JJMIE

Volume 18, Number 3, September. 2024
ISSN 1995-6665
Pages 455- 460
https://doi.org/10.59038/jjmie/180301
Editor-in-Chief: Prof. Ali M. Jawarneh

Jordan Journal of Mechanical and Industrial Engineering

Laser Machining of Kevlar Polypropylene Composites: Effect of Continuous versus Modulated Wave Operational Mode

Saurabh Kumar Singh, Pankaj Yadav, Sambhrant Srivastava*, Amit Bhaskar, Brihaspati Singh

Department of Mechanical Engineering, Rajkiya Engineering College Azmgarh, Aikbalpur, Devgaon, Azamgarh, Uttar Pradesh, 276201, India

Received 16 Jan 2024 *Accepted 17 Jun 2024*

Abstract

Kevlar fabric reinforced plastics (KFRPs) are a type of composite material that consists of many layers of fabrics. In recent years, laser machining has surpassed both traditional and unconventional techniques because of its noncontact machining mode. In this research, polypropylene (PP) was used to reinforce Kevlar-129 fiber. Ten Kevlar layers were compressed-molded between Polypropylene layers to make the laminates. Cutting profiles of 25 mm x 25 mm was accomplished with the aid of fiber laser machining gear operating at a wavelength of 1070 nm with minimum laser power of 250 W and maximum of 400 Wand cutting speeds of 400 mm/min to 1000 mm/min with an interval of 200 mm/min with N_2 as assisting gas at 10 bar. Kevlar polypropylene (K-PP) laminates' failure behavior was studied to see how much the polymeric matrix affected them. Scanning electron microscopy is another tool for studying the surface morphology. The first factor to think about is the very minimum of laser power required to make the incision. High power and low cutting speed generated clean cuts, while low power and high speed had laminate scribing. SEM analysis was performed on the surfaces that had been laser cut. In K-PP, the study of the laser-irradiated surface revealed that the K-PP material had a presence of recast/re-solidified polymer on the Kevlar fabric. Surface quality was found to be highest when cutting at 100 Hz compared to the other two modes. To better understand how laser machining affects Kevlar laminates, an investigation on surface roughness was carried out.

Keywords: Kevlar,Kevlar Fabric Reinforced Plastics, Fiber Laser, Laser Machining,Surface Roughness.

1. Introduction

Kevlar fiber reinforced polymers (KFRPs) are renowned for their remarkable tensile strength and stiffness properties. Kevlar is a synthetic fiber made from chains of poly paraphenylene terephthalamide. These polymer chains exhibit a significant degree of molecular length and possess a high level of alignment, characterized by robust covalent bonds between adjacent chains along the fiber axis and comparatively weaker hydrogen bonding in the perpendicular direction. Consequently, Kevlar displays anisotropic qualities. It has superior strength-to-weight ratio compared to steel, boasting a five-fold improvement. Additionally, it demonstrates notable resilience to elevated temperatures and corrosion.

Kevlar is widely recognized as a lightweight and superior strength engineering composite material, making it highly suitable for various applications in the aviation, the armed forces, and automobile industries. There are several types of Kevlar fibers that are commercially accessible, including K-29, K-119, K-49, K-100, K-129, K-149, AP and KM2 [1]. Among these options, K-129 demonstrates remarkable versatility as a fiber and has found extensive utilization in various industrial contexts, including but not limited to interior panels and structural components for aircraft. The initial four types are employed in both high as well as low velocity impact scenarios, serving purposes such as providing protection against stabbing and personal body armor. Parts made of composite materials can usually be made relatively close to their net shape,[2]–[5] but they still need to be machined to remove extra material to meet standards or make holes for joining [6]–[8]. Hence, it is imperative to optimize the machining process parameters for composites [9]–[12].

Non-conventional machining techniques, such as abrasive waterjet (AWJ), the longitudinal-torsional ultrasonic vibration milling (LTUVM) and laser machining, have been documented as effective methods for achieving successful machining of composites with satisfactory surface finish [13]–[15] The hygroscopic properties exhibited by numerous polymers and fibers, along with the potential for retaining abrasive pieces in the matrix and fibers, which contaminates the composites and makes them less strong during abrasive water jet (AWJ) cutting.

