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Investigation of the Effects of CO_2 Laser Processing Parameters on Kerf Width and Depth in Basalt Fiber Reinforced Epoxy Composites

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Abstract – This study focused on the effect of processing parameters of CO_2 laser on kerf width and depth of basalt fiber reinforced epoxy composite. In this research, the Taguchi method has been followed to optimize the laser power, scanning speed, and frequency for minimum thermal damage and a maximum rate of cutting. Laser parameters resultant in nine different experimental combinations were studied. The obtained results showed that, in general, an increase in the laser power led to larger and more profound kerf structures, while an increase in the scanning speed worked oppositely. For example, at 20 W with a speed of 100 mm/s and frequency with 5 kHz, the interaction without apparent material removal gave place to a narrow and shallow kerf. In this case, when increasing the power to 45 W and the speed of the process to 100 mm/s, the kerf that was obtained was very much wider and deeper to a minimum depth of 130 m. Higher laser frequencies resulted in increased energy accumulation on the material surface; hence, this showed greater material removal and greater depths during kerf formation. The range for optimum balance between kerf width and depth was for a power of 45 W, speed of 200 mm/s and frequency of 50 kHz. This gave a reasonably deep and wide kerf with less thermal damage. These results have further established guidelines that could be useful in the optimization of laser processing for basalt composites for applications involving fine material removal and surface texturing.

Keywords – CO_2 laser processing, Basalt fiber reinforced composites, Kerf width and depth

I. INTRODUCTION

Fiber-reinforced plastic (FRP) is a lightweight, high-strength material that is frequently utilized in daily products and aerospace applications. The varied responses of the alternating matrix and fiber components to cutting instruments make traditional FRP machining difficult. Tool wear and uneven results may emerge from this variability. This includes non-contact material removal methods, such as laser machining application, which are effective as an alternative solution. Laser machining is an ideal option for FRP treatment due to the fact that it comes with accurately performed material removal devoid of contact-related problems that arise with conventional methods [1]. The other accessory methods for machining, including micro-ablation surface texturing, might otherwise do additional improvement towards enhancing composite material properties. Successful surface texturing has been implemented in a wide variety of applications, including friction reduction, mechanical seal wear reduction, and MEMS adhesion mitigation, improving magnetic storage device stiction. The techniques of grooving and dimple formation include the alteration of features on the surface; hence, they are effective in disallowing improvements of the mechanical properties. These enhancements may enable composite materials to serve with improved performance and durability for different applications in practice [2]. Surface roughness is one of the most critical aspects in quality issues concerning manufactured components. Since fiber-reinforced polymer composites exhibit non-homogeneous characteristics, ensuring surface roughness with precision is an issue. Surface roughness, Ra, is measured through a stylus-type professional device. The radius of the tip of those devices creates a

