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Optimization of Kerf Deviations in Pulsed Nd:YAG Laser Cutting of Hybrid Composite Laminate Using GRA

The aim of this research is to identify the optimum levels of leading laser cutting parameters for accomplishing precise cut geometry with better quality for cutting of newly developed Basalt-Glass-Kevlar 29 hybrid FRP composite laminate. The total of 42 experiments have been performed on a 2.34 mm thick laminate using a 250W pulsed Nd:YAG laser cutting system. Lamp current, pulse width, standoff distance, compressed air pressure, and cutting speed have been selected as variable laser cutting parameters. Thereafter, grey relational analysis approach has been adopted to single index optimization of top and bottom kerf deviation, simultaneously. These optimal solutions have been validated by comparing the results of confirmation experiments and found satisfactory improvement. Standoff distance has been observed as the most influencing parameter for both top and bottom kerf deviation.

Keywords: Nd:YAG laser; Hybrid composite; Laser cutting; Kerf deviation; grey relational analysis; Optimization.

1. INTRODUCTION

In recent years, hybrid fiber reinforced polymer (FRP) composite materials are gaining the attention of researchers due to improved mechanical, structural properties as compared to their individual's composites [1]. The properties of the hybrid composite materials are decided by the kind of the matrix material, reinforcement material, geometry of the reinforcement material, orientation, stacking sequence and their content percentage. Glass, Carbon, Kevlar, Basalt are the types of some common fibers using as reinforcing agents for hybridization of FRP composite materials [2,3]. Hybrid composites of these fibers are widely used in the marine, automobiles and aerospace industries etc.

Composite materials are designed and fabricated with exact shape and size as per desired areas of application in industries. Although for complex shapes and intrinsic profiles, their machining is required. Matrix cracking, uncut fibers, delamination, increased surface roughness, and reduced tool life are serious issues in the machining of FRP composite materials through conventional machining techniques like turning, drilling and milling etc. These issues pave the way for the use of advanced machining techniques for machining of these materials. In recent years, the main focus for the machining of FRP composites has been laid on Abrasive water jet machining (AWJM) and Laser beam machining (LBM) process [4,5]. Shukla and Tambe [6] successfully performed AWJ cutting of Kevlar fiber reinforced polymer composites. They have determined the quality of cut in terms of top kerf width, bottom kerf width and surface roughness. Though both AWJM and

LBM processes have been found out to have several advantages for machining the composites, yet AWJM possesses some negative effects such as moisture absorption, delamination because of inadequate depth of cut.

The non-contacting and localized nature of LBM is able to provide complex geometries with adjacent tolerances, narrow kerf widths and limited heat affected zone (HAZ) in cutting of composites [7]. In LBM, a highly intense and coherent laser beam removes material from the surface of the workpiece by the interaction, melting and vaporization [8]. In laser beam cutting (LBC), the geometry of cut defines in terms of kerf quality characteristics. Top and bottom kerf width, top and bottom deviation, and kerf taper are the key kerf quality characteristics of laser cut surface. The loss of material during laser cutting is known as kerf. The width of the kerf is termed as kerf width and the waviness of kerf is known as kerf deviation [9]. Limited studies have been conducted to evaluate the performance of the laser beam cutting of FRP composite materials. Gautam and Pandey [10] observed that lamp current is the most significant parameter for both the top kerf deviation and bottom kerf deviation in pulsed Nd:YAG laser cutting of Kevlar-29 fiber reinforced composite laminates. Yilbas et al. [11] performed laser micro-cutting of Kevlar laminate and observed the influence of cutting speed on cut geometry.

In the literature survey, it has been observed that most of the work is carried out on single FRP composites. A very less amount of work has been found in the field of laser cutting of hybrid composite materials. Gautam and Mishra [12] performed pulsed Nd:YAG laser cutting on 1.35 mm thick Kevlar-29 and Basalt fiber based hybrid composite sheet. They evaluated the geometrical accuracy of the cut in the terms of kerf width, kerf deviation, and kerf taper. Moreover, they employed an integrated approach based on Grey relational analysis and genetic algorithm (GRGA) for single index optimization of different kerf qualities. In this

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study, it has been also revealed that the appropriate settings of operating parameters help to achieve highly precise and accurate cut geometry. In another study [13], they improved the dimensional accuracy of the laser cut quality of Kevlar-29/basalt fiber-reinforced hybrid composites through parametric optimization by using Teaching learning-based optimization approach.