Laser machining has become significantly significant owing to its noncontact machining mode, surpassing other conventional and non-conventional methods [16]–[19].

* Corresponding author e-mail: sambhrantsrivastava4@gmail.com.

Various research groups have conducted optimization studies on cutting settings in order to get the highest quality cuts when employing laser machining for Fiber Reinforced Polymers (FRPs)[20]–[22]. Delamination was reported to be significantly lower at low power and low scanning speed during laser machining. This research highlights the potential of optimizing laser machining parameters to enhance the quality of the machining process. Several studies have been conducted in order to enhance the reduction of thermal damage and heat affected zones that occur during laser machining [23]–[26].

The investigation and enhancement of bonding between fibers and matrices in Kevlar based composites have been the subject of study conducted by many groups. The enhanced interfacial bonding was identified as the primary factor contributing to the heightened strength of the composite.[27]–[29]

The study [30] used Kevlar strands coated with dopamine and embedded in a matrix made of olefin block co-polymer (OBC). In a study [31], it was demonstrated that the hydrothermal growth of ZnO nanowires on aramid fibers resulted in a peak load improvement of almost tenfold compared to the original, untreated fibers. In their study, [32] researchers included aramid textiles, commonly known as Kevlar, as interlayers within carbon based composites.

Laser machining has demonstrated significant efficacy in the machining process of a diverse range of composites, encompassing Carbon fiber reinforced plastics (CFRP), Glass fiber reinforced plastics (GFRP), and Kevlar laminates [33]. Nevertheless, laser machining is plagued by the generation of heat impacted zones, which might have adverse effects by inducing abrupt and unforeseen failures.

The literature frequently discusses the utilization of laser machining on traditional thermoset-based Kevlar laminates [34], [35]. However, there is a scarcity of research on the machining of Kevlar laminates based on thermoplastic materials. Therefore, an endeavor is undertaken to comprehend the mechanism behind laser machining of Kevlar-polypropylene laminates. This research project focuses on examining the influence of frequency on laser-machined KFRPs.

The following factors are analyzed in relation to the phenomenon: (i) The minimum amount of laser power necessary to cut the profile. (ii) Effect of cutting speed and frequency. (iii) Examination of surface morphology through the utilization of scanning electron microscopy. The data on the surface roughness is also documented.

2. Materials and Methodology

2.1. Manufacturing of Kevlar-polypropylene Laminates

Kevlar (K-129) plain weave cloth was used as reinforcement and Polypropylene sheets were used for the matrix. Compression molding, which can hold up to 200 tons, was used to make laminates. The laminates were fabricated by interleaving 10 layers of Kevlar between Polypropylene layers. The polymer beads were processed using extrusion to form thin sheets with a width of 250 mm. Table 1 lists the properties of constituent materials. Thickness of the Polypropylene sheets were 0.016-0.02 mm and Kevlar fabric was 0.2 mm.

During molding, 10 bar of curing pressure was applied for 6 minutes, at curing temperature of around 190°C, followed by water cooling until 100°C. The chamber was evacuated to a pressure of 500 mm of Hg. The measured thickness was 2.3 mm, and the fiber volume fraction was found to be 0.52.

Table 1. Properties of Kevlar and Polypropylene sheets (taken from manufacturer's sheet)

	Kevlar Fabric (K-129)	Polypropylene
Make	DuPont	Reliance Polymers
GSM	190	
Density (g/cm^3)	1.45	0.95
Grade	802F	Repol CO15EG
Yield Strain	3.3 %	11 %
Tensile Strength	-	27 MPa
Melting Point		230°C
Fabric/Sheet Thickness	0.2mm	0.016 -0.02 mm

2.2. Laser Machining

Laminates were cut by Fiber laser (Maker: Sahajanand Laser Tech. Ltd. Gujrat, India) with wave length of 1064 nm and cool water. With a gas pressure of up to 10 bar, N_2 is used as an assisting gas. The diameter of the nozzle is 1 mm, and the stand-off distance is 1.5 mm. The laser cutting machine is shown in Figure 1.

