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Modeling of laser transmission contour welding process using FEA and DoE

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ABSTRACT

In this research, a systematic investigation on laser transmission contour welding process is carried out using finite element analysis (FEA) and design of experiments (DoE) techniques. First of all, a three-dimensional thermal model is developed to simulate the laser transmission contour welding process with a moving heat source. The commercial finite element code ANSYS® multi-physics is used to obtain the numerical results by implementing a volumetric Gaussian heat source, and combined convection–radiation boundary conditions. Design of experiments together with regression analysis is then employed to plan the experiments and to develop mathematical models based on simulation results. Four key process parameters, namely *power*, *welding speed*, *beam diameter*, and *carbon black content* in absorbing polymer, are considered as independent variables, while maximum temperature at weld interface, weld width, and weld depths in transparent and absorbing polymers are considered as dependent variables. Sensitivity analysis is performed to determine how different values of an independent variable affect a particular dependent variable.

1. Introduction

Laser transmission welding (LTW) involves localized heating at the interface of two overlapping thermo-plastic parts to be joined to produce strong, hermetically sealed welds with minimal thermal and mechanical stress, no particulates and very little flash. In this process, it is necessary for one of the plastics to be transparent to laser radiation and the other to absorb the laser energy, to ensure that the heating is concentrated at the joint region. Most of the plastics in their natural state are transparent to the laser radiation at the wavelength of Nd:YAG or diode lasers. Plastic parts are rendered laser absorbing by compounding it with appropriate additives, such as carbon black. Laser transmission welding with its range of concepts has already been adapted into several industrial applications. Laser transmission welding of plastic is advantageous in that it is non-contact, non-contaminating, precise, and flexible process, and it is easy to control and automate [1].

Contour welding variant of LTW involves relative motion between the laser beam and the thermoplastic parts. In this process, either a focused laser beam is moved over the workpiece surface along a predefined path or the laser source is kept fixed and the workpiece moves to make a continuous weld following the weld seam geometry. This movement allows a continuously operating laser beam to irradiate a line of specific width of the material at the part interface to form a joint [2].

Numerical methods are in widespread use for either modeling or optimizing the performance of the manufacturing technologies. That has been advanced due to the large diffusion of the personal computer and the numerical algorithms. A number of attempts have been made to simulate the laser transmission welding process by analytical and numerical techniques. Potente et al. [3] analyzed the heating phase in laser transmission welding of nylon 6. The material properties are assumed to be constant and the effect of heat convection during the welding process is ignored. A correction factor is added in order to allow for the different temperature profile in case of an absorbing part having a low absorption coefficient. Kennish et al. [4] established an analytical heat transfer model of laser transmission welding process to predict the process capabilities and weld characteristics. Their model gives an approximate solution for peak temperature at the weld interface as a function of depth. Becker and Potente [5] developed a two-dimensional thermal model to simulate the heating phase of LTW using finite element method (FEM) and compared the results with collected data from experiments with polypropylene. The effects of beam scanning speed and laser power on the melt layer thickness are studied. Russek et al. [6] presented an analytical thermodynamic model of LTW. The equation of energy conservation is solved for different steps of approximation to indicate the influence of the convective as well as the diffusive heat flow on the energy density distribution. Experimental and theoretical results are compared to prove that

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the validity of the process is in good agreement. Ilie et al. [7] presented a study on effects of laser beam scattering phenomena in a semi-transparent polymer induced by their compositions in the LTW process. Experimental measures made on PMMA samples charged with different sized silica particles at two concentrations confirmed their modeling results. Mayboudi et al. [8] developed a two-dimensional heat transfer model of LTW of unreinforced nylon 6 in a T-like joint geometry. It was found that this two-dimensional heat transfer model is capable of predicting the molten zone depth as well as transient temperature distribution along the weld line. Ven and Erdman [9] developed a two-dimensional FE model of LTW, in which the first dimension is into the material and the second dimension is perpendicular to the path of the laser. The material considered is polyvinyl chloride. The mathematical model is programmed in MATLAB®, a product of Math Works. This 2-D model for a T-joint geometry uses an energy balance method to calculate the temperature at the nodes throughout the materials at specified time steps. A three-dimensional thermal model of LTW solved with FEM is presented by Mayboudi et al. [10] for polyamide 6 with lap joint geometry. The temperature distribution obtained from the model is compared with the thermal imaging observations for a lap joint geometry exposed to a stationary diode laser beam. Mahmood et al. [11] developed a three-dimensional FE model for transient heat analysis of laser transmission micro-joining process. The FE code ABAQUS® is used to model and analyze the problem. The spatial and temporal temperature distribution is calculated using a three-dimensional heat conduction equation in a domain, considering only one half of the overlap materials due to symmetry nature of the system. Coelho et al. [12] developed an analytical model to analyze the beam spot shape influence in high speed laser lap welding of thermoplastic films. Weld quality and efficiency are compared for beam spots with circular and elliptical geometry. Engineering parameters viz. minimum energy density, maximum velocity, and the minimum *beam diameter* needed to achieve a temperature that corresponds to the welding temperature are predicted by the model. Ilie et al. [13] determined the laser beam weldability of ABS plates by combining both experimental and theoretical aspects. In computing the temperature field within the materials and at the interface, the first principle of heat transfer is used taking into account a perfect contact between the two components subjected to welding. The thermal model is employed in a FE code COMSOL®. Acherjee et al. [14] developed a three-dimensional FE thermal model to simulate the laser transmission welding of polyvinylidene fluoride to titanium, with a distributed moving heat flux. The simulation algorithm is programmed as a macro-routine within the ANSYS® FE code. In their recent publication, Acherjee et al. [15] presented a numerical investigation on the effect of carbon black on temperature field and weld profile during laser transmission welding of polymers by considering polycarbonate as work material.

