Optics & Laser Technology 87 (2017) 64–71

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Finite element thermal analysis for PMMA/st.st.304 laser direct joining

Furat I. Hussein [a], Kareem N. Salloomi [b,*], E. Akman [c], K.I. Hajim [d], A. Demir [c]

[a] Mechatronics Department, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad, 10071 Iraq
[b] Automated Manufacturing Department, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad, 10071 Iraq
[c] Laser Technologies Research and Application Center, Kocaeli University, Kocaeli, 41275 Turkey
[d] Dijlah University College, Baghdad, Baghdad, 10071 Iraq

ARTICLE INFO

Article history:
Received 26 August 2015
Accepted 30 July 2016

Keywords:
Laser joining
Thermal modeling
Spatial and temporal investigation
Infrared thermography

ABSTRACT

This work is concerned with building a three-dimensional (3D) ab-initio models that is capable of predicting the thermal distribution of laser direct joining processes between Polymethylmethacrylate (PMMA) and stainless steel 304(st.st.304). ANSYS® simulation based on finite element analysis (FEA) was implemented for materials joining in two modes; laser transmission joining (LTJ) and conduction joining (CJ). ANSYS® simulator was used to explore the thermal environment of the joints during joining (heating time) and after joining (cooling time). For both modes, the investigation is carried out when the laser spot is at the middle of the joint width, at 15 mm from the commencement point (joint edge) at traveling time of 3.75 s. Process parameters involving peak power (P_p=3 kW), pulse duration (τ=5 ms), pulse repetition rate (PRR=20 Hz) and scanning speed (v=4 mm/s) are applied for both modes.

1. Introduction

The availability of new materials and design constraints impose utilizing multicomponent engineering structures and high end consumer products where several types of materials are involved. Polymers/metals coupling is a vivid example of such multi-component structures. The large extent of differences in their physical, mechanical and chemical properties, as well as the extreme variance between polymers amorphous molecular structure and metals crystalline structure disrupt their bonding probability [1].

Conventional joining of polymers to metals usually is carried out by mean of traditional mechanical joining, adhesive joining or both technologies. Mechanical joining has its limitations and drawbacks such as extensive preparations or machining requirements, poor flexibility in terms of design, weight, high cost and low production rate. Adhesive joining methods have some restrictions in term of environmental considerations on the emission of volatile organic compounds, low production rate, low temperature resistance and low chemical resistance in chemical environment [2,3].

Polymers and metals can be joined by laser overlap joining with two configurations; laser transmission joining (LTJ) and laser conduction joining (CJ). The former type is based on the difference in the optical properties between polymers and metals. As the laser radiation passes through the transparent polymer and incident on the opaque metal surface at the interface of the joint, part of the absorbed optical energy will transfer back towards the polymer by conduction and cause melting of a thin layer which in turn spread and coalescence with the metal surface due to an applied pressure. In the later type the laser radiation is irradiated on the metal back surface of the joint, the deposited energy transfers in the metal towards the interface zone by conduction and reaches the interface causing the same action as in the LTJ [4].

Joining processes of polymers to metals can be optimized by monitoring and modeling the thermal system of the joints. Thermal interaction between polymers and metals occurs at the interface region in a closed zone as well as inside their bulks as a result monitoring may not provide sufficient, direct and accurate information. Therefore, it is recommended to apply a numerical investigation to build up a virtual thermal model based on finite element analysis (FEA) to draw a depiction about such interactions [5].

Laser joining of polymers to metals has been investigated numerically by many specific researches for studying the different aspects of such processes. Mian et al. [6] build a FEA model for laser micro-joints between dissimilar biomaterials polyimide and titanium to study the full-field stress distribution inside and outside the joint in order to predict failure occurrence.

Mahmood et al. [7] employed the FEA technique for modeling a laser transmission micro-joining process between titanium and polyimide. They studied the effect of the working parameters (speed and power) on the temperature distribution across the

* Corresponding author.
E-mail addresses: furatnejjar@uobaghdad.edu.iq (F.I. Hussein), kareemsalloomi@yahoo.com (K.N. Salloomi), eakman29@gmail.com (E. Akman), kamseisas@gmail.com (K.I. Hajim), arifdkou@gmail.com (A. Demir).

http://dx.doi.org/10.1016/j.optlastec.2016.07.017
0030-3992/

joint and their effect on the joint bonding. Acherjee et al. [8] developed a 3D heat transfer model for polyvinylidene fluoride to titanium laser direct joining process. The model was employed for predicting the transient temperature field across the joint as well as the joint dimensions. Farazila et al. [9] established a 2D thermal conductive FEA model to study the temperature distribution during laser joining of dissimilar materials for three types of joints; PET/A5052, PET/SUS304 and PET/Cu joints.

Dhorajiya et al. [10] developed a 3D finite element model to simulate the transmission laser microjoining of two dissimilar materials (titanium and polyimide). Computationally, the main goal of this model was to obtain a combination of laser parameters for microjoining of titanium and polyimide and that was experimentally verified to confirm the good joining conditions.

Rodríguez-Vidal et al. [11] presented A two-step method for the conductive joining of glass reinforced polyamide to steel for different metal pretreatment conditions. In the first step, the steel was structured locally on a micro-scale level, to ensure adhesion with the polymeric counterpart. In the second step, the opposite side of the micro-structured metal is irradiated by means of a laser source. The required interface temperature was chosen through the assistance of finite element method represented by the commercial software package Comsol Multiphysics.