Experiments utilized three operational modes: continuous and modulated wave with frequencies of 100 Hz and 10000 Hz. Laser powers of 250W, 300W, 350W and 400W were used at four different velocities: 400 mm/min, 600 mm/min, 800 mm/min and 1000 mm/min. Profile of 25 mm square were machined for each combination (3 at each combination). Job description for laser machining is shown in Figure 2.

2.3. Characterization Tests

Laser-machined surfaces were analyzed by looking at SEM pictures at 80x and 200x magnification on a Hitachi tabletop microscope.

The surface roughness of samples cut by a fiber laser was evaluated using a Taylor Hobson talysurf, which is a portable stylus-type surface roughness measurement equipment that relies on contact-based measurements.

3. Results and Discussion

On all of the Kevlar laminates, a high-power fiber laser was used to cut the profile of square specimens. The laminates were cut with a method called "ablation." In Fig. 3, the results of laser tests are shown as a function of the ratio of laser power and scanning speed termed as line energy. Cutting means a through cut where whole thickness of laminate has been cut by laser whereas in scribing, whole thickness of the laminates was not cut. It is often shown in J/mm. It is a way to figure out how much laser power is required to cut a unit length. It is the result of the two most important factors, laser power and scanning speed, working together. Pulsed lasers have the capability to generate a substantial amount of peak power, although their average power output remains quite modest. Threshold values of line energy for 10 layer laminates is in between 25 J/mm in continuous mode whereas it was 22.5 J/mm for 100 Hz modulated laser and 18.75 J/mm for the modulated laser at 10000 Hz frequency.

But, there were found some variations such as in continuous mode and modulated mode of 100 Hz, cutting was seen at 300 W and 800 mm/min which leads to line energy of 22.5 J/mm whereas at the line energy is 24 J/mm resulting at 400 W and 1000 mm/min scribing was seen. It is thought that the extra damage caused due to more time (as cutting speed was lower) was just enough to separate the materials, while at higher speed could not separate the materials. So, line energy between 21 – 24 J/mm will be thought of as a changeover area for K-PP. It is also important to know that the plastic matrices let 60% or more of the laser light through. Because of this, most of the energy is taken up by the Kevlar threads. Consequently, the laminates undergo machining when heat travels from the Kevlar strands to the grids by conduction. Cut samples are shown in fig. 4.

