highlighted, emphasizing not so much the physical interpretation of the obtained results, but the essence of numerical modeling.**

Keywords: laser transmission welding (LTW), numerical modeling, simulation, temperature, HAZ, thermal degradation, flow, stress.

I. INTRODUCTION

Laser transmission welding (LTW) was proposed in the 1980s. It represents a laser impact on two details placed on top of each other, the upper one being transparent and the lower one being opaque [1], [2]. The transparent part transmits the laser beam, and the opaque part absorbs it, generating heat that melts the parts. After cooling, a joint is obtained.

The formation of welded joints with suitable mechanical properties requires the correct determination of the required amount of heat in the welding zone. Overheating results in stress cracking and the formation of bubbles [3]. The parts do not connect well if the heating is insufficient.

Determining the appropriate welding parameters can be done experimentally or through calculations. The numerical simulations are a very convenient and frequently used tool for calculations. Reliable experimental determination of temperature is difficult. The use of thermocouples is accompanied by an impact of the laser beam on them. The use of thermal cameras also does not offer great accuracy because most laser-transparent polymers are infrared-opaque. The use of numerical simulations leads to a reduction in process setup time and cost. The mass adoption of computer aided design (CAD) systems and numerical simulation with computer-aided engineering (CAE) modules enables the successful simulation of LTW. In recent years, a large number of collectives have been working in this direction [4].

In this work, the various aspects of numerical modeling of LTW are considered.

II. LITERATURE REVIEW

Publications that review the progress of the LTW numerical simulations focus on the essence of the method, treating its physical and technological side. They consider different techniques, materials to be welded, process parameters (wavelength, impact duration, power, speed, etc.), results obtained (temperature fields, stresses, strains, voids, etc.) and their interrelationship.

The issue of numerical modeling of LTW is usually considered in the context of the physical side of the process. Hu et al. [4] review the simulation of temperature

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field, stress, melt flow field and thermal degradation, citing 90 literature sources. They offer a flowchart that describes the simulation process, depending on the chosen physico-mathematical model. Also, in their work they present the different models of heat input, the influence of absorbers, process optimization techniques and the obtained results. The issues of calibration, verification and validation are commented on but not clearly highlighted. They pay little attention to the characteristics of the numerical models themselves, focusing more on the physical interpretation of the results.

A. Physico-mathematical models

The heating of the parts is due to the absorption of electromagnetic waves from the laser beam in the opaque material. The law of Lambert-Beer is used to model the absorption in LTW [5]:

$$I(z) = I_0 e^{-kz} \tag{1}$$

where $I(z)$ is the laser pawer density along the direction of the part thickness, I_0 is the laser power density on the top surface of opaque part, k is the absorption coefficient, and z is the depth along the direction of part thickness.

Absorption in transparent material is most often assumed to be zero [5].

The authors use different physico-mathematical models to describe the LTW process. The model in which the process is described by the Fourier law of heat conduction [6] – [9] placed in the law of conservation of energy has received the greatest spread:

$$\mathrm{div}\big(\boldsymbol{\lambda} \cdot \mathrm{grad}(T)\big) + Q = V\rho\dot{U} \tag{2}$$

where $\boldsymbol{\lambda}$ is the tensor of material properties, which are functions of the temperature T, Q is the heat quantity in the studied volume, and U is the specific enthalpy.

LTW is accompanied by the occurrence of temperature deformations and their corresponding stresses. The resulting stresses in the welding process can exceed the strength limit of a material. Even at lower values, residual stresses occurring after cooling would reduce the overall load-carrying capacity of the joint. For these reasons, a number of authors determined the stress and strain state in the welded parts. This necessitates solving the thermo-mechanical problem. The algorithm for numerical modeling of LTW is given in [7].

According to the source, strain can be divided into temperature - $\boldsymbol{\varepsilon}^{th}$, elastic - $\boldsymbol{\varepsilon}^{el}$, plastic - $\boldsymbol{\varepsilon}^{pl}$, creep - $\boldsymbol{\varepsilon}^{cr}$ and swelling - $\boldsymbol{\varepsilon}^{sw}$ parts:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{el} + \boldsymbol{\varepsilon}^{pl} + \boldsymbol{\varepsilon}^{th} + \boldsymbol{\varepsilon}^{cr} + \boldsymbol{\varepsilon}^{sw}. \tag{3}$$

The temperature strains depend on the temperature amplitude. To consider this setup, it is necessary to solve the transient problem.

