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Laser circular cutting of Kevlar sheets: Analysis of thermal stress filed and assessment of cutting geometry

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ABSTRACT

A Kevlar laminate has negative thermal expansion coefficient, which makes it difficult to machine at room temperaures using the conventional cutting tools. Contararily, laser machining of a Kevlar laminate provides advantages over the conventional methods because of the non-mechanical contact between the cutting tool and the workpiece. In the present study, laser circular cutting of Kevlar laminate is considered. The experiment is carried out to examine and evaluate the cutting sections. Temperature and stress fields formed in the cutting section are simulated in line with the experimental study. The influence of hole diameters on temperature and stress fields are investigated incorporating two different hole diameters. It is found that the Kevlar laminate cutting section is free from large size asperities such as large scale sideways burnings and attachemnt of charred residues. The maximum temperature along the cutting circumference remains higher for the large diameter hole than that of the small diameter hole. Temperature decay is sharp around the cutting section in the region where the cutting terminates. This, in turn, results in high temperature gradients and the thermal strain in the cutting region. von Mises stress remains high in the region where temperature gradients are high. von Mises stress follows similar to the trend of temperature decay around the cutting edges.

1. Introduction

Laser cutting of non-metallic materials offers significant advantages over the conventional cutting processes. Some of these advantages include fast processing time, localized heating, precision of operation, and low cost. Laser cutting involves with the high intensity laser processing of the materials, which generates thermally induced problems due to the attainment of high temperatures and large temperature gradients in the cutting section. High temperature defects sites are usually take place in the form of thermal erosion, charred residues or dross attachment, and striations while the high temperature gradients results in high thermal stress levels causing material failure through crack formations in the cut sections. Although controlling of laser interaction parameters minimizes the thermal defect sites in the laser cutting geometries, further investigations are needed for the cutting conditions resulting in almost thermal stress free laser cutting sections. On the other hand, the conventional cutting of Kevlar laminate requires cryogenic cutting process because of the frictional force generated during the thermal expansion of the laminate material in the cutting section. The frictional force suppresses the cutting process and lowers the quality of the end product. The cryogenic cutting process also adds an extra machining cost to the cutting process. The laser cutting of such materials via high power lasers eliminates this extra cost and provides high quality end products because of the high precision of operation. Laser cutting of holes in such materials complicates the stress field because of the moving heat source along the hole circumference [1]. Although the process can be assumed to be involved with two-dimensional plane heating problem, this assumption fails for the thick materials cutting. Therefore, the cutting process becomes three-dimensional and non-symmetric heating problem involving with a moving heat source. Analytical solution of such problem requires considerable assumptions, yet the findings may not be compatible for the real applications of laser cutting process. Consequently, numerical investigation of thermal stress field developed around the laser cut circular edges becomes essential.

Considerable research studies were carried out to examine laser machining of Kevlar and polymeric composite materials. Laser machining of vinylester/glass blended with nanofillers was

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investigated by Nagesh et al. [2]. They used three nanofillers including nickel nanopowder, carbon black and Closite 15-A. They incorporated Grey–Taguchi method to optimize the laser power, cutting speed, air pressure and nanofiller content for the multiple responses such as surface damage width and taper angle. Laser machining of Kevlar and thermal efficiency analysis was carried out by Sahin et al. [3]. They demonstrated that the exergy efficiency was lower than the energy efficiency. The energy and exergy efficiencies predicted were related to the resulting cut section and it was also shown that the cutting quality improved significantly at high energy and exergy efficiencies. Laser machining of Kevlar fiber reinforced laminates and the effect of polyetherimide versus polypropylene matrix was studied by Chouhan et al. [4]. They indicated that o prominent observation on the laser-irradiated surface was: less recast/resolidified polymer covered the Kevlar fabric in polyetherimide as compared to a thicker polymeric layer in Kevlar - polypropylene. In addition, they evaluated the heat affected zone. A comparative study of the conventional machining technologies over the laser machining technology for cutting composite materials was carried out by Shanmugam et al. [5]. They indicated that the structural integrity of the composite was required to machine the substrate materials within required accuracy. They also suggested that cutting of composites using laser was an option, and experiments were also conducted to reveal the extent of using the laser machining technique. Laser machining of fibre-reinforced polymeric composite materials was investigated by Negarestani and Li [6]. They examined the effects of laser pulse length, wavelength, power density, scanning speed, and assisting gas on the material behavior. They also included the comparison of the laser machining process with other machining processes such as mechanical and water jet machining. A parametric study for the CO_2 laser cutting of Kevlar-49 composite was carried out by El-Taweel et al. [7]. They introduced the Taguchi technique to identify the effect of laser cutting parameters on the quality of cut sections, namely, kerf width, dross height, and slope of the cut. Analytical method examining the laser hole cutting in Kevlar laminates was introduced by Al-Sulaiman et al. [8]. They demonstrated the effect of workpiece thickness on the cutting quality in terms of dross attachments and sideways burnings at the cut edges.