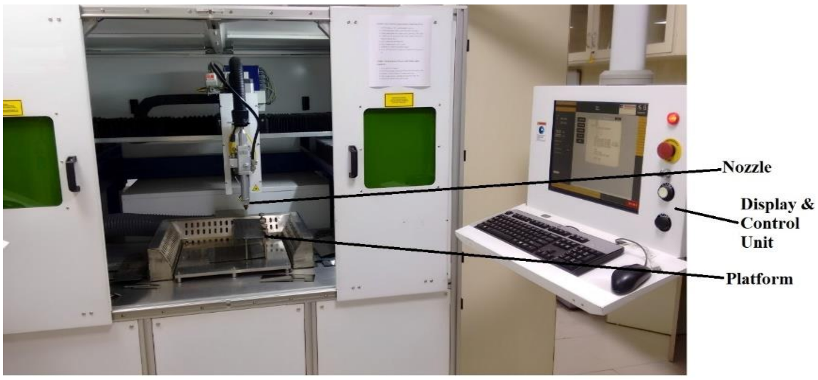

Figure 1. Fiber Laser Machine

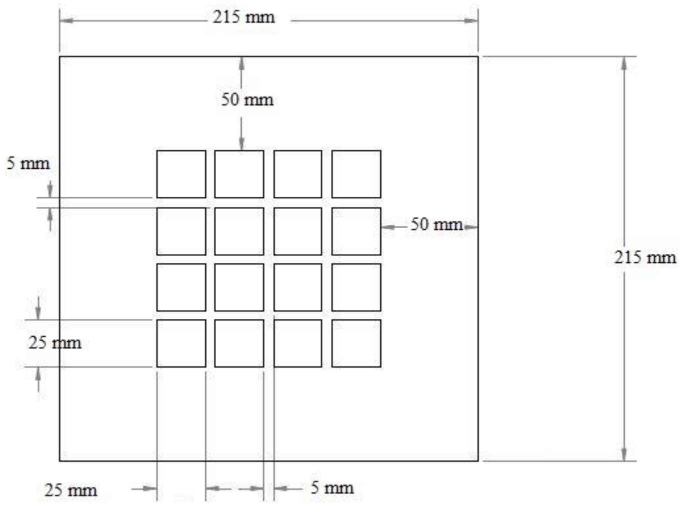

Figure 2. Job Description

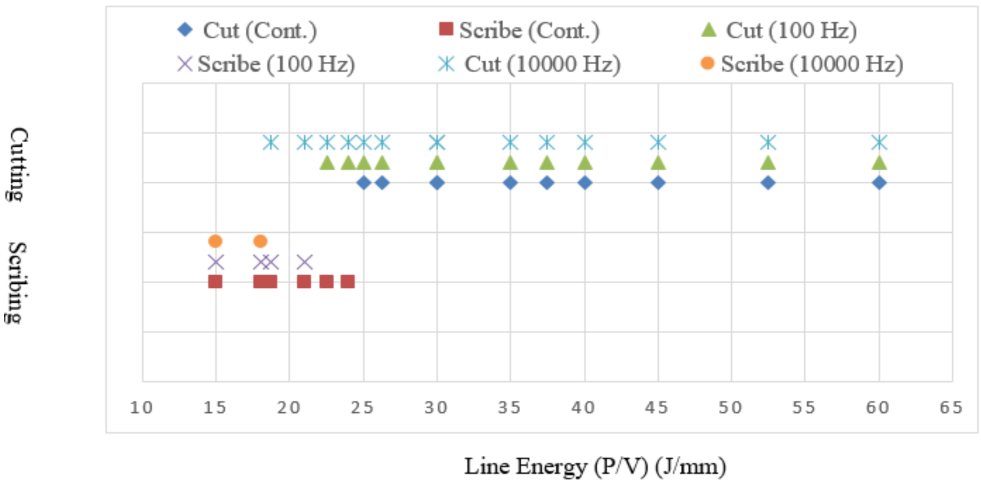

Figure 3. FLM of K-PP causing scribing and cutting at Different P/V (J/mm)

With a contact-type measuring instrument (Model: Taylor Hobson talysurf), the surface roughness of FLM-cut laminates was recorded. Figure shows how the surface roughness (Rq values) changes in the cut area for 10-layer K-PP laminates with continuous and modulated modes. Surface roughness of laser machined Kevlar-Polypropylene laminate increases with either increasing the laser power or increasing the cutting speed [36]. At different modes it was observed that cutting at 100 Hz produced better surfaces than other two modes. Best surfaces were obtained at low power and low cutting speed necessary to cut in modulated wave with 100 Hz frequency mode [37] as seen in fig 6.

To investigate the origin of machining-induced fractures that were found to be both mechanical and thermomechanical in nature, SEM images (Fig.5) laser-cut sections of the surfaces of the unfiltered samples were collected. When cutting with a laser, the polymer that is being cut becomes molten beneath or beyond the surface that is being hit by the laser. When a laser beam hits a Kevlar blend, both of the polymeric matrices melt. The capillary/wicking action also facilitates the rise of the molten polymer. On a laser-created surface, gas pressure is an important factor to consider. Because of the high-pressure assist gas (10 bars of N_2) and the use of Kevlar-PP laminates, the reduced melt flow index of the polymer demonstrates that less polypropylene flows to the surface that was cut by the laser. Laser-machined surfaces show recast polymeric layers because the liquid polymer's temperature drops rapidly with the help of a cooling gas.

The slowest speed at which any of the laminates could be cut was 400 mm/min, and the fastest speed ranged from 800 mm/min to 1000 mm/min, based on how much laser power was used and in which mode.