challenge in measuring the troughs. As a result, the surface data filter may not be adequate, particularly for fine surface features. This constraint highlights the necessity of enhancing measurement methodologies or exploring substitute approaches to attain a more precise surface characterization [3]. Laser structuring offers tremendous design flexibility by enabling micrometer-level precision in targeted pretreatment without requiring masking. Recent research has demonstrated how well laser structuring may prepare FRP surfaces for metal coating applications. This is an important step toward local functionalization, as it can enhance wear resistance [4]. Hazzan et al. present recent progress in laser texturing for hard and ultra-hard materials, with the focus being on repeatable achievement of quality results [5]. An evaluation is given to the effects of laser mechanisms in generated damage and surface integrity that depend on wavelength, beam kind, pulse duration, fluence or scanning speed. Besides controlling and manipulating the textures, the study assesses the cutting performance of various textures and contributes to practical concerns-once again demonstrating the role of texture size, geometry, area ratio, density, and orientation. While it is possible to create surface texturing by the method of PLA, the quality of the textures may be degraded by melt debris, allotropic phase transitions, recast layers, porosity, and cracking. The best results, in order to remove flaws and create acceptable texture profiles, are obtained by considering pulse duration in the range of ns—fs, fluences over the ablation threshold, and well-calibrated multi-pass scanning rates. Singh et al. [6] investigates how to use a pulsed CO2 laser system to optimize the kerf geometry quality parameters when cutting hybrid composites made of Coir fiber, carbon fiber, and epoxy resin. The two main quality factors that are taken into account are surface roughness (SR) and kerf taper (KT). The predictive models were obtained based on key process variables, including gas pressure, cutting speed, pulse frequency, and pulse width. The morphological characterizations were done for assessing the effects of machining variables on the kerf widths. Thus, the influence of various laser cutting variables around the quality of hybrid composite made up of Coir fiber, carbon fiber, and epoxy resin was assessed. High accuracy was shown by the second-order surface response model for both SR and KT. The photothermal conversion characteristics of three types of carbon fibers (CFs) and their sizing amounts were assessed on cutting CFs with fiber lasers by measuring the laser absorptivity. The determination of the cutting process was thus done through multiphysics simulations and an analysis of the kerf cross-sectional morphology. In this paper, the laser cutting process is more familiar with the study of morphology, chemical composition, and mechanical properties of the CF kerf. The outcomes showed that while both techniques created composite nonwoven fabrics with comparable tensile strengths, laser-cut CFs had lower mechanical characteristics in the heat-affected zone than mechanically cut CFs. Furthermore, there was a linear correlation between the laser power and the crucial cutting-off speed of the CFs [7]. With a pulse frequency of 1.5 Hz and a pulse duration of 0.7 ms, the laser interaction with the composite samples was conducted under experimental circumstances that varied the energy density (128 to 1915 J/cm^2), pulse energy (1 to 3 J), and mean power (0.4 to 6.5 kW). The majority of the absorbed energy was transformed into thermal energy, which resulted in damage like evaporation, cracking, and melting, which created defects that looked like craters. The main shape of the crater was regular; at lower energy densities, it became elliptical, and at greater densities, it became round. With the exception of conditions of maximal exposure, the crater area grew continuously with rising energy densities [8]. In addition to mechanical removal driven by temperature changes during pulsed laser machining of CFRP composites, Tao et al. [9] investigates a material removal mechanism based on thermal evaporation and oxidation of both fiber and matrix. To verify the suggested process, comparative ablation experiments were carried out in both air and vacuum. The findings show that, in a vacuum, recoil pressure increases mechanical removal because there is no atmospheric pressure present. Carbon fiber jetting speeds have been observed to approach 45 m/s. Airflow influences the total removal efficiency by lowering the average temperature while raising the instantaneous temperature in the laser processing zone. Leone et al. [10] presents the effect of pulse power and time on cutting speed in laser cutting of basalt fiber-reinforced composite by a 450 W QCW fiber laser working in the pulsed wave regime. Experiments were performed with the purpose of studying the influence of pulse power, pulse time, and cutting speed. Kerf quality and shape were analyzed from external surfaces and section. The most important thermal damages included fiber protrusion, matrix degradation, and droplets of resolidified basalt at the kerf borders. On the kerf wall, there was a layer of resolidified basalt mixed with carbonized matrix.

Cutting speed had the leading effect on kerf dimensions and heat affected zone extension, whereas pulse power and duration had secondary influences on kerf features. The impact of feed rate and laser power on cut quality and subsequent tensile strength is investigated. The quantitative assessment of the areas affected by laser impact on the cutting edge was done using optical micrographs. The analysis shows that, especially at lower feed rates, a reduced load-bearing area resulting from modifications in the fiber-matrix structure generated by laser impact dramatically reduces tensile strength [11]. Lei et al. [12] discussed how texture design and laser parameters affect material performance, optimization techniques, and developed techniques for improving the performance of textures. This chapter goes into great detail concerning the fundamental theories and the ways Laser Surface Texturing-LST-enhances wettability and friction characteristics. Application areas presented in the review include metals, non-metals, and composites and underlined how material properties, surface texture, and laser parameters are highly related. Different geometric features, patterns, and distributions of surface texture can be achieved by varying laser parameters such as pulse width, power density, and pulse number. Variations in these parameters might have a strong impact on micro topography, roughness, hardness, and surface energy, thus modifying friction and wetting performance.