However, in LBC, the selection of the optimal solutions of process parameter for improved cut quality is a tough task due to the non-linear relationship between input and output variables. Therefore, different statistical and artificial intelligence (AI) based optimization techniques have been employed by various researchers such as Taguchi methodology, genetic algorithm, teaching learning based optimization etc. [10, 14,15]. However, these techniques are able to provide optimal solutions but some of these are not robust in nature. Thereby, the search for robust optimization technique is still in the way. These factors motivated the present research work. In recent years, Grey relational analysis (GRA) proves its suitability to search optimal solutions in a complex system. GRA is a robust nature technique. It suggests an efficient solution to the large range of discrete data problem with uncertainty [16–18]. Tamrin et al. [19] employed GRA approach to determine multiple-objective optimization of different thermoplastics such as PMMA, PC and PP for a higher dimensionally precise cut with the reduced heat-affected zone (HAZ) as a function of grey relational grades. Tsai and Li [20,21] used GRA to optimize cutting parameters in laser cutting of QFN packages and flash memory modules with special shapes. They have ensured the robustness of GRA approach on the basis of confirmation experiments.

In the present work, 42 experiments have been performed on the pulsed Nd-YAG laser for the cutting of 2.34 mm thick Basalt- Kevlar 29-Glass fiber based hybrid composite laminate. Lamp current, pulse width, standoff distance, air pressure and cutting speed have been considered as input parameters whereas the top and bottom kerf deviations have been selected as responses. Thereafter, grey relational analysis (GRA) has been employed to determine the optimal levels of input laser parameters by using experimentally gathered data. Lastly, the obtained optimal solutions have been validated by conducting confirmation experiments. Moreover, parametric analysis has been also discussed.

2. EXPERIMENTAL PROCEDURE

2.1 Material

In the present work, three distinct fibers viz. Kevlar-29, Basalt, and Glass have been used as a reinforcing agent in the epoxy-based polymer matrix. The hand-layup method was used to fabricate the hybrid composite laminate. A mild steel mold having dimensions of 330 mm×330mm×10mm was used for fabrication purpose. The resin glue was prepared by mixing epoxy and hardener in the ratio of 5:1 with a little amount of thinner as well.

The mechanical and thermal properties of a hybrid composite laminate can be altered as to the application

by changing the stacking sequence of the fibers used in fabricating the material. Hence, the stacking sequence for the fabricated composite laminate was [B-90°/G-45°/K-90°/G-45°/B-90°] for 5 layers as shown in Fig. 1. The physical properties of the fabricated hybrid composite laminate are tabulated in Table 1.

2.2 Experimentation

After fabrication of hybrid composite laminate, a 250 W pulsed Nd: YAG laser system developed at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore has been employed for conduction of experiments. The specifications of the employed laser system are tabulated in Table 2.

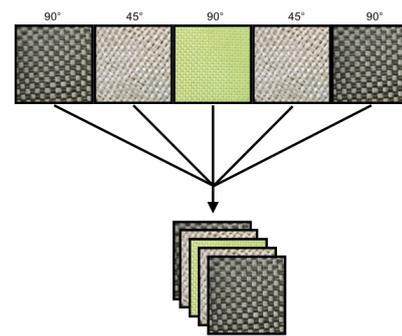


Figure 1. Layers of fibers used in a hybrid composite laminate

Table 1. Properties of the hybrid composite laminate

Basalt-Glass-Kevlar-29 based hybrid fiber		
Property	Value	
Total volume (cm ³)	59.106	
Volume fraction	Matrix	40.35
	Fiber	59.65
Total weight (g)	72	
Weight fraction	Matrix	47.20
	Fiber	52.80
Density (g/cm ³)	1.218	

Table 2. Specification of pulsed Nd:YAG laser setup

Specification	Values/range
Laser wavelength	1064 nm
Beam diameter	10 mm
Beam divergence (full angle)	6 m rad
Average pump power	5 Kw
Average output power (max)	250 W
Peak power (max)	5 kW
Pulse energy (max)	100 J
Pulse width	1-20 ms
Pulse repetition rate	1-200 Hz
Focused spot size on job	600 μm

Response Surface Methodology (RSM) based on Box-Behnken Design (BBD) with two center points has been used to design the experiments. BBD consists of less number of experiments with higher resolution and avoided extreme points as compared to Central Composite Design (CCD). Total 42 experiments have been performed using three levels of five leading laser cutting parameters such as lamp current (*I*), pulse width (*PW*), standoff distance (*SOD*), air pressure (*p*) and cutting speed (*S*). Table 3 consists of the levels of input process parameters with their levels. A 20 mm long straight cut

has been performed at each combination of cutting parameters. Thereafter, the geometrical quality of the cut surface has been quantified in terms of top kerf deviation (TKD) and bottom kerf deviation (BKD) of the cut.

