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Analysis of weld geometry and liquid flow in laser transmission welding between polyethylene terephthalate (PET) and Ti6Al4V based on numerical simulation

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ABSTRACT

The laser transmission welding of polyethylene terephthalate (PET) and titanium alloy Ti6Al4V involving the evaluating of the resultant geometry and quality of welds is investigated using a fiber laser in this paper. A 3D transient numerical model considering the melting and fluid flow is developed to predict the weld geometry and porosity formation. The temperature field, molten pool and liquid flow are simulated with varying laser power and welding speed based on the model. It is observed that the weld geometry predictions from the numerical simulation are in good agreement with the experimental data. The results show that the porosity consistently appears in the high temperature region due to the decomposition of PET. In addition, it has also been found that the molten pool with a vortex flow pattern is formed only in the PET layer and the welding processing parameters have significant effects on the fluid flow, which eventually affects the heat transfer, molten pool geometry and weld formation. Consequently, it is shown adopting appropriate welding processing parameters based on the proposed model is essential for the sound weld without defects.

1. Introduction

Laser transmission welding is a technique being increasingly used for joining laser-transparent and laser-absorbent dissimilar materials. Dissimilar materials by joining metal and plastic could yield numerous excellent properties including light weight, corrosion resistance, high strength, good heat and electrical conductivity, which are often demanded in the aircraft, motor vehicles and electronics industries [1]. In the conventional techniques, the adhesives and mechanical fixing by the bolts and screws are commonly adopted to join the dissimilar materials. However, the use of adhesives has the drawbacks like lacking of long-term stability and curing induced shrink [2], while mechanical fixing often requires long processing time and high production costs or is limited by the shape and size [3]. To alleviate these problems and obtain high quality joints, laser transmission welding is considered to be one of promising candidates and widely used to join dissimilar materials.

Laser transmission welding provides many advantages over adhesives or screws fixing. During the laser transmission welding, one of the parts is required to be transparent for the used laser and the other must have high absorption property [4,5]. The laser penetrates through the transparent part and absorbed by the absorbent material, which causes the heating and melting of the materials in the local joining region [4]. Many researchers reported successful joining of dissimilar materials by using the laser transmission welding method. Katayama et al. [6] showed that the stainless steel plate and thin non-crystalline polyamide sheet joined in laser transmission welding yielded the maximum shear tensile load of the joint strength over 3300 N. Ghorbel et al. [7] evaluated the effects of welding processing parameters on the geometry of seam, defects and crystallinity in the laser diode transmission welding of polypropylene. Wang et al. [2] studied the feasibility of laser transmission joining of polyethylene terephthalate (PET) and titanium. They discovered that the Ti–C bond influenced the mechanical strength of the joints. Yusof et al. [8] investigated the effects of anodizing an A5052 surface in the pulsed Nd: YAG laser joining of PET and aluminium alloy (A5052). They found that the anodizing process could improve the shear strength of the laser joined specimens. Wahba et al. [9] joined the AZ91D with PET using a high power diode laser. They noticed that gas bubbles were generated and expanded inside the polymer region. Although the

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progressive experimental research work could make the dissimilar materials joined successfully and improve the joint strength, the temperature field and melting behavior under the different welding processing conditions have still not been understood well yet.

Recently, numerical methods have been introduced to analyze and improve the laser transmission welding process. Kennish et al. [10] proposed a heat transfer model to predict weld characteristics during laser transmission welding. In their model, the peak temperature at the weld interface between the two materials was solved. Mayboudi et al. [11] presented a three-dimensional (3D) transient thermal model of laser transmission welding for the lap-joint of unreinforced polyamide specimens. In their simulation, the heat conduction along the beam travel direction was accurately calculated and the molten zone depth and temperature distribution were predicted. Acherjee et al. [12] developed a transient numerical model to investigate the influence of the carbon black on the temperature distribution and weld profile. The weld pool dimensions were numerically computed and the effect of the carbon black on the weld pool geometry was revealed in their results. Liu et al. [13] proposed a model considering the scattering effect of the laser-transparent part on the intensity profile of heat source. The results indicated that the light scattering had significant influence on the laser intensity and modeling the heat source considering light scattering could lead to a correct laser source in the numerical simulation of laser transmission welding. Wang et al. [14] studied the thermal degradation of polyamide based on the 3D transient thermal model during laser transmission welding. They calculated the temperature-time data of the point located at the maximum temperature and predicted the power induced materials degradation. Most of the above numerical simulations are however focused on the temperature field distribution of the welding region based on the heat conduction and radiation. The melting behavior, fluid flow and the related convection heat transfer involved in the welding process were not considered, which will limit the capability of revealing the details of the laser transmission welding process and predicting weld geometry accurately.