This study examines the impact of CO_2 laser processing parameters on the depth and kerf width of epoxy composites reinforced with basalt fibers. Precise laser tracks were applied to the composite surface by adjusting important laser parameters such laser power, scanning speed, and frequency. This enabled identifying the optimal settings for minimal thermal damage while ensuring maximum cutting efficiency. Although laser processing in carbon fiber-reinforced composites has been studied extensively, there have been relatively few reports focusing on basalt fiber-reinforced composites. This paper adds to the literature by providing detailed insight into the laser material interaction for basalt composites and defining parameter guidelines for baseline performance improvement with reduced degradation.

II. Materials and Method

A. Material

For this study, the reinforcement material was basalt fabrics [0°/90°] with a surface density of 200 g/m². The used basalt fabrics for this study were obtained from Dost Kimya Company. As a matrix material, Biresin Sika CR80 epoxy resin and Biresin Sika CH 80-2 hardener were utilized. It hardens in room temperature conditions. The hardener will be added to the epoxy resin at a weight ratio of 100:30. Fourteen-layered laminated composites were fabricated by the vacuum infusion method. Under vacuum conditions, these composites were kept for 24 hours at room temperature. Then the composite was demolded and post cured in an oven at 60 °C for 4 hours. Composite plate specimens measuring 400 mm × 400 mm were fabricated. The total number of 14 plies in the composite samples and a sample thickness of approximately 1.8 mm. The composite plates were then cut to the desired sample dimensions using a water jet cutter.

B. Laser Surface Texturing Process

Material processing with CO2 lasers offers distinct advantages over other laser technologies in many application processes, especially when operating on composite materials. Its long wavelength beam structure of 10.6 µm generally allows better energy absorption, especially in materials with organic and polymeric components. Thus, this allows the CO2 laser to process composite materials more effectively. In particular, the high-energy density and wide effect area of the laser provide a precision treatment opportunity on the material surface-especially for materials with complex structures, like basalt fiber-reinforced composites. The frequency used during the experimental study is 25 kHz by a CO_2 laser operating at a maximum power of 130W. The air-cooled system creates stability in the laser during processing, while the standoff distance value is determined to be 4 mm. The above parameters will play a major role in ensuring homogeneous energy distribution of a laser on the material and create the desired structures on the surface. The output of the experiments, some kinds of channels and structures have been treated by using a CO2 laser on the surface of basalt fiber-reinforced composites. Compressed air sent from the nozzle acts together with the laser beam on the surface and melt and by-products obtained due to laser processing are effectively removed. CO2 lasers have a large size of spot, enabling large areas in composite

materials to be fast and controllably processed. Figure 1: Schematic of the laser surface texturing process of basalt fiber reinforced composites. This system is designed for processing basalt fiber-reinforced composite materials. The lens focuses the laser beam to then be directed to the surface with the help of the nozzle. Compressed air coming from the nozzle assists in the removal of the waste materials formed on the surface during processing. The SOD is fixed at 4 mm, which determines the distance of the laser from the targeted surface.

