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Investigation of the relationships of process parameters, molten pool geometry and shear strength in laser transmission welding of polyethylene terephthalate and polypropylene

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This study concerns the laser transmission welding (LTW) of polyethylene terephthalate (PET) and polypropylene (PP) which are widely used in the automotive, aerospace and medical industries. The relationships of process parameters, molten pool geometry (both width and depth) and shear strength (*SS*) in LTW process are systematically investigated through finite element method (FEM), response surface methodology (RSM) and experiments. Thereinto, the relationships between the molten pool depths to width (*D*/*W*) ratio and *SS* are firstly investigated. Firstly, a three-dimensional thermal model is developed to simulate the temperature field and molten pool geometry of the LTW process. The simulation results are confirmed by experiments. Then RSM is utilized to design the experiments and establish the mathematical relationships between the process parameters and molten pool geometry based on the simulation results. The interaction effects of the process parameters on the molten pool geometry are analyzed. Finally, the simulation results are further used for searching the relationships between the molten pool *D*/*W* ratio and the *SS* (from tensile experiments). The maximum value of the *SS* and the corresponding molten pool *D*/*W* ratio is found. The result reveals that the molten pool *D*/*W* ratio has a significant influence on the *SS*. Moreover, this finite element model can also play a commendable guiding role in the LTW experiments with acceptable accuracy.

1. Introduction

The requirements of thermoplastics welding have been increasing from the viewpoint of energy waste, environment problem, design requirements, cost saving and so on. Moreover, the material properties of thermoplastics, such as insulation, excellent strength-to-weight ratio, excellent erosion resistance, lightweight, make them an attractive choice numerous engineering applications where ceramics and metals have traditionally been used. However, the thermoplastics welding by general welding procedures are considered normally to be difficult to weld, which is due to incompatible structural, physical and chemical properties [1–3]. Laser transmission welding (LTW) technology has overcome this problem and it has a lot of advantages, such as non-contact, non-pollution, high welding speed, high accuracy, flexibility, easy to manipulate. Therefore it has been considered as a promising technology for plastics welding [4]. In the LTW process, the moving laser beam passes through the upper transparent material and then penetrates on the opaque surface of the lower absorbing material. More specifically, firstly, the thermal energy absorbed by the opaque part produces the heat at the weld interface of both materials. Afterwards, the opaque part will heat up and this heating can cause the two materials to be softened at the weld interface. Finally, a welding area is formed between the two materials.

With the development of numerical methods such as response surface methodology (RSM), genetic algorithm (GA) and artificial neural network (ANN), more attentions have been concentrated on developing mathematical models to predict and optimize the LTW process. Liu et al. [4] modeled and predicted the laser transmission bonding process between titanium coated glass and polyethylene terephthalate (PET) based on RSM, and the results showed that when the laser power, bond speed and film thickness were 11.2 W, 4 mm/s and 163 nm, high bonding quality could be achieved. Wang et al. [5] developed mathematical models between the joining process parameters and desired responses with the help of RSM. The mathematical models were then used to optimize the process parameters of the laser transmission joining process. The predicted values nearly agreed with the experimental values, which showed that the models could predict the desired responses adequately and optimize the joining process parameters efficiently. RSM models between the process parameters and desired responses of the LTW process were studied by Wang et al. [6]. At the same time, GA was used to optimize the desired responses.

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Acherjee et al. [7] developed the mathematical models of the LTW process and discussed the interaction effects of the process parameters on the desired responses.