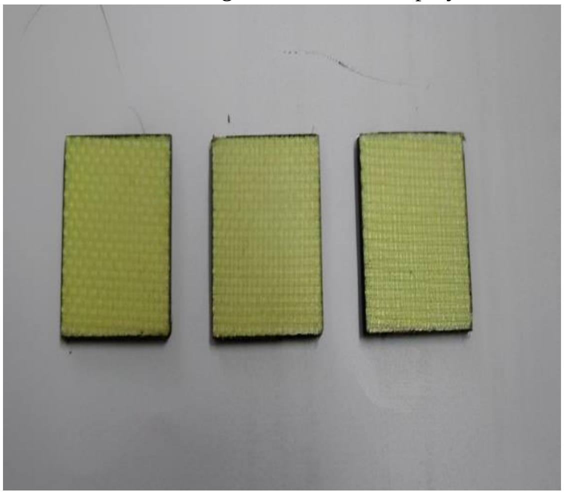

Figure 4. Cut Samples

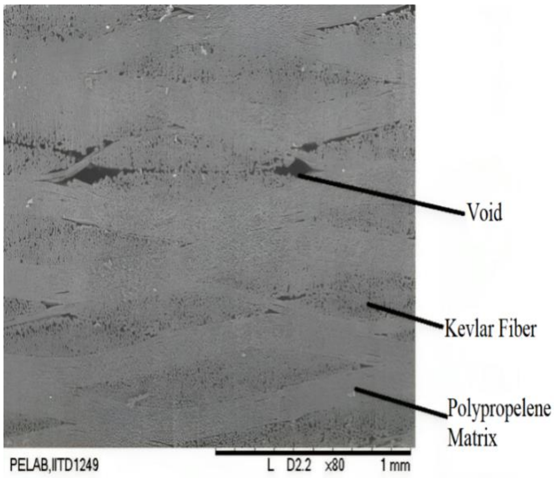

Figure 5. SEM image of cut surface

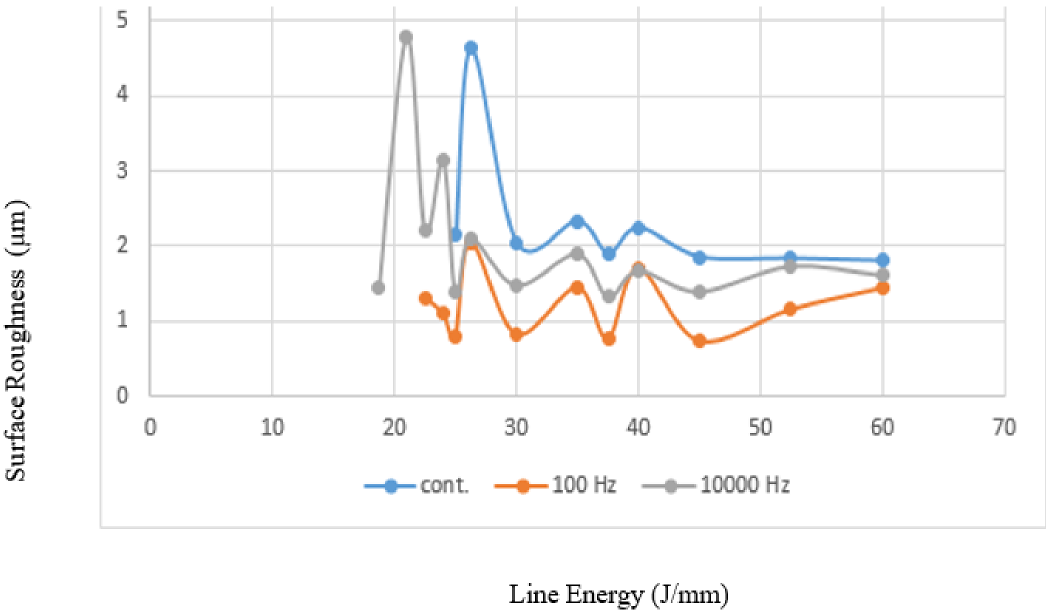

Figure 6. Surface Roughness Variations at different cutting parameters

4. Conclusion

Low power and high cutting speed caused laminate scribing, while high power and low cutting speeds produced clean cuts. In continuous wave mode, scribing occurs at 1000 mm/min cutting speeds for any power level and at a cutting speed of 800 mm/min with 250 W laser power, otherwise produced clean cut. At 100 Hz cutting was clean up to 800 mm/min while scribing occurs at 1000 mm/min. At 1000 mm/min, some clean cuts were observed at 10000 Hz. In SEM pictures of K-PP, it was seen that the surface of K- PP, the matrix moves more slowly and makes recast layers on the fibers' surface. Cutting at 100 Hz was shown to produce superior surfaces to the other two modes. The best results were achieved when cutting at a low power and slow speed using a modulated wave with a 100 Hz frequency mode.

Acknowledgements

The authors thank to Mechanical Engineering Department & Centre for Bio- Medical Engineering, IIT Delhi and Mechanical Engineering Department, Rajkiya Engineering College, Azamgarh.

References

[1] E. Reashad Bin Kabir and E. Nasrin Ferdous, "Kevlar-The Super Tough Fiber," *Int. J. Text. Sci.*, vol. 1, no. 6, pp. 78–83, Jan. 2013, doi: 10.5923/J.TEXTILE.20120106.04.

[2] Institute of Electrical and Electronics Engineers. DMI College of Engineering Student Branch, Institute of Electrical and Electronics Engineers. Madras Section., and Institute of Electrical and Electronics Engineers, *International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT) - 2016 : 3rd-5th, March 2016*. .