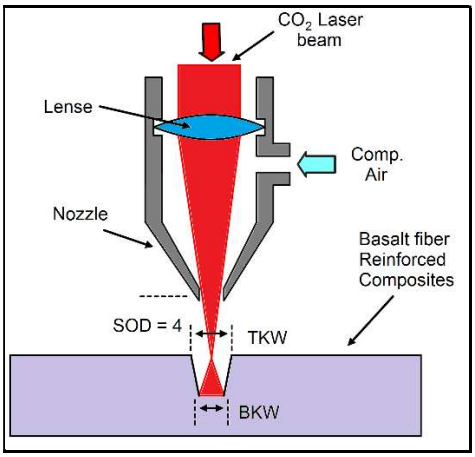

Fig. 1 Laser processing schematic of basalt fiber reinforced composites

In the present work, basalt fibre-reinforced polymer composite materials were studied through experimental analysis by CO_2 laser for the creation of kerf (material cutting trace). The Taguchi experimental design method was applied for the optimization of the experimental parameters to improve the results of the process. The Taguchi method is a statistical optimization technique widely employed in quality engineering that offers maximum information using a limited number of experiments. This can save costs, time and labour in determining the best combination for multi-parameters associated with multi-levels. Besides that, it minimizes the effect of noise factors on robustness within the process. The results have implications for basic understanding and possible applications of the texturing process for material property enhancement. Table 1: Laser surface treatment parameters-sample coding. In the experiment, the Taguchi method was used for planning the power of the laser, the rate of cutting, and frequency. The kerf structures on the basalt-reinforced composite surface were made for nine different combinations. The parameters used in this study were determined as laser power (20, 32, 45 W), laser speed (100, 200, 300 mm/s) and frequency at (5, 25, 50 kHz). In developing the experimental matrix, the Taguchi L9 orthogonal design method was used, and the results obtained under each experimental condition were analysed. As can be seen from this study, the Taguchi method forms an important advantage in examining the effects of process parameters on performance and determining the most appropriate combination. Thanks to this method's advantages, high efficiency and quality were reached during the laser treatment processes. It presents valuable information on laser-cutting processes executed on basalt fiber-reinforced polymer composite materials.

Table 1. Laser processing parameters of basalt fiber reinforced composites

Exp. No.	Laser Power (W)	Speed (mm/s)	Frequency (kHz)
1	20	100	5
2	20	200	25
3	20	300	50
4	32	200	5
5	32	300	25
6	32	100	50
7	45	300	5
8	45	100	25
9	45	200	50

C. Optical Microscope Surface Characterization

The surface characterizations of basalt fiber-reinforced composites were made by an Evident-Olympus BX 53 MRF model microscope. This high-performance optical microscope is well known for high-resolution imaging with superior clarity, hence allowing a closer look at the microstructural features on laser-processed surfaces. For the observation of processed areas on the laser surface-treated basalt fiber-reinforced composites, the magnification in the optical microscope was selected as 20X. Therefore, all of the traces created on the surface by the laser would be integrated into the image.

D. Roughness Characterization

A non-contact laser profilometer called Nanovea PS50 to find out the surface topography of the laser-treated basalt fiber-reinforced composites was used. This technology enabled the visualization of the exactness of surface roughness parameters without any need for physical contact with the material. The raw state data were analysed using the DigitalSurf application-only version 6.2.7487, provided by Mountains Technology. As a result, three-dimensional surface topography representations were generated according to the specifications set out by the ISO 25178 standards. Moreover, the images that were required for carrying out the analysis of the laser-induced surface topographies were generated in accordance with what was stipulated under the ISO 4287 standards. The laser profilometer allowed a thorough overview of all laser-treated surfaces by scanning the sample surfaces, which have been hit with various laser settings across an area of 3 mm x 5 mm.

III. RESULTS AND DISCUSSIONS

A. Surface Optical Microscope Characterization

Figure 2 shows optical microscope images of laser-processed sections. In each experiment, the effects of laser power, speed, and frequency on kerf morphology show different results. In Figure 2-a, since the laser power is low (20 W), speed is low (100 mm/s), and frequency is low (5 kHz), a thinner and narrower kerf is observed in the section region. The laser's combination of low energy input and low speed has a limited effect on the material. The kerf width indicates that the laser removes only a small amount of material. In Figure 2-b, the laser power is kept constant (20 W), but the speed is increased (200 mm/s). The high speed caused the laser to stay on the material for a shorter time, which led to a narrower and shallower section structure. Although the number of laser pulses increases as the frequency increases (25 kHz), no intense effect on the material is observed. In Figure 2-c, a process was applied that increased the speed even more (300 mm/s). In this case, the kerf width was considerably narrower, and a shallower cavity was formed on the surface. The high frequency (50 kHz) mitigated the thermal effects of the laser on the material, which reduced the material removal and decreased the kerf depth. In Figure 2-d laser power was increased to 32 W and the speed was kept medium at 200 mm/s. Since the power is increased, the laser had more effect on the material hence the kerf section became broader. Thermal damage and deep cavities can be observed on the surface. In Figure 2-e, the laser power remained constant (32 W), but the speed was increased (300 mm/s). Due to the high speed, material removal decreased, but since the power level was sufficiently high, the kerf width and depth remained at a medium level. This caused a smoother cavity to form on the surface. In Figure 2-f, the laser power was kept constant (32 W), but the speed was reduced (100 mm/s) and the frequency was increased (50 kHz). This combination resulted in more energy accumulation on the material and deeper kerf formation. Quite significant thermal effects along with deeper pits on the surface were obtained. Figure 2-g laser power increased to maximum level of 45 W and highest value for speed, 300 mm/s. The high value for the scanning speed set up a limitation for the effect of the laser in this case, and the depth of the kerf is accordingly relatively low. Although the power was high, the high speed limited the material removal. In Figure 2-h, low speed (100 mm/s) and high power (45 W) were used. In this case, the laser's effect on the material was quite intense, resulting in a wide and deep kerf formation. The thermal damage on the surface also became more apparent. In Figure 2-i, the laser power was kept at the highest level (45 W), and the speed was kept at the medium level (200 mm/s). These parameters gave a balanced result in terms of kerf width and depth. The laser's effect on the material was observed to create a more pronounced cross-section due to the balance of power and speed, as well as a wide and deep kerf structure.