The fluid flow in the molten pool plays a significant role in the heat transfer and hence the weld formation in laser transmission welding. Semak et al. [15] reported that under welding conditions, about 70–90% of the laser intensity absorbed in the laser interaction zone is carried away to the surrounding zone by the melt flow and thus the convection-related energy cannot be ignored in energy balance calculations. Coelho et al. [16] studied the white and transparent films of polypropylene and polyethylene welding and also found that the melt flow is an important factor to achieve high-strength welds. However, few research papers about the numerical modeling considering the melting behavior and fluid flow in the laser transmission welding have been reported. To predict the temperature distribution accurately and obtain the sound and defect-free weld bead, a 3D model by taking the melting behavior into consideration is developed for the laser transmission welding of PET and titanium alloy (TiAl4V) and presented in this paper. During the welding processing, the fiber laser penetrates through the PET and absorbed by the TiAl4V layer. The produced heat is transferred from the TiAl4V to the PET layer. Based on the model, the temperature distribution, molten pool geometry and fluid flow in the PET layer have been calculated. The simulated weld zone demonstrates good agreement with the experimental results, which proves the validity of the proposed numerical model. In addition, the molten pool and fluid flow under the different welding conditions and the effects of welding processing parameters on the weld formation are analyzed. The formation of porosity in the weld zone has also been identified. Therefore, the proposed method is useful for understanding the laser transmission welding process and improving the joint quality, especially for preventing degradation, oxidation or burning phenomena in the weld.

The rest of the paper is summarized as follows: In Section 2, the laser transmission welding experiments are described and the experimental results are shown. The description of the numerical modeling including the heat source model, boundary conditions and numerical calculation are provided in Section 3. Section 4 introduces the model validation, molten pool geometry and fluid flow, effects of welding parameters, and porosity formation in the weld bead. Finally, the conclusions of the current research are given in Section 5.

2. Experiment of laser transmission welding

2.1. Experimental set-up

In this study, the PET and Ti6Al4V are selected as the experimental materials. The chemical composition of Ti6Al4V and molecular structure of PET are shown in Table 1. The PET is the transparent part and Ti6Al4V is served as the absorbent layer. During the laser transmission welding process, the incident laser beam penetrates the PET layer and is absorbed by the Ti6Al4V layer, which generates heat at the interface to form the weld. The materials are cut into the dimension of 35 mm × 15 mm and used for lap joint welding as shown in Fig. 1. The thicknesses of PET and Ti6Al4V are 1 mm and 2 mm, respectively. The welding direction is in vertical direction on the figure. To avoid pollution and oxide film formation and ensure good contact between the two materials, the contacting surface of the Ti6Al4V was polished by using the 320, 400 and 600 grit papers and then cleaned by alcohol carefully prior to welding experiments. The top and bottom surfaces of PET were also cleaned using alcohol to prevent the transmittance being affected by the surface contaminants before laser transmission welding.

2.2. Laser transmission welding experiment

All the experiments of the laser transmission welding were conducted using the SPI G3.0 Laser (fiber laser) with continuous wave.

Table 1
Chemical composition of the Ti6Al4V (wt.%) and molecular structure of PET [17,18].

Element	Chemical composition (wt%)							
	Ti	Al	V	Fe	O	C	N	Y
Ti6Al4V	BAL	6.22	3.94	0.19	0.16	0.008	0.003	<50 PPM
PET	Molecular formula