Although laser cutting of Kevlar was investigated previously [8,9], the main focus was to evaluate the cut geometries in terms of sideways burning as well as thermal stress analysis for the straight cut sections. The circular cutting of Kevlar laminates and thermal stress analysis was left for the future study. Laser cutting of different shapes has significant effect on the thermal stress fields and end product quality because of the heat transfer in the cutting section. Laser cutting of small holes modifies the heat transfer rates and creates the self-annealing effect in the cutting section because of small volume of material around the cutting section. Since Kevlar has low thermal conductivity, temperature increase in the cutting edges becomes substantial while increasing the amount of combusted material in the cutting section. This, in turn, gives rise to attainment of large temperature gradients and thermal induced strains in the cutting vicinity. If the combustion is not controlled, the excessive temperature rise can cause the sideways burnings and attachment of charred residues. In addition, the large differences in the thermophysical properties of the matrix and the fibre reinforcement gives rise to irregular cutting sections because of a large charring of the polymetric matrix while affecting the mechanical performance of the machined parts [10–14]. Consequently, extension of the previous studies [8–14] towards investigating the temperature and stress fields in cutting section becomes essential. In the present study, laser cutting of circular shapes in Kevlar laminates and thermal stress analysis in the cutting section is investigated. Temperature and stress fields are predicted numerically using the finite element code and the experiments are carried out to validate the temperature predictions. In addition,

Table 1
Laser cutting conditions used in the experiment.

Cutting speed (cm/s) (mm/min)	Scanning ang. speed (rad/s)	Power (W)	Nozzle gap (mm)	Nozzle diameter (mm)	Focus setting (mm)	N_2 pressure (kPa)	Gaussian parameter (m)
15	20	790	1.5	1.5	127	550	0.003

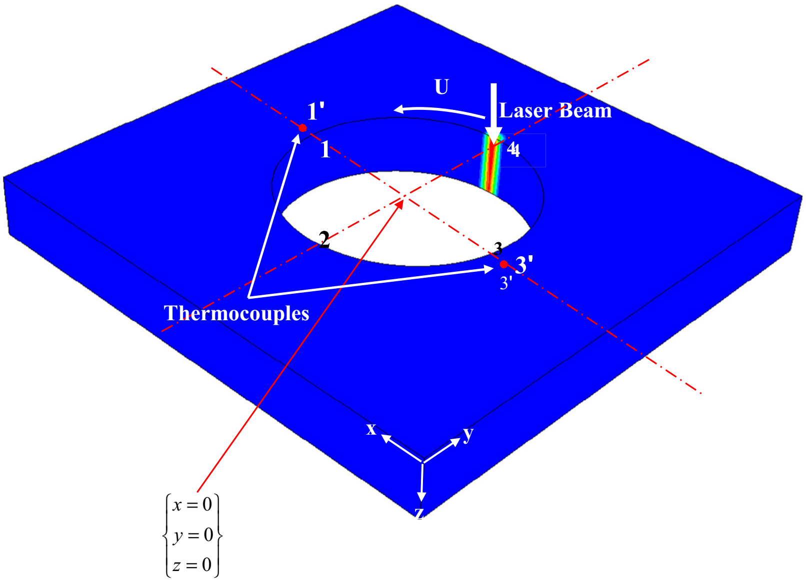

Fig. 1. A schematic view laser cutting process, location of thermocouples and coordinate system.