As a result, increasing laser power generally results in wider and deeper kerf structures, whereas increasing speed reduces this effect. The frequency of the laser pulses increases, which affects the material removal rate.

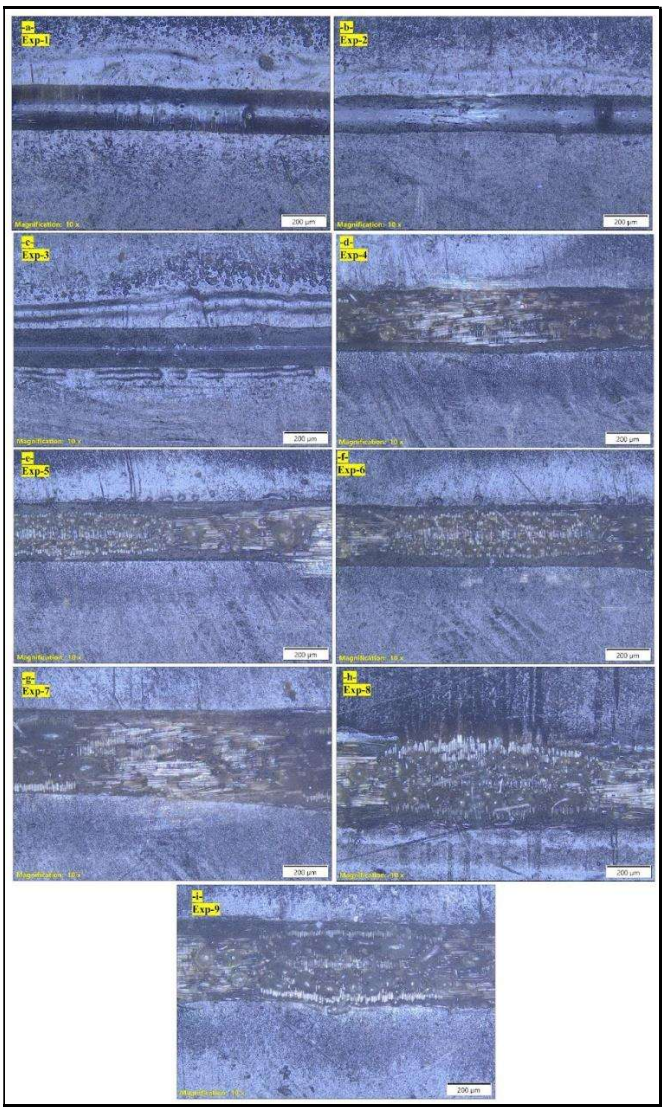

Fig. 2 Optical microscope laser induced kerf images.

B. Roughness Characterization

Figure 3-a for the case of low power 20 W of Exp-1, with low speed of 100 mm/s and low frequency of 5 kHz, less energy was applied on the material that might result in shallow formation of kerf on the surface. The 3D surface morphology of laser kerf has been analysed to note the effect of laser processing parameters for each experiment as illustrated in Figure 3. A red area on a surface can indicate low material loss and a shallow cavity structure. Figure 3-b (Exp-2) illustrates that the same power and frequency laser treatment was processed but at higher speed at 200 mm/s. Due to the increase in the scanning speed, energy density on material may reduce less material removal could occur. Hence, a less deep kerf can be seen on the surface showing smaller depth difference. In Figure 3-c (Exp-3), speed was set up to 300 mm/s. High speeds may cause the material to scan faster with the laser. This can possibly result in less removal of material on the surface hence a shallower kerf. Very relative flatter and less differenced in depth are evident on the surface. In Figure 3-d the laser power becomes more enormous, at 32 W in this case, and more energy is being provided to the material. Due to the higher power, increased kerf can be formed on the surface. More profound grooves and complex morphologies might be created on the surface for medium speed (200 mm/s) and at low frequency.