[3] T. Rangaswamy and R. Nagaraja, "Machining of Kevlar Aramid fiber reinforced polymer composite laminates (K-1226) using solid carbide step drill K34," in *AIP Conference Proceedings*, Jul. 2020, vol. 2247, doi: 10.1063/5.0004763.

[4] R. Balcha, J. Bhaskaran, P. J. Ramulu, and B. B. Tesfamariam, "Mechanical Behaviour Assessment of Banana Fibres Reinforced Polymeric Composite with Aluminium-Powder Filler," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 17, no. 2, pp. 269–279, 2023, doi: 10.59038/jjmie/170210.

[5] A. A. Victor and U. E. Inyang, "Development and Properties Characterization of Polyethylene Based Composite Using Coconut Fiber," *JJMIE*, vol. 81, no. 2, 2024.

[6] R. Teti, "Machining of Composite Materials," *CIRP Ann.*, vol. 51, no. 2, pp. 611–634, 2002, doi: 10.1016/S0007-8506 (07)61703-X.

[7] R. Komanduri, "Machining of fiber-reinforced composites," *Mach. Sci. Technol.*, vol. 1, no. 1, pp. 113–152, 1997, doi: 10.1080/10940349708945641.

[8] B. K. Rajamanickam Vinayagamoorthy, Nagamalai Rajeswari, "Optimization Studies on Thrust Force and Torque during Drilling of Natural Fiber Reinforced Sandwich Composites," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 8, no. 6, pp. 385–392, 2014

[9] A. Koplev, A. Lystrup, and T. Vorm, "The cutting process, chips, and cutting forces in machining CFRP," *Composites*, vol. 14, no. 4, pp. 371–376, Oct. 1983, doi: 10.1016/0010-4361(83)90157-X.

[10] D. F. Liu, Y. J. Tang, and W. L. Cong, "A review of mechanical drilling for composite laminates," *Compos. Struct.*, vol. 94, no. 4, pp. 1265–1279, Mar. 2012, doi: 10.1016/J.COMPSTRUCT.2011.11.024.

[11] A. Díaz-Álvarez, M. Rodríguez-Millán, J. Díaz-Álvarez, and M. H. Miguélez, "Experimental analysis of drilling induced damage in aramid composites," *Compos. Struct.*, vol. 202, pp. 1136–1144, Oct. 2018, doi: 10.1016/j.compstruct. 2018.05. 068.