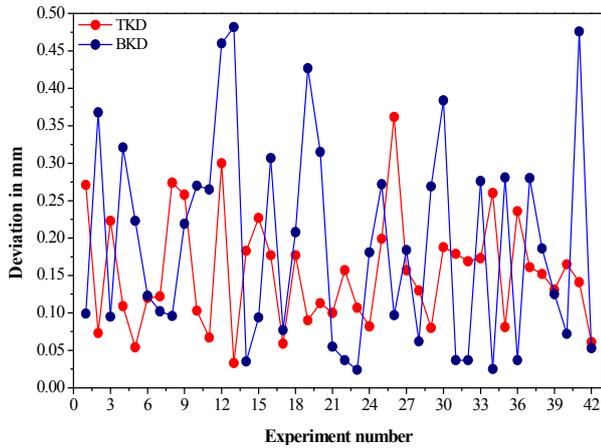


Figure 2. Variation of measured values of top and bottom kerf deviation

Table 3. Laser cutting parameters and levels

Factor	Unit	Levels		
Lamp current	Amp	180	200	220
Pulse width	Ms	2	2.5	3
Standoff distance	Mm	1	1.5	2
Pressure	kg/cm ²	8	10	12
Cutting speed	mm/min	100	150	200

Equation 1 and 2 have been used to calculate the TKD and BKD. The variations of TKD and BKD for all 42 experimental runs are plotted in Fig. 2.

$$TKD = (KW_{\max} - KW_{\min})_{Top\ side} \quad (1)$$

$$BKD = (KW_{\max} - KW_{\min})_{Bottom\ side} \quad (2)$$

Here, KW denotes the kerf width of the laser cut at the top and bottom side of the cut. In this study, 4 measurements of kerf width of each cut have been measured for higher resolution.

3. GREY RELATIONAL ANALYSIS (GRA)

GRA is one of the widely used optimization techniques which is based on a specific concept of information. This concept is known as the grey system theory [17]. In this, a situation without information is represented by black color and with full information by white color, whereas a situation between these two extremes is described by grey system. This whole concept is based on a set theory. In recent years, the implementation of GRA is increased to identify the optimal solutions in various fields like manufacturing, environmental, economic and management systems [22]. Figure 3 visually depicts the colour phenomena of grey system.

In GRA, grey relational grades (GRG) are evaluated to single index optimization of multiple quality characteristics. The complete process is performed in two stages i.e. data pre-processing and grey relational generating. In data pre-processing original experimental data is transformed into a comparable sequence within the range of 0 and 1. This is required to avoid the deviational errors. In this step, Eq. 3-5 are used to normalize experimental data

as per their characteristics such as lower-the-better, nominal-the-best and higher-the-better. In the present study, the primary aim is to reduce kerf deviations, therefore lower-the-better function has been used.

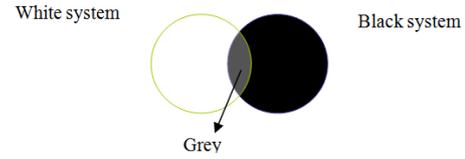


Figure 3. Grey system

$$Z_{ij} = \frac{\max(Y_{ij}) - Y_{ij}}{\max(Y_{ij}) - \min(Y_{ij})} \quad (\text{lower-the better}) \quad (3)$$

$$Z_{ij} = 1 - \frac{Y_{ij} - Y_i}{\max(Y_{ij}) - Y_i} \quad (\text{nominal-the-best}) \quad (4)$$

$$Z_{ij} = \frac{Y_{ij} - \min(Y_{ij})}{\max(Y_{ij}) - \min(Y_{ij})} \quad (\text{higher-the-better}) \quad (5)$$

where Z_{ij} is the normalized value for i^{th} experiment for j^{th} response and Y_{ij} is the i^{th} normalized value for j^{th} response.