Figure 3-e (Exp-5), the experiment is at the same power level at 32 W with increased speed of 300 mm/s. The energy distribution will be wide on the material due to the high speed value which can develop a shallow kerf structure. It can be seen that the surface formation is much smoother than that in Exp-4 and shallow. In Figure 3-f (Exp-6) power 32 W, low speed 100 mm/s, and frequency of 50 KHz. Higher the frequency, more are the impacts with the material; hence, more energy is transferred, probably leading to a deeper and coarser structure on the kerf. In this case, the blue and green areas might represent more removal of materials to the surface and extremes; hence, forming deeper pits. Figure 3-g (Exp-7) has used the highest power level of 45 W and the highest speed of 300 mm/s. This could be too high and may reduce the density of energy on the material to give rise to more limited material removal and smoother structure at the surface. Hence, deep kerf formation may not be observed. In Figure 3-h (Exp-8) applying a high power and a low speed, the energy will be able to accumulate more on the material, and further make the kerfs deeper and irregular on the surface. It can see that there are large cavities and complex structures on the surface. In Figure 3-i (Exp-9), the same power-frequency combination at the same speed is considered but kept at a moderate level at 200.00 mm/s. With this, one can form a deep but more regular kerf structure on the surface. More controlled and regular surface structure could be observed upon comparing with Exp-8. Frequency is another important parameter that could considerably affect surface roughness.

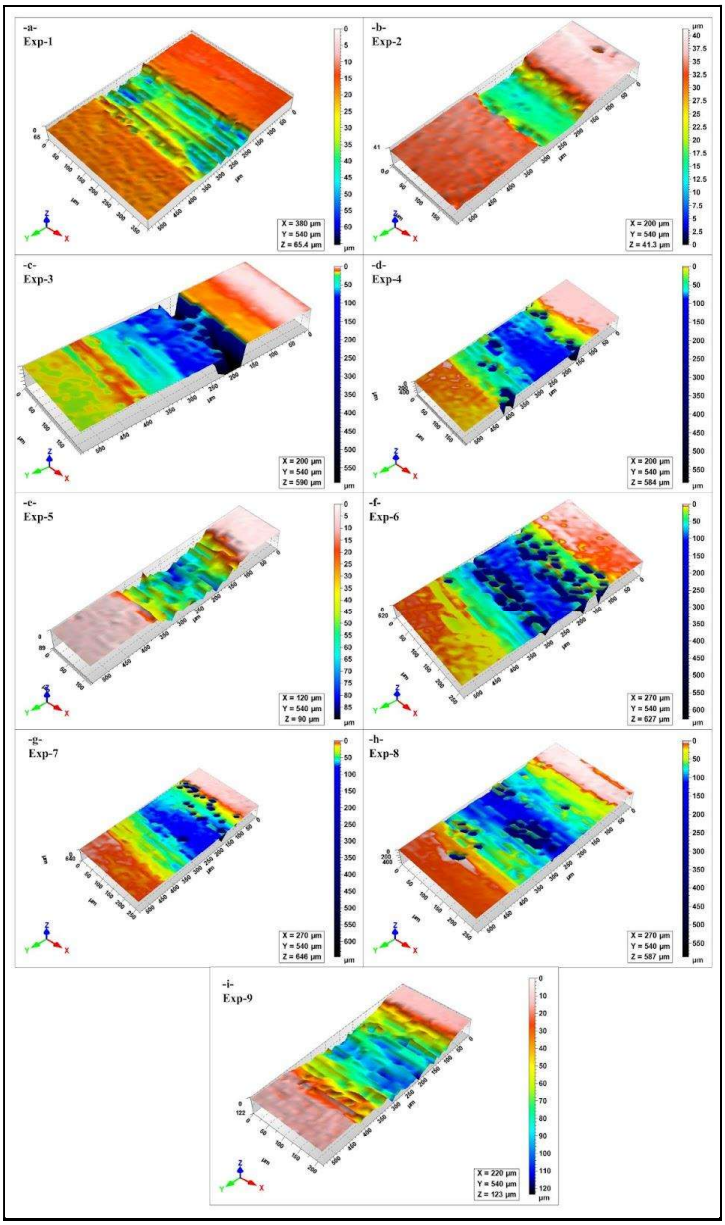

Fig. 3 3D laser processed line kerf width and depth (a-c) 20W, (d-f) 32W, (g-i) 45W.