According to the mode of occurrence, the strains can be divided into elastic and plastic. For elastic strains, Hooke's generalized law applies, which relates them linearly to stress:

$$\boldsymbol{\varepsilon} = \mathbf{S}\boldsymbol{\sigma}. \tag{4}$$

where **S** is fourth order tensor of the compliance and $\boldsymbol{\sigma}$ is the stress tensor.

The assessment of the plastic properties of the welded parts is done by applying one of the criteria for the plasticity. In [7] they use the Von Mises criterion. Another possibility is to use the Drucker-Prager criterion [10].

Polymers are viscoplastic materials. Viscoplasticity is a time-dependent mechanical behaviour of materials in which the evolution of plastic strains depends on the loading rate. This property can be described by Perzyna model [7]:

$$\sigma = \left[1 + \left(\frac{\dot{\varepsilon}^{pl}}{\gamma}\right)^{m}\right]\sigma_0 \tag{5}$$

where σ and σ_0 are the dynamic and static yield stress of the material, $\dot{\varepsilon}^{pl}$ is the equivalent plastic strain rate, and m and γ are the strain rate hardening and material viscosity parameters, respectively.

LTW is accompanied by the formation of a liquid phase. The continuum formulation is based on the mass, momentum and energy conservation laws [3], [11], respectively:

$$\frac{\partial\rho}{\partial t} + \mathrm{grad}(\rho\mathbf{v}) = 0, \tag{6}$$

$$\begin{aligned} &\frac{\partial(\rho\mathbf{v})}{\partial t} + \mathrm{grad}(\rho\mathbf{v}\mathbf{v}) = -\mathrm{grad}P + \\ &+ \mathrm{grad}\big(\mu.\mathrm{grad}(\mathbf{v})\big) + \rho\mathbf{g}\beta_T(T - T_r) - \frac{\mu}{K}\mathbf{v}, \end{aligned} \tag{7}$$

$$\mathrm{grad}(\lambda\mathrm{grad}T) = c\left(\frac{\partial T}{\partial t} + \mathrm{grad}(T\mathbf{v})\right) - \tilde{Q}, \tag{8}$$

where ρ is the material density, $\mathbf{v}$ is the velocity vector, μ is the dynamic viscosity, $\mathbf{g}$ is the acceleration of gravity, β_T is the volume expansion coefficient, T_r is reference temperature, K is porous medium permeability, c is effective heat capacity, and $\tilde{Q}$ are volumetric heat sources.

The porous medium permeability can be expressed by Caman-Kozeny equation [12]:

$$K = K_0\frac{(1-f_s)^3}{f_s^2}, \tag{9}$$

$$K_0 = \frac{d_0^2}{180}, \tag{10}$$

where d_0 is an average solid particle diameter, f_s is assumed with linear approximation between solidus – T_S, and liquidus – T_L, temperature:

$$f_s = \begin{cases} 1 & \text{for} \quad T < T_S \\ \frac{T_L - T}{T_L - T_S} & \text{for} \quad T_S \le T \le T_L \\ 0 & \text{for} \quad T > T_L \end{cases}. \tag{11}$$

B. Initial and boundary conditions

The most important boundary condition is the laser beam, which will be discussed in the next subsection.

The initial conditions depend on the chosen physico-mathematical model. Solving the heat problem requires setting the initial temperature, which is most often room temperature in the range of 20° to 27° C [13], [14]. The solution of the mechanical problem is carried out assuming that there are no strains and stresses at the beginning of the process.

The boundary conditions for solving the heat problem are convective and radiative heat exchange. Some authors ignore them [15], [16], and others consider their joint influence by setting the heat transfer coefficient (HTC) [8], [17]. The authors in [13] consider only radiation heat transfer, using the Ray Tracing method, an optical method to compute the optical propagation of laser beams. Liu et al. ignore radiative heat transfer and consider only convection [5].