Thereafter, Eq. 6 is used to calculate Grey Relational Coefficients (GRC) for all the obtained data after normalization.

$$G_{ij} = \frac{\Delta_{\min} + \lambda \Delta_{\max}}{\Delta_{ij} + \lambda \Delta_{\max}} \quad (6)$$

where G_{ij} is the grey relational coefficient for the i^{th} experiment and j^{th} response. While, Δ denotes the absolute difference between Y_{oj} and Y_{ij} . Y_{oj} represents the ideal normalized value of j^{th} response. Moreover, Δ_{\min} and Δ_{\max} are the minimum and maximum values of Δ , respectively. λ is the distinguishing coefficient having between 0 and 1. In this study, the value of λ is taken as 0.5. After calculating GRC's for each experiment, Eq. 7 is used to calculate Grey Relational Grades (GRG).

$$G_i = \frac{1}{m} \sum G_{ij} \quad (7)$$

where m is the number of responses.

4. RESULTS AND DISCUSSION

4.1 GRA based multi-objective optimization

In the initial phase of GRA, the scattered data was firstly transformed into normalized data by using Eq. 3. Then, grey relational coefficients (GRC's) and grey relational grades (GRG's) have been calculated by using Eq. 6 & 7 and tabulated in Table 4. The variation of GRG's for all experimental run is shown in Fig. 4. The optimum levels of laser cutting parameters have been identified by calculating the difference of maximum and minimum average GRG for each parameter. From Table 5 it has been observed that optimum levels of input parameters are at lower levels of pulse width, standoff distance and air pressure; the medium level of lamp current and higher levels of cutting speed i.e. $I = 200$ A, $PW = 2$ ms, $SOD = 1$ mm, $P = 8$ kg/cm² and $S = 200$ mm/min. From this analysis, it has been observed that SOD is the most influential parameter for both TKD and BKD.

Table 4: Calculated Normalized values, Deviational sequence, GRC, and GRG

Exp. No.	Normalization		Deviational sequence		GRC		GRG
	TKD	BKD	TKD	BKD	TKD	BKD	
1	0.276	0.836	0.723	0.163	0.408	0.753	0.580
2	0.878	0.248	0.121	0.751	0.804	0.399	0.602
3	0.422	0.844	0.577	0.155	0.464	0.763	0.613
4	0.768	0.351	0.231	0.648	0.683	0.435	0.559
5	0.936	0.565	0.063	0.434	0.886	0.535	0.710
6	0.735	0.783	0.264	0.216	0.654	0.698	0.676
7	0.729	0.829	0.270	0.170	0.648	0.745	0.697
8	0.267	0.842	0.732	0.157	0.405	0.760	0.583
9	0.316	0.574	0.683	0.425	0.422	0.540	0.481
10	0.787	0.462	0.212	0.537	0.701	0.482	0.591
11	0.896	0.473	0.103	0.526	0.828	0.487	0.657
12	0.188	0.048	0.811	0.951	0.381	0.344	0.362
13	1.000	0.000	0.000	1.000	1.000	0.333	0.666
14	0.544	0.975	0.455	0.024	0.523	0.954	0.738
15	0.410	0.847	0.589	0.152	0.458	0.765	0.612
16	0.562	0.382	0.437	0.617	0.533	0.447	0.490
17	0.920	0.884	0.079	0.115	0.863	0.812	0.837
18	0.562	0.598	0.437	0.401	0.533	0.554	0.543
19	0.826	0.120	0.173	0.879	0.742	0.362	0.552
20	0.756	0.364	0.243	0.635	0.672	0.440	0.556
21	0.796	0.932	0.203	0.067	0.710	0.880	0.795
22	0.623	0.971	0.376	0.028	0.570	0.946	0.758
23	0.775	1.000	0.224	0.000	0.689	1.000	0.844
24	0.851	0.657	0.148	0.342	0.770	0.593	0.681
25	0.495	0.458	0.504	0.541	0.497	0.480	0.488
26	0.000	0.840	1.000	0.159	0.333	0.758	0.545
27	0.623	0.650	0.376	0.349	0.570	0.588	0.579
28	0.705	0.917	0.294	0.082	0.629	0.857	0.743
29	0.857	0.465	0.142	0.534	0.777	0.483	0.630
30	0.528	0.213	0.471	0.786	0.514	0.388	0.451
31	0.556	0.971	0.443	0.028	0.529	0.946	0.738
32	0.586	0.971	0.413	0.028	0.547	0.946	0.746
33	0.574	0.449	0.425	0.550	0.540	0.476	0.508
34	0.310	0.997	0.689	0.002	0.420	0.995	0.707
35	0.854	0.438	0.145	0.561	0.774	0.471	0.622
36	0.382	0.971	0.617	0.028	0.447	0.946	0.696
37	0.610	0.441	0.389	0.558	0.562	0.472	0.517
38	0.638	0.646	0.361	0.353	0.580	0.585	0.582
39	0.702	0.779	0.297	0.220	0.626	0.693	0.660
40	0.598	0.895	0.401	0.104	0.554	0.826	0.690
41	0.671	0.013	0.328	0.986	0.603	0.336	0.469
42	0.914	0.936	0.085	0.063	0.854	0.887	0.871