In Figure 4-a, in this experiment where the laser power is 20 W, low speed (100 mm/s) and low frequency (5 kHz) were used. With these parameters, a non-wide kerf formation is observed on the surface. Although the depth is not too much, the minimum depth is around 40 μm and the kerf width is quite limited. It is seen that less material is removed by the laser with low energy and a shallower cavity is formed on the surface. In Figure 4-b, the same power (20 W) was used and the speed was increased (200 mm/s). In the experiment, the kerf width is narrower in width and reduced its depth. Increase in the speed reduced the effect of the laser on the material and reduced the material removed. This resulted in narrower and less deep kerf formed on the surface. The minimum depth was around 25 μm. In Figure 4-c, the laser power was 20 W and the speed was increased to the highest level (300 mm/s). Under these conditions, the kerf width was quite narrow and the depth was quite shallow. High speed caused the laser energy to have less effect on the material and the minimum depth remained around 80 μm. The kerf cross-sectional area is small and the material removal rate is low. In Figure 4-d, the speed was set to 200 mm/s in this experiment where the laser power was increased to 32 W. Kerf width and depth increased with this process performed at medium speed and higher power level. The effect of the laser on the material became more apparent with the increase in power and created deeper cavities. The minimum depth was around 90 μm and the kerf cross-sectional area was larger than in previous experiments. In Figure 4-e, the power was again at 32 W level but the speed was set to 300 mm/s. Despite the process performed at high speed, the kerf width and depth remained at medium level due to the effect of the power. The minimum depth was around 70 μm. High speed reduced the amount of material removal, but the kerf cross-sectional area expanded due to the effect of 32 W power. In Figure 4-f, the laser power was set to 32 W, the speed to 100 mm/s and the frequency to 50 kHz. Under these conditions, both the kerf width and depth increased considerably. This experiment, which was conducted at low speed and high frequency, led to a more effective use of laser energy on the material. The minimum depth was around 120 μm and the kerf width was also quite large. In Figure 4-g, the laser power was set to 45 W and the speed to 300 mm/s, and the kerf depth was less due to the effect of the high speed. Although the power was high, the speed reduced the material removal rate and the kerf width remained limited. The minimum depth was around 80 μm. In Figure 4-h, the laser power was set to 45 W and the speed to 100 mm/s. Using high power at low speed led to a deeper kerf formation on the surface. The minimum depth reached 130 μm and a wide kerf section was observed. The laser effect on the material is more intense and the cavity is deeper and wider. In Figure 4-i, the power is again determined as 45 W and the speed is 200 mm/s. In this experiment performed at medium speed, the kerf width and depth increased in a balanced manner. The minimum depth was approximately 90 μm and a distinct kerf section was formed on the surface. The laser energy was spread over a wide area on the material and the depth and width increased in a balanced manner.