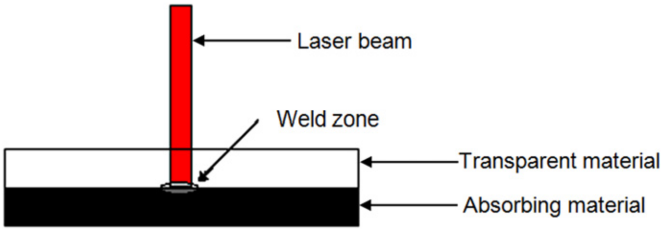

Fig. 1. Principle of laser transmission contour welding process.

Laser transmission contour welding process is systematically modeled and analyzed in this paper, through sequential application of FEA and DoE techniques. FEA is one of the several numerical methods that can be used to solve complex problems and is the dominant method used today. DoE is a systematic approach to investigation of a system or process in order to discover an unknown effect, to test or establish a hypothesis, or to illustrate a known effect. Response surface methodology and Taguchi orthogonal array technique are among the best known DoE techniques, which are widely used for empirical modeling and optimization of manufacturing processes, including laser welding process [1,16–18]. In the present work, a three-dimensional FE model, for laser transmission welding of polycarbonate with a moving laser beam, has been constructed, firstly. DoE along with regression analyses are then employed to plan the experiments and to develop regression models based on simulation results. Last but not least, sensitivity analysis is performed to analyze the parameter sensitivity of responses of interest.

2. Finite element simulation

The configuration of laser transmission contour welding process with lap joint geometry used in this study is illustrated in Fig. 1. Since the physical aspects and technical details of modeling and validation of the developed thermal model are described in [15], the general conditions of the model are summarized in brief.

Fig. 2 shows the true dimension of the sample and one half of the model at the bond region with symmetric boundary conditions that is used for this study. The geometric model is meshed using the SOLID 70 thermal-brick elements. The interface between the joining materials is modeled with two separate sets of nodes corresponding to two different materials. Coupled degrees of freedom are applied at the interface of the coincident nodes. The materials considered are natural and opaque polycarbonates. Temperature dependent physical properties (thermal

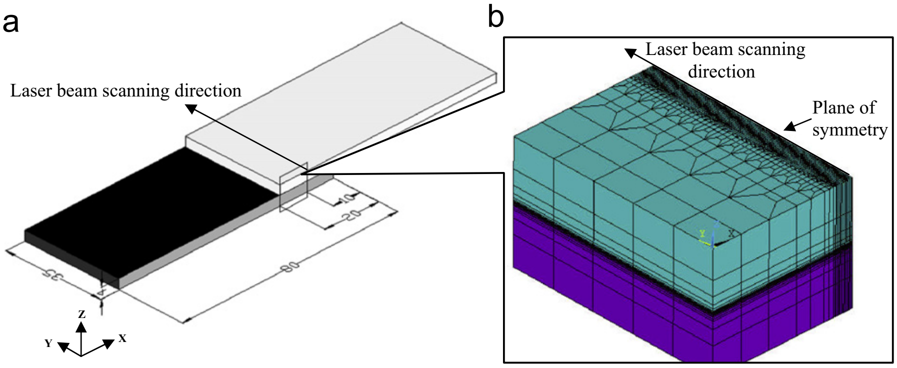

Fig. 2. (a) Schematic of the sample and (b) one half of the model at the bond region with symmetric boundary conditions (dimensions are in mm).