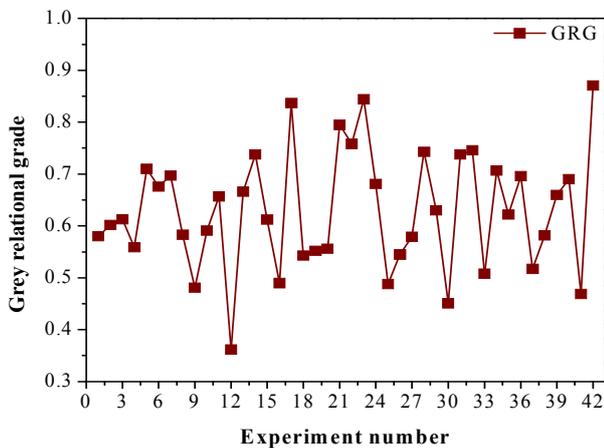


Fig 4: Variation of GRG values for all 42 experiments

Table 5. Average grey relational grade by factor level

Factor	Level 1	Level 2	Level 3	Max-Min	Rank
<i>I</i>	0.6302	0.6598	0.5303	0.1294	2
<i>PW</i>	0.6661	0.6197	0.6198	0.0464	4
<i>SOD</i>	0.6997	0.6289	0.5574	0.1424	1
<i>P</i>	0.6544	0.6203	0.6295	0.0341	5
<i>S</i>	0.6126	0.6185	0.6767	0.0641	3

4.2 Experimental validation

A confirmation experiment has been performed to validate the optimal levels of cutting parameters obtained through employed GRA approach. The parameters were tuned at *I*=200Amp; *PW*=2ms; *SOD*=1mm; *P*=8kg/cm² and *S*=200mm/min.

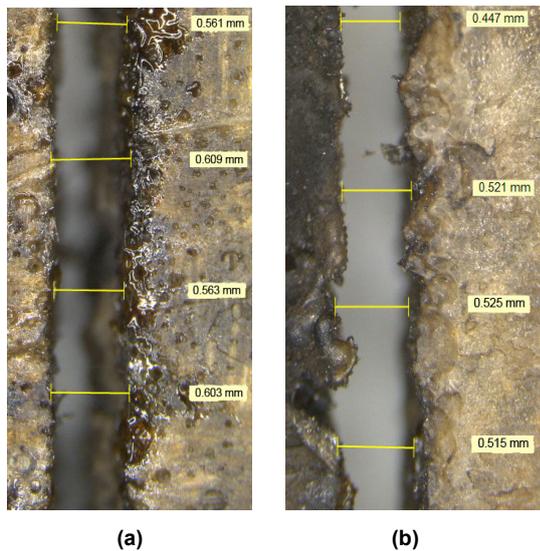


Figure 5. Micrographic images of kerf deviations at optimal setting (a) Top side and (b) bottom side of cut

An overall improvement of 14.50 % has been registered in both responses as compared to the initial experimental trial. TKD and BKD are improved by 18.64 % and 10.34%, respectively. Table 7 consists of the results of the confirmation experiment. Figure 5 (a-b) are shown the micrographic images of the top and bottom side of the cut at optimal parametric settings.