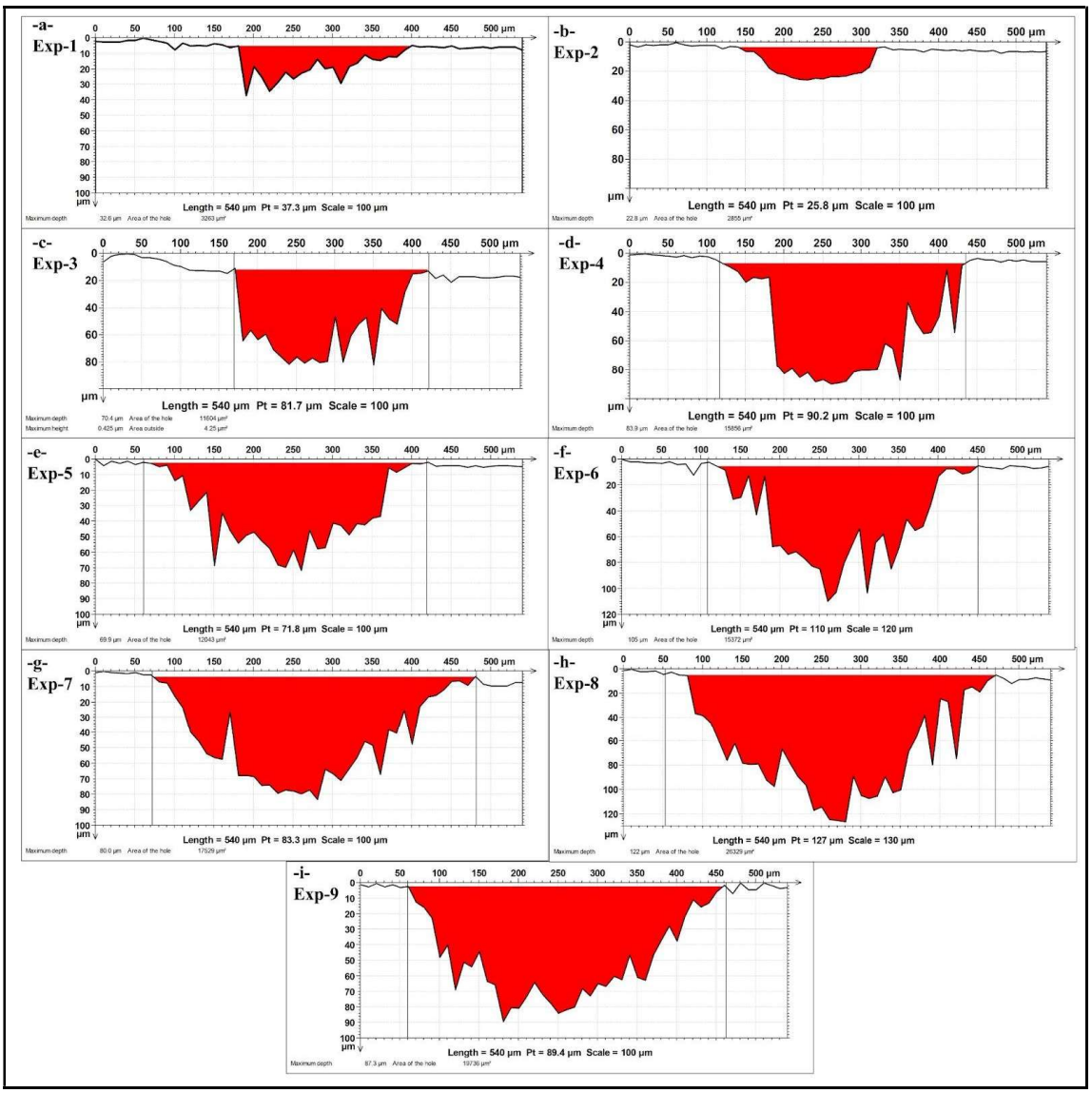

Fig. 4 2D laser processed line kerf width and depth cross-sections and kerf cross-sectional area comparison (a-c) 20W, (d-f) 32W, (g-i) 45W

IV. CONCLUSION

The work investigates the effect of processing parameters in the CO_2 laser method on kerf width and depth in basalt fiber-reinforced epoxy composites. In order to observe the influence of the parameters on characteristics, nine experiments were performed by changing the laser power (20, 32, and 45 W), scanning speed (100, 200, and 300 mm/s), and frequency (5, 25, and 50 kHz). The results showed that higher power tends to widen and deepen the kerf structures, while higher speeds tend to decrease the material removal rate. Accordingly, the optimum laser settings of a medium power, moderate speed, and high frequency-32 W, 200 mm/s and 50 kHz, respectively-offer minimum thermal damage besides an efficient cut. These settings, therefore, have given a kerf depth of about 90 µm while keeping the width well-controlled. In this combination, therefore, an effective balancing of energy distribution has been achieved that remarkably minimized defects while attaining the intended geometry of the kerf. This study reported new findings in laser machining of basalt composites, optimized process parameters involved in pursuing cuts of good accuracy with minimal degradation.

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