For the current paper, the work was performed in order to develop a nonlinear transient 3D finite element model for PMMA/st.st.304 joining in LTJ and CJ modes. With these models the spatial and temporal temperature distributions as well as the beads dimensions were investigated across the joint. The modeling was carried out by ANSYS Multiphysics package software Release 11.0 using Ansys Parametric Design Language (APDL).

2. Materials and setup

Amorphous thermoplastic transparent polymer type Polymethylmethacrylate (PMMA) of $100 \times 30 \times 2$ mm and stainless steel 304 alloy (st.st.304) of $100 \times 30 \times 1$ mm were experimentally joined using an 1.064 μm wavelength pulsed Nd:YAG system (class4) type GSI Lumonics JK760TR Series at Kocaeli University Laser Technologies Research and Applications Center (LATARUM) [4]. The laser specifications are 0.3–50 ms range pulse duration, 500 Hz maximum pulse repetition rate, 100 J maximum pulse energy and 600 W maximum average power. Fig. 1 shows the laser joining setup and joints configuration for both modes CJ and LTJ. The obtained overlapped joints were done on one side by a single pass of the laser beam over the joint, the joining line is at the middle of the overlapped area as shown in Fig. 1c.

3. Thermal modeling with FEA

3.1. Heat transfer considerations

The spatial and temporal heat distribution in a material irradiated with a moving heat source can be modeled with the three dimensional heat conduction equation [12]:

$$\rho c\left(\frac{\partial T}{\partial t} - v\frac{\partial T}{dx}\right) = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) + g(x, y, z, t) \quad (1)$$

where T is the absolute temperature, t is the time, x, y and z are Cartesian coordinates, K is the thermal conductivity, ρ is the density, C is the specific heat, v is the scanning speed and g is the rate at which heat is supplied to the solid per unit time and volume.

The rate of heat supply to the PMMA due to laser irradiation q can be neglected because of the penetration depth of the 1.064 μm Nd:YAG wavelength in the PMMA is so large compared with the thickness of the PMMA layer. This may justify the assumption of the full transparency of the PMMA [13]. For the metal side, the laser beam is assumed as a point heat source with a Gaussian manner distribution whose intensity and shape vary with the penetration depth and radius in both joining modes [14]:

$$g(x, y, z) = I_{st}\,\alpha \exp\left(-\frac{r^2}{r_0^2}\right) \quad (2)$$

where I_{st} is the laser beam intensity on the stainless steel 304 surface, α is the absorption coefficient, r_o is the laser beam radius, $r=\sqrt{x^2+y^2}$ is the radial distance of any point from beam center on the surface of the material, where x and y are the Cartesian coordinates of that point.

In LTJ mode the laser beam power suffers some losses due to the reflectivity at the PMMA and stainless steel 304 surfaces and absorption inside PMMA bulk during its transmission. While in CJ mode there is one optical loss due to stainless steel 304

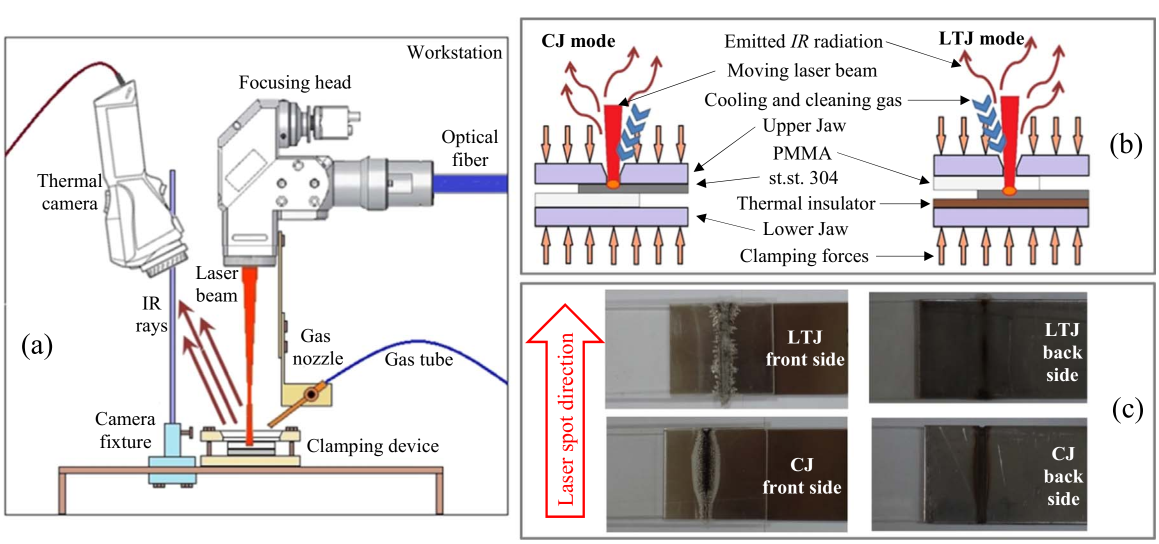

Fig. 1. (a) Experiment setup, (b) joining modes; LTJ and CJ and (c) CJ and LTJ samples.