4.3 Parametric effects

Analysis of TKD

Figures 6-8 visually depict the variation of TKD as a function of I - SOD , I - S and SOD - PW respectively. From Fig. 6 it has been observed that TKD decreases with an increase in the value of lamp current, whereas TKD increases with increase in standoff distance. The main reason is behind that with an increase in standoff distance, the diversion of an incident laser beam also increases and affects the higher area during cutting.

It results of higher deviation in the top side of kerf. On the other side, the higher lamp current reduced the value of TKD. Generally, higher lamp current increases the rate of energy absorption by composite surface. But in the present study, the workpiece is fabricated by Kevlar-29 and Basalt fibers, which have higher heat resistant properties. Therefore, deviation in the top side of the kerf decreased with an increase in lamp current. Figure 7 shows that lower values of TKD may be found at higher values (175-200 mm/min) of cutting speed and medium values (190-210 A) of the lamp current. It is a well-known fact that higher cutting speed reduces the kerf widths due to minimizing the contact time between

the incident laser beam and composite surface. Moreover, Eq. 1 & 2 are also express that top and bottom kerf deviations are the function of top and bottom kerf widths.

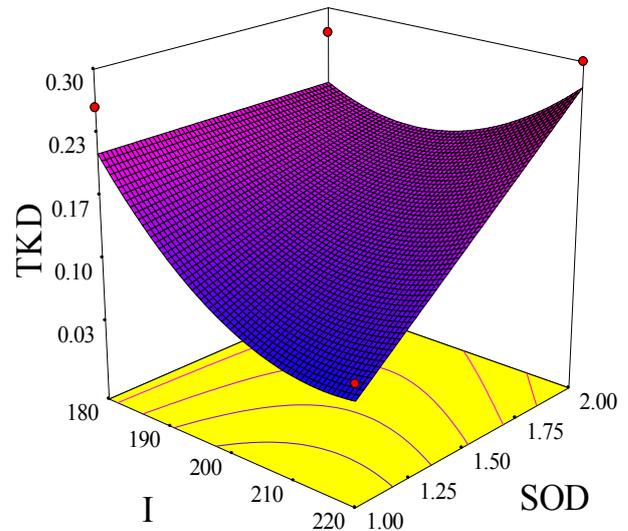


Figure 6. 3-D Surface plot for variation of TKD as a function of I and SOD

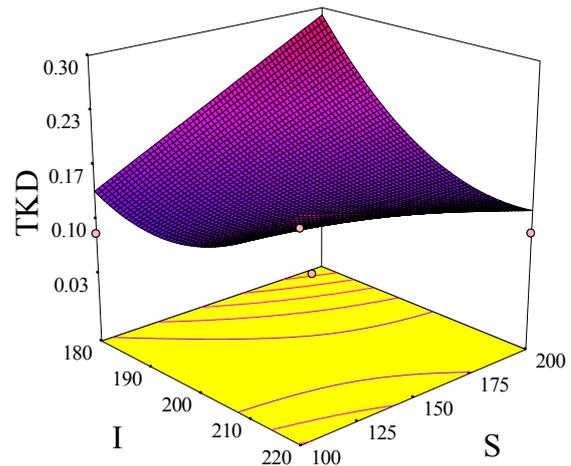


Figure 7. 3-D Surface plot for variation of TKD as a function of I and S

The combined effect of standoff distance and pulse width on the top kerf deviation is shown in Fig. 8. From Fig. 8 it has been found that lower values of TKD can be achieved at lower values of standoff distance and pulse width. Figure 9 (a-b) visually depicts the micrographical images of top and bottom kerf deviations at higher settings of lamp current, pulse width and medium settings of standoff distance, air pressure and cutting speed.

Table 7: Confirmation Tests Results

S. No.	Kerf quality characteristics	Experimental value		GRA technique		% Improvement
		Setting	Experimental values	Optimum Setting	Experimental values	
1	TKD	I = 200 Amp; PW = 2 ms; SOD = 1 mm; P = 10 kg/cm ² ; S = 150 mm/min	0.059	I = 200 Amp; PW = 2 ms; SOD = 1 mm;	0.048	18.64
2	BKD		0.087	P = 8 kg/cm ² ; S = 200 mm/min	0.078	10.34

