Optics and Lasers in Engineering 50 (2012) 204–209

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

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

Laser cutting of Kevlar laminates and thermal stress formed at cutting sections

B.S. Yilbas*, S.S. Akhtar

ME Department, KFUPM, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Article history:
Received 15 June 2011
Received in revised form
27 July 2011
Accepted 5 September 2011
Available online 22 September 2011

Keywords:
Laser
Cutting
Kevlar
Thermal stress

ABSTRACT

Laser cutting of Kevlar laminates is carried out and thermal stress field developed in the cutting region is predicted using the finite element code. Temperature predictions are validated through the thermocouple data. The morphological changes in the cutting section are examined by incorporating optical and scanning electron microscopes. It is found that temperature predictions agree well with the thermocouple data. High values of von Mises stress are observed at the cutting edges and at the mid-thickness of the Kevlar laminate due to thermal compression formed in this region. The laser cut edges are free from whiskers; however, striation formation and some small sideways burning is observed at the kerf edges.

1. Introduction

Kevlar has unique properties, such as high tensile strength, high toughness, and chemical stability at high temperature, in aromatic polyamides. Kevlar is widely used as a friction material in automotive industry and as combustion protection material in aerospace industry. The net shaping of the Kevlar laminates is difficult using the conventional machine tools due to whiskers formation and loose fibers around the machine edges. In addition, the specific energy required for machining is higher than most of the engineering materials. Moreover, laser machining offers considerable advantages over the conventional techniques. Some of these advantages include high quality end product, precision of operation, and low cost. Laser cutting eliminates the whiskers emanating from the machined edges due to thermal effect. Although unwoven Kevlar laminates are easy to bend, the development of re-solidified regions at the kerf edges and the formation of heat affected zone in the cut section increases brittleness of laser machined Kevlar laminates in this region. This, in turn, limits the practical application of the machined laminates. Consequently, investigation in temperature and stress fields in the laser cut regions becomes essential.

Considerable research studies were carried out to examine laser interactions with Kevlar. Al-Sulaiman et al. [1] investigated laser cutting of Kevlar laminates and influence of assisting gas jet on the cutting quality. The findings revealed that the influence of assisting gas pressure was significant on the quality of the cutting section, in which case, out-of-flatness and the kerf width ratio improved considerably at high assisting gas pressures. The parametric study on CO_2 laser cutting of Kevlar-49 composite was carried out by El-Taweel et al. [2]. They showed that the laser output power was the most significant affecting the parameter on the quality of cut edges. Laser hole cutting in Kevlar laminate was investigated by Al-Sulaiman et al. [3]. They indicated that the main effects of cutting parameters had significant influence on the mean Kerf width and dimensionless damage size, which was more pronounced at the workpiece bottom surfaces. Machinability of small diameter holes for circuit connection in multi-layer printed wiring boards was examined by Hirogaki et al. [4]. They made comparison between Kevlar fiber and fiber reinforcement wiring boards for drilling of small hole diameter for circuit connection. Thermal efficiency analysis of laser hole cutting in Kevlar was carried out by Sahin et al. [5]. The energy and exergy efficiencies predicted were related to the resulting cut quality, and findings revealed that cutting quality improved significantly at high energy and exergy efficiencies. Laser cutting of Kevlar composites was carried out by Chen and Chen [6]. They used a heating analysis to predict the heat affected zone in the cutting section. Thermal damage in laser cutting of aramid/epoxy laminates was investigated by Di Ilio and Tagliaferri [7]. They demonstrated the presence of thermal cracks in the laser induced damaged sites due to increased brittleness of the laser heated region. The influence of heat treatment on the mechanical properties of Kevlar-29 fibers was examined by Yue et al. [8]. They indicated that the heat treatment did not influence notably the Young's modulus of a single fiber. The effect of thermal conductivity on laser machining of unidirectional carbon/epoxy laminates was

* Corresponding author.
E-mail address: bsyilbas@kfupm.edu.sa (B.S. Yilbas).

0143-8166/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.optlaseng.2011.09.004

investigated by Pan and Hocheng [9]. They showed that laser grooving parallel to fiber orientation produced smaller heat affected zone than that of grooving perpendicular to fiber orientation.

Laser cutting of Kevlar laminates was investigated previously [10] and the main emphasis was to examine cutting quality and the kerf width size. However, thermal stress developed in the cut section is left obscure, which has considerable influence on the practical application of the machined Kevlar laminates. Consequently, in the present study, laser cutting of unwoven Kevlar laminates is considered and thermal stress developed in the cutting section is examined. An experiment is carried out to assess the cutting quality while finite element code ABAQUS is used to predict temperature and stress fields in the cutting section. Temperature rise in the vicinity of the cutting section is measured using the thermocouple.