Certain authors consider the contact between the welded parts as not ideal and study the influence of its imperfections. Liu et al. [5] took this fact into account and found that it resulted in a different width of the weld pool in the lower and upper parts. According to [18] Thermal Contact Conductance – TCC, can be determined by the equation

$$TCC = \frac{\Delta T}{q} \tag{12}$$

where q is the heat flux caused by temperature difference - ΔT.

Welded parts most often have different roughness in different directions. Wang et al. use a model to account for this difference [11].

In the mechanical task, the fastening of the welded parts [10] or clamping force (pressure) is set [11], [19].

The boundary conditions in the numerical modeling of the liquid phase are the boundaries of the weld pool. They depend on the melting point [3], [20].

Very often, authors consider symmetric joints and account for this in numerical models [7], [17], [21]. This leads to a reduction in computational time, as demonstrated in [5].

C. *Laser beam modeling*

Aden [15] model the laser beam using the "Henyey-Greenstein phase function" - p:

$$p(\mu) = \frac{1}{2}\frac{1-g^2}{(1+g^2-2g\mu)^{3/2}}, \tag{13}$$

$$\mu = \cos(\theta), -\pi < \theta < \pi, \tag{14}$$

where θ is the scattering angle and a random variable, g gives the degree of anisotropy.

LTW is performed by impulses. Most often, authors ignore this and use a quasi-simultaneous heat source. For this purpose, the linear energy is used [21]:

$$E = \frac{P}{v} n, \tag{15}$$

where P is the laser power, v is the feed rate and n is the number of repeats.

Pulse train modeling is computationally intensive, as it requires solving the problem with a large number of increments. Chen et al. [22] model laser welding as a sequence of three pulses.

The laser beam can be modeled as moving [8], [16] or as stationary [6], [17]. Nguyen et al. [21] define the Peclet number, which gives a qualitative estimate of the temperature distribution in the body, which depends on the speed of the laser beam. They use the equation

$$P\acute{e} = \frac{v w_0}{a}, \tag{16}$$

where w_0 is the beam diameter and a is the thermal diffusivity.

The efficiency of the laser is determined by the dependence [5]:

$$\eta = \frac{P_A}{P_E}, \tag{17}$$

where P_A is the laser output power, and P_E represents the nominal laser power.

There are different patterns of heat flow distribution in the absorbent part. They can be divided into two main types volumetric and surface heat source model. The choice depends on the thickness of the welded parts. In both cases, a Gaussian distribution is most often used, which for surface cases has the form [11]:

$$q = \eta_t \frac{P_A}{\pi R^2} \exp\left(-\left(\frac{r^2}{R^2}\right)\right), \tag{18}$$

where R is the radius of spot on the upper surface of absorption specimen, r is the distance from each point on the upper surface of the absorbed specimen to the center of the laser spot, η_t the transmittance of the transparent specimen, P_A is the laser power.

Chen et al. [23] define the volumetric heat source by dependence:

$$q(x,y,z,t) = \frac{9Q}{\pi H R_0^2\left(1-\frac{1}{e^3}\right)} . \\ .\exp\left(-\frac{9}{R_0^2 \log\left(\frac{H}{z}\right)}\left((x-vt)^2+y^2\right)\right), \tag{19}$$

where, H is the thickness of heat source, R_0 is the diameter of laser spot, v is welding speed, Q_l is the laser energy absorbed by laser-transparent part.

Other heat flux distribution functions are M-shape beam [15], which is described with a polynomial function:

$$I_M \begin{cases} I_{MO} \sum_{n=0}^{3} a_n \left(\frac{r}{R}\right)^{2n}, 0 \le r \le R \\ 0, \ r > R \end{cases}, \\ I_{MO} = \frac{P}{\pi R^2 \sum_{n=0}^{3} \frac{a_n}{n+1}}, \tag{20}$$

where R is the beam radius, a_n are the polynomial coefficients.

It is possible to use Goldak's double ellipsoid [10]. Some authors use a combination of volume and surface heat source.

D. Material models

The modeling of the heat distribution is possible with linear and nonlinear material properties. Wang et al. used material model with constant conduction and specific thermal capacity [17]. Moust of the authors used nonlinear relation between thermal properties and temperature [24]. Ali et al. used nonlinear specific thermal capacity and constant conductivity [8].