[12] K. Ciecieląg, "Study on the Machinability of Glass, Carbon and Aramid Fiber Reinforced Plastics in Drilling and Secondary Drilling Operations," *Adv. Sci. Technol. Res. J.*, vol. 16, no. 2, pp. 57–66, 2022, doi: 10.12913/22998624/ 146079.

[13] A. Hejjaji, D. Singh, S. Kubher, D. Kalyanasundaram, and S. Gururaja, "Machining damage in FRPs: Laser versus conventional drilling," *Compos. Part A Appl. Sci. Manuf.*, vol. 82, pp. 42–52, Mar. 2016, doi: 10.1016/j.compositesa. 2015. 11.036.

[14] A. K. Dubey and V. Yadava, "Laser beam machining—A review," *Int. J. Mach. Tools Manuf.*, vol. 48, no. 6, pp. 609–628, May 2008, doi: 10.1016/j.ijmachtools.2007.10.017.

[15] J. Xu, P. Feng, F. Feng, H. Zha, and G. Liang, "Subsurface damage and burr improvements of aramid fiber reinforced plastics by using longitudinal–torsional ultrasonic vibration milling," *J. Mater. Process. Technol.*, vol. 297, Nov. 2021, doi: 10.1016/j.jmatprotec.2021.117265.

[16] F. Chegdani and M. El Mansori, "Mechanics of material removal when cutting natural fiber reinforced thermoplastic composites," *Polym. Test.*, vol. 67, pp. 275–283, May 2018, doi: 10.1016/j.polymertesting.2018.03.016.

[17] A. P. Marugán, F. P. G. Márquez, J. M. P. Perez, and D. Ruiz-Hernández, "A survey of artificial neural network in wind energy systems," *Appl. Energy*, vol. 228, pp. 1822–1836, 2018.

[18] K. Sadashiva and K. M. Purushothama, "Investigation on Mechanical and Morphological Characteristics of Ramie/Silk with Epoxy Hybrid Composite of Filler OMMT Nanoclay," *J. Text. Assoc.*, vol. 84, no. 2, pp. 101–111, 2023, doi: 10.59038/jjmie/170212.

[19] L. S. Yousuf, "The effect of temperature on the stresses analysis of composites laminate plate," *JJMIE*, vol. 13, no. 4, 2019.

[20] X. Tan, J. Zhang, J. Shan, S. Yang, and J. Ren, "Characteristics and formation mechanism of porosities in CFRP during laser joining of CFRP and steel," *Compos. Part B Eng.*, vol. 70, pp. 35–43, Mar. 2015, doi: 10.1016/j.compositesb.2014.10.023.

[21] A. Riveiro *et al.*, "Experimental study on the CO 2 laser cutting of carbon fiber reinforced plastic composite," *Compos. Part A Appl. Sci. Manuf.*, vol. 43, no. 8, pp. 1400–1409, Aug. 2012, doi: 10.1016/j.compositesa.2012.02.012.

[22] G. Caprino and V. Tagliaferri, "Maximum cutting speed in laser cutting of fiber reinforced plastics," *Int. J. Mach. Tools Manuf.*, vol. 28, no. 4, pp. 389–398, 1988, doi: 10.1016/0890-6955(88)90052-1.

[23] PriyankLohiya, A. B. Agrawal, A. Agrawal, and A. K. Jain, "Thermal Behaviour of Epoxy Composites Filled with Micro-sized LD Slag Particulates," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 17, no. 4, pp. 645–651, 2023, doi: 10.59038/jjmie/170418.

[24] C. Leone, I. Papa, F. Tagliaferri, and V. Lopresto, "Investigation of CFRP laser milling using a 30W Q-switched Yb:YAG fiber laser: Effect of process parameters on removal mechanisms and HAZ formation," *Compos. Part A Appl. Sci. Manuf.*, vol. 55, pp. 129–142, Dec. 2013, doi: 10.1016/ j.compositesa.2013.08.004.