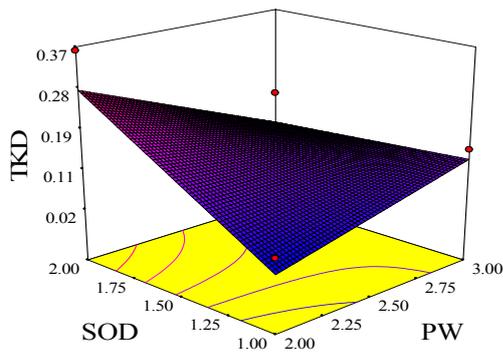


Figure 8. 3-D Surface plot for variation of TKD as a function of SOD and PW

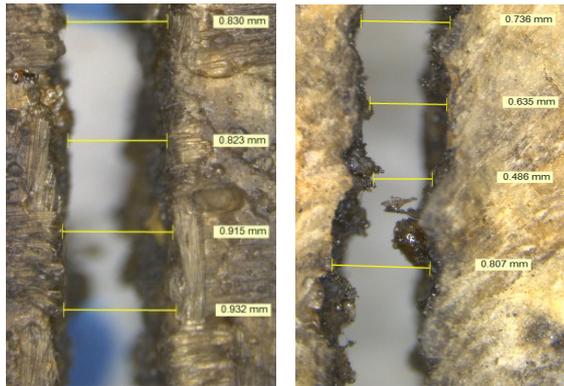


Figure 9 (a-b). Micrographic images of kerf deviations at I at 220 Amp, PW at 3 ms, SOD at 2 mm, P at 10 kg/cm^2 and S at 150 mm/min (a) Top side and (b) bottom side of cut

Analysis of BKD

In the laser cutting of hybrid composite laminate, it has been observed that the effect of process parameters is different for both kerf deviations. Figures 10-13 show the variation of BKD due to the combined effects of S - P , P - I , S - SOD and PW - I respectively.

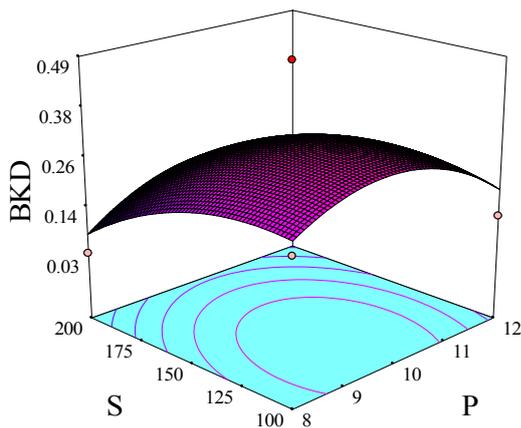


Figure 10. 3-D Surface plot for variation of BKD as a function of S and P

It has been observed from Fig. 10 and 11 that BKD decreases with sink in the value of compressed air pressure. Lower air pressure provides sufficient time to burn fibers of the composite. Thereby, the deviation is less at the bottom side of the cut. At this stage, the thermo-mechanical properties of different constituents fibers such as Kevlar-29, basalt and glass of the hybrid composite play an important role to decide the quality of

cut. The increment in cutting speed (100-200 mm/min) and decrement in lamp current (180-220 Amp) tries to decrease the kerf deviation at the bottom side of the cut.

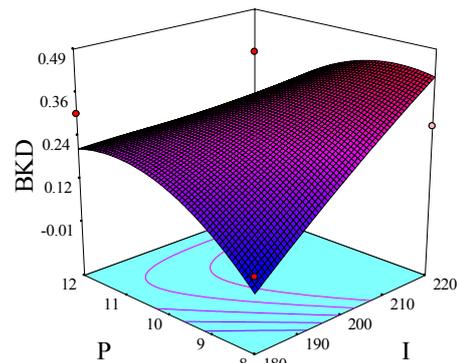


Figure 11. 3-D Surface plot for variation of BKD as a function of P and I

Figure 12 shows that the kerf deviation at the bottom side of cut increases with an increase in the value of standoff distance (1-2 mm), whereas BKD reduces with decrease in pulse width and lamp current shown in Fig. 13. Irregular cuts and shapes have been observed at the bottom side of the composite laminate due to the distinct properties of constituent fibers used in the hybrid composite laminate. Moreover, the viscosity of matrix phase or epoxy resin also affected the quality of laser cut. Figure 14 (a-b) shows the droplets of epoxy resin deposited at the bottom side of the cut.