Phase transitions give rise to a large gradient in specific heat capacity. This necessitates the use of latent heat to reduce the non-linearity in the task [5].

When solving the thermo-mechanical problem, the non-linear mechanical properties of the material are taken into account [7].

Liquid phase in the weld pool is assumed as laminar, Newtonian and incompressible [3].

Modeling of plastic deformations in LTW is possible using material ductility criteria. In [7] they use the von Mises criterion. Another possibility is to use the Drucker-Prager criterion [10].

E. Numerical and computer models

Potente et al. propose an analytical model for the temperature field in welded parts [25]. They compare the obtained results with experimental data.

Taha et al. [26] determine the temperature field by the control volume technique (CVT). In this method, the calculation domain is divided into numerous non-overlapping control volumes surrounding each grid point, where the temperature is calculated. The differential equations are integrated over each control volume based on some assumed profile to yield a linear algebraic equation for the concerned grid point. They give details of the mesh and compare the results with experimental data.

Xu et al. used the volume of fluid method (VOF) [20] to solve the fluid flow problem. To solve the same problem, Chen et al [22] used computational fluid dynamics (CFD) and finite volume method (FVM), combined with pressure implicit operator splitting (PISO) algorithm.

The main part of the authors aims to determine the temperature field by solving equation (2) using the finite element method. The most commonly used programs are ANSYS [5] [7], [17], COMSOL [8], [15], [16], [21], [27] and ABAQUS [6], [9], [28]. They allow the implementation of appropriate fixed and moving functions for the heat flow. All these programs are suitable for solving the thermo-mechanical problem.

Solving the fluid mechanics problem is done using ANSYS Fluent [11], [22]. Thise program implement FVM.

Aden modeled the propagation of the laser beam through the details using the program ZEMAX [15].

Most authors model the welding of two prismatic parts or representative volumes of such a shape, but there are exceptions. Xu et al. [20] modeled a sandwich structure consisting of two plates and ribs.

The number of nodes and time steps make it possible to determine the amount of computational work, and from there to judge the computation time.

It is possible to model LTW in 2D [29], but at present it is mostly solved transient 3D problem. This raises the question of proper time discretization. Very often, this issue is not considered in details, assuming a priori that the presented solution satisfies the requirement of independence of the results of the time increment. Some authors pay attention to this issue. Chen et al. [22] give information on the about the time increment.

The discretization of the space is carried out with the type of finite elements depending on the type of problem being solved and the specific program for implementing the numerical method. Most often, the authors use finite elements with a hexahedral shape, but triangular prisms [8], [28] and tetrahedron [23] are also used. The simulation of LTW by solving the heat problem is performed using SOLID 70 in ANSYS [17], [7] and type DC3D8 in ABAQUS [28]. Deformation problem requires SOLID45 in ANSYS [7] and C3D8T in ABAQUS [10]. Liu et al. [5] use CONTA173 and TARGE170 contact elements.

The discretization of space is performed using the local mesh refinement technique. This allows to reduce the amount of computational work. Often the authors do not explicitly comment on the issue of the number of finite elements used, but put a figure from which to determine them. Some authors pay special attention to this issue. Asséko et al. [27] used 2250 elements, [24] - 391762, [23] - 770000. There is a tendency to increase the number of used elements, which is related to the development of computing technology. A limitation for the elements used is the calculation time, which is mostly not commented on. Chen et al. [24] give the calculation time, which is 2.8 minutes per set of parameters.

The setting of the laser beam is carried out through special built-in functions in the used program or through subroutines that were created by the authors.

F. Results

The obtained results depend on the type of the solved task. The most important feature of LTW is the temperature field. They are a measure of the quality of the weld joint. Determination of the temperature field allows to determine the shape and dimensions of the weld pool and heat affected zone (HAZ) [6], [21]. By solving the fluid problem, the flow rate in the bath and the resulting gaps or bubbles can be determined [3], [20]. The latter model bubbles by removing material above a certain temperature. The change of the temperature field in the welding process serves to determine the temperature deformation [7], [11]. It is divided into elastic and plastic [7]. The strain field serves to determine the stresses during welding and the residual stresses [7]. Table 1 gives a summary of the type of problems solved, the required inputs and the results obtained.