[25] M. Muramatsu, Y. Harada, T. Suzuki, and H. Niino, "Infrared stress measurements of thermal damage to laser-processed carbon fiber reinforced plastics," *Compos. Part A Appl. Sci. Manuf.*, vol. 68, pp. 242–250, 2015, doi: 10.1016/ j.compositesa.2014.08.033.

[26] N. Alshabatat, U. Al-qawabeha, S. Al-qawabah, and K. E. Awwad, "Toughness of AISI O1 and AISI D2 Alloy Steels by Controlling the Grain Size During Heat Treatment," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 1, no. 2, pp. 431–439, 2024, doi: https://doi.org/10.59038/jjmie/180215.

[27] S. K. S. Sambhrant Srivastava, "Fabrication and Testing of Nano Bio-silica, Hemp, and Bamboo Fibre-Reinforced Chitosan Bio-composite Material," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 18, no. 2, pp. 401–410, 2024, doi: https://doi.org/10.59038/jjmie/180212.

[28] A. M. Al-Huneidei and I. S. Jalham, "Studying the properties of polymer blends sheets for decorative purposes," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 7, no. 1, pp. 41–48, 2013.

[29] A. A. A. Rahman, O. J. Adeboye, A. Adebayo, and M. R. Salleh, "Behaviour and Some Properties of Wood Plastic Composite Made from Recycled Polypropylene and Rubberwood," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 17, no. 2, pp. 281–287, 2023, doi: 10.59038/jjmie/170211.

[30] S. Fu *et al.*, "Combined effect of interfacial strength and fiber orientation on mechanical performance of short Kevlar fiber reinforced olefin block copolymer," *Compos. Sci. Technol.*, vol. 108, pp. 23–31, Feb. 2015, doi: 10.1016/j.compscitech.2015.01.001.

[31] H. S. Hwang, M. H. Malakooti, B. A. Patterson, and H. A. Sodano, "Increased interyarn friction through ZnO nanowire arrays grown on aramid fabric," *Compos. Sci. Technol.*, vol. 107, pp. 75–81, Feb. 2015, doi: 10.1016/J.COMPSCITECH.2014.12.001.

[32] N. Ni, Y. Wen, D. He, X. Yi, T. Zhang, and Y. Xu, "High damping and high stiffness CFRP composites with aramid non-woven fabric interlayers," *Compos. Sci. Technol.*, vol. 117, pp. 92–99, Sep. 2015, doi: 10.1016/j.compscitech.2015.06.002.

[33] D. Kalyanasundaram, S. Gururaja, P. Prabhune, and D. Singh, "Open hole fatigue testing of laser machined MD-CFRPs," *Compos. Part A Appl. Sci. Manuf.*, vol. 111, pp. 33–41, Aug. 2018, doi: 10.1016/j.compositesa.2018.05.005.

[34] B. S. Yilbas, F. Al-Sulaiman, C. Karakas, and M. Ahsan, "Laser cutting of multilayered Kevlar plates," *J. Mater. Eng. Perform.*, vol. 16, no. 6, pp. 663–671, Dec. 2007, doi: 10.1007/S11665-007-9107-2.

[35] B. S. Yilbas and S. S. Akhtar, "Laser cutting of Kevlar laminates and thermal stress formed at cutting sections," *Opt. Lasers Eng.*, vol. 50, no. 2, pp. 204–209, Feb. 2012, doi: 10.1016/j.optlaseng.2011.09.004.

[36] H. Chouhan, D. Singh, V. Parmar, D. Kalyanasundaram, and N. Bhatnagar, "Laser machining of Kevlar fiber reinforced laminates – Effect of polyetherimide versus polypropylene matrix," *Compos. Sci. Technol.*, vol. 134, pp. 267–274, Oct. 2016, doi: 10.1016/J.COMPSCITECH.2016.08.026.

[37] D. Kumar and S. Gururaja, "Investigation of hole quality in drilled Ti/CFRP/Ti laminates using CO2 laser," *Opt. Laser Technol.*, vol. 126, Jun. 2020, doi: 10.1016/j.optlastec.2020.106130.