As know, using the methods above could predict the welding properties of the LTW adequately and enhance the welding quality with the need of a large number of welding experiments. However, the LTW experiments are expensive and time-consuming. In the meanwhile, with the popularization of computers, also with the evolution of the numerical simulation technology, more and more researchers have chosen the finite element simulation which is inexpensive and saves a great deal of time to simulate the LTW process. Mahmood et al. [8] set a three-dimensional heat transfer model to determine the optimum process parameters of jointing polyimide and titanium. It was found that with a power of 4.0 W, good bonding could be formed when the scanning speed was between 600 and 2000 mm/min. Acherjee et al. [9] presented a transient simulated model to analyze the LTW process. It turned out that the carbon black had a considerable influence on the temperature field and weld pool geometry. Mayboudi and Birk [10] developed a two-dimensional thermal finite element model of the LTW for T-joint. The 2D model was used to predict the transient temperature distribution along the welding path as well as the depth of the molten zone. A three-dimensional transient thermal model of LTW was developed by Van de Ven et al. [11] to investigate the LTW process of polyvinyl chloride and the error between the model and experimental values was 4.3%. Mian and Mahmood [12] modeled a three-dimensional uncoupled finite element analysis for glass and polyimide. Casalino et al. [13] studied the thermo-morphologic and mechanical behavior of thermoplastic polymers during the laser welding by means of FEM. The results revealed that laser welding of thermoplastics polymers could be simulated both for the keyhole and conduction welding conditions. Acherjee et al. [14] set a three-dimensional thermal model to simulate the LTW process for joining polyvinylidene fluoride and titanium with a moving heat flux. Zoubeir and Elhem [15] developed a finite element model to predict the temperature field and the residual distribution after the LTW process of a mini-tank. The results showed that both the temperature generated and the clamping pressure greatly influenced the bending phenomena during the LTW process. Kennish et al. [16] developed a thermal model of the LTW to predict the temperature field and weld characteristics. The model gave an approximate solution for the maximum temperature at the weld interface as a function of the depth. Becker et al. [17] presented a two-dimensional thermal model to simulate the heating phase of the LTW and the simulation results showed a good agreement with the experimental values. Acherjee et al. [18] developed a three-dimensional thermal model with a volumetric Gaussian heat source to simulate the laser transmission contour welding process. Sensitivity analysis was performed to study the effect of the different process parameters on the output parameters. Acherjee et al. [19] modeled and analyzed the simultaneous LTW process of polycarbonates using an FEM–RSM integrated approach. The effects of process parameters on the temperature field and weld bead dimensions were investigated and the mathematical models were further used for selecting the optimal process parameters to obtain an acceptable welding. Review the past literatures, most of the researchers devoted to developing the mathematical models or simulating the temperature field or optimizing the process parameters. However, rarely few comprehensive ideas are explicitly proposed to predict molten pool geometry of the LTW process accurately, which are further used to develop mathematical models for detailed process parameters study and systematically investigate the influence of molten pool depths to width (D/W) ratio on the shear strength.

In this paper, the materials used are 1 mm thick transparent polyethylene terephthalate (PET) and 2.5 mm thick polypropylene (PP) charged with 2% of carbon black. PET is known as transparent and the transparency of PET is about 90% in the near infrared region. PP is known as a semi-crystalline thermoplastic and consists of crystalline areas with a high degree order and amorphous areas with disordered polymer chains. Both of them are widely used in the automotive, aerospace and medical industries [1,2], and they are welded by a wave radiation with a near infrared diode laser. Fig. 1 shows the schematic diagram of the laser transmission welding process. In the study, the relationships of process parameters, molten pool geometry and shear strength is studied in detail through finite element method (FEM), response surface methodology (RSM) and experiments. Moreover, the relationships between the molten pool depths to width (D/W) ratio and the shear strength (*SS*) are firstly investigated through FEM and experiments. Firstly, a three-dimensional thermal model is developed to simulate the temperature field, by which the molten pool geometry of the LTW process is obtained, and the model is validated with welding experiments. Then RSM is applied to design the experiments and establish the mathematical relationships between the process parameters (*laser power-P*, *welding speed-S*, *stand-off-distance-F*) and the molten pool geometry (weld width-*WW* and molten depths in the transparent PET and absorbing PP – *DTA*) based on the simulation results. In addition, the interaction effects of the process parameters on the molten pool geometry are analyzed. Finally, the relationships between the molten pool D/W ratio and the *SS* are studied in detail. A matching curve of the influence of molten pool D/W ratio on the *SS* (from tensile experiments) is drawn to achieve the maximum shear strength and the corresponding molten pool D/W ratio.

2. Finite element simulation of molten pool geometry during LTW process

The actual dimensions of the sample and the lapped portion are presented in Fig. 2. It can be seen that the dimensions of PET are 40 mm × 20 mm × 1 mm and PP are 40 mm × 20 mm × 2.5 mm. The dimensions of the lapped portion are 20 mm × 20 mm and the direction of welding is in the *Y*-direction.

2.1. Theoretical description of the model

Use of the energy conservation law to the LTW process results in a governing equation for heat transfer in the thermoplastic specimen, which is shown below:

$$\frac{\partial E}{\partial t} + V_S * \nabla E = Q_L + \nabla(K\nabla T) \tag{1}$$

where E is the energy density, V_s is the relative velocity, Q_L is the power input in per unit volume, K is the thermal conductivity, T is the temperature.

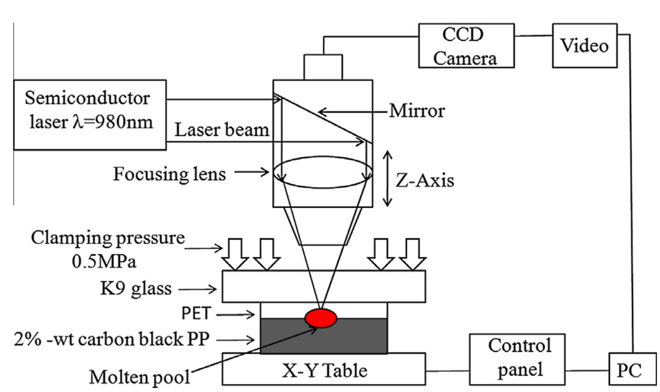

Fig. 1. Schematic of the laser transmission welding process.