TABLE 1 PROBLEM AND RESULTS

Type of the problem	Input variables	Results
Laser beam propagation	Laser rays	Rays of radiation, temperature field
Heat propagation	Heat flux from the laser beam	Temperature field, welding pool, HAZ, maximum temperature
Thermo-mechanical	Heat flus from the laser beam, clamping force, fixing	Temperature field, strains, stresses, residual stress
Fluid	Heat flux from the laser beam	Temperature field, velocity of the fluid flow, gaps, bubbles and key holes

E. Calibration, verification and validation

Most often, the authors use the numerical models to study the influence of the physical parameters and the main focus falls on obtaining results that match as well as possible the obtained experimental data in the specific welding conditions.

The calibration is the process of the determination of appropriate parameters of the model to bring the simulation results closer to the experimental ones. Model parameters can be divided into two main groups: parameters that are from the physical world (physical parameters) and parameters that derive from the mathematical description, numerical model, or programming algorithm (model parameters). The first group of parameters includes: geometric dimensions, material density, thermal conductivity, specific heat capacity, gap between details, emissivity, transmittance, reflectivity, melting temperature, absorption coefficient, latent heat, heat convection coefficient, initial temperature, liquid dynamic viscosity, glass transition temperature, decomposition temperature, thermal expansion coefficient, heat deflection temperature, compressive strength, modulus of elasticity, Poisson's ratio, tensile strength, flexural strength, elongation at break and laser parameters. The laser parameters are power, laser efficiency, laser wavelength, frequency, laser beam spot shape and dimensions, energy density, and travel speed. The second group of parameters includes the time step, number of finite elements, number of nodes, correction coefficients of the energy density and shape of the laser beam and all approximating parameters in the material models. Model parameters can be divided into those that have no physical meaning and the solution should not depend on them, and those that affect the physical parameters. The latter are used for calibration. The results obtained are temperature field, maximum temperature, pool shape and size, HAZ shape and size, stressed and strain state, equivalent stresses, residual stresses, flow rate, laser beam propagation.

LTW modeling is accompanied by idealizations that lead to unacceptable differences in the results of simulations and experiments. One possible approach to reconcile the differences is by using some of the model parameters as calibrations. This should be clearly defined, and it is necessary to highlight the scope of the solution. This issue is greatly underestimated by most authors and often remains outside the discussion. However, some authors comment on it. Labiase et al. [30] calibrate a thermo-mechanical numerical model using an overall error function:

$$E_{TOT} = \sum_{i=1}^{N} \left(\frac{F_{EXP}(i) - F_{MOD}(i, C_1, C_2, C_n)}{F_{EXP}(i)} \right) \qquad (21)$$

where F_{EXP} is the experimental strength, F_{MOD} is the computed strength, C_i are control point, and N is the number of calibration cases.

In another work of the same team [9], they performed calibration on emissivity and absorption coefficient. Xu et al. [31] vary with volumetric heat source and use the geometry of the keyhole as a criterian to calibrate the thermal model. Wang et al. [32] calibrate a thermomechanical model using two release coefficients that are involved in the residual stress formulas.

Obtaining reliable results at numerical modeling of LTW requires the steps of verification and validation. The first one is an assessment of the accuracy of the solution to a computational model by comparison with known solutions. The second is the assessment of the accuracy of a computational simulation by comparison with experimental data.

The verification process is greatly underestimated in LTW modeling. Some authors mention it without emphasizing it [5]. Most often, the authors proceed to the validation stage without verifying the numerical model, using their own experimental data for this purpose.

III. CONCLUSIONS

There has been significant progress in the ability to solve individual physics problems, most often with results for the temperature field. The joint solution of problems with several physical laws is still very limited, with the greatest experience in the thermo-mechanical problem.

Numerical models of LTW for structures with complex configuration are very rare.

Most often, the description of numerical models of LTW is incomplete, especially in its part with time and space discretization and computational performance.

The calibration of numerical models is done in different ways, but the most authors do not describe this stage. Few authors discuss the issue of model verification. The main emphasis is on validation.

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