2. Experimental procedures

The Kevlar sheets were commercially available and were obtained as sheets of 1 mm thickness. The laser used in the experiments was a CO_2 laser (LC-αIII-Amada) delivering a nominal output power of 2000 W in the pulsed mode with adjustable frequencies. The laser beam was focused down to a 0.3 mm diameter spot with a 127 mm focal length lens. A flow of N_2 gas from a conical nozzle was supplied co-axially with the laser beam to aid the cutting process and avoid oxidation. Laser cutting experiments were repeated for various cutting parameters. In this case, increasing cutting speed beyond 6 m/min while keeping the laser power intensity constant resulted in partial cutting of the Kevlar laminate. However, reducing the cutting speed at the same laser power intensity caused large sideways burning around the cut edges. In addition, the same effect was observed when laser power intensity was increased while keeping the cutting speed the same. Therefore, the laser cutting parameters resulting in less sideways burning and dross were selected to examine the cutting edge morphology and thermal stress field. The laser cutting parameters are given in Table 1. The experiments were repeated three times to ensure consistency and accuracy of the resulting cut edges.

The morphological examination of the laser cut sections was carried out using optical and Jeol 6460 electron microscopes (SEM).

To validate temperature predictions the K type thermocouple was used to monitor the temporal variation of surface temperature at the location 0.2 mm away from the cut edge surface along the *y*-axis. This was necessary to avoid the melting of the surface of the thermocouple during the laser cutting process. The thermocouple was made from chromel–alumel with a sensitivity of 40 μV/°C and it had about 1 μs response time. The thermocouple output was calibrated according to the previous study [11]. The experimental error related to the thermocouple measurements was determined using the experimental repeatability; therefore, the experiments were repeated three times and the error was estimated in the order of 5%.

3. Finite element analysis of thermal stress

Finite element discretization was carried out using the ABAQUS software [12] while Fig. 1 shows the schematic view of laser cutting process and coordinate system. The simulation is performed in ABAQUS/Standard and consists of sequential thermal-stress analysis. In the sequential thermal-stress analysis, 142,468 elements are used while 132,140 hexahedral elements are used for the thermal-stress analysis. In addition, for the heat transfer analysis, mesh used elements of type DC3D8 (8-node linear heat transfer brick) and stress analysis used C3D8 (8-node linear stress brick). The temperature data are transferred to the elements used for the stress analysis through the connectivity matrix. This provided less computational time for the converged results. The fixed boundary conditions are applied on both the ends of the workpiece resembling the experimental laser heating situation. In the stress analysis, displacements are stored by ABAQUS at the nodal positions as a solution variable, and loads are defined as prescribed displacements and forces. Employing the interpolation

Table 1
Laser cutting conditions used in the experiment.

Cutting speed (m/min)	Power (W)	Frequency (Hz)	Nozzle gap (mm)	Nozzle diameter (mm)	Focus setting (mm)	N_2 pressure (kPa)
6	600	1500	1.0	1.5	127	600

Table 2
Properties of Kevlar used in the simulations.

Density = 1440 kg/m^3
Specific heat = 1400 J/kg K
Thermal conductivity = 0.04 W/m K
Modulus of elasticity, E = 31 GPa
Poisson's ratio = 0.36
Coefficient of thermal expansion = −4E−006 K^{-1}
Yield stress = 2.7 GPa

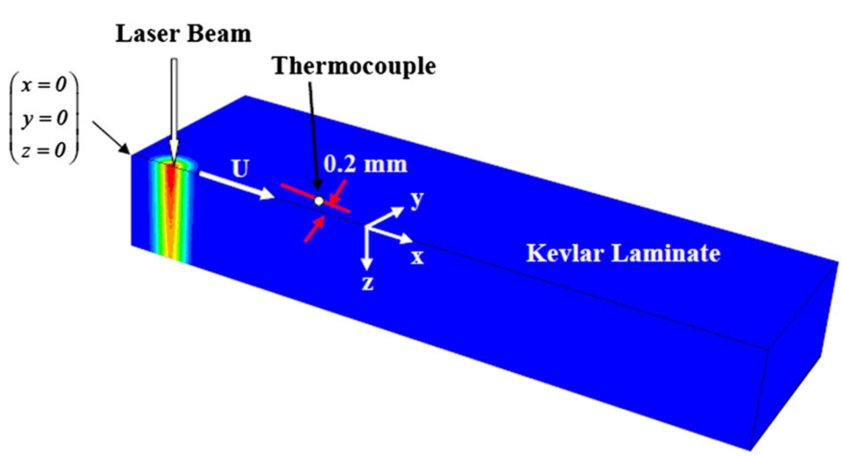

Fig. 1. A schematic view of laser cutting of Kevlar laminate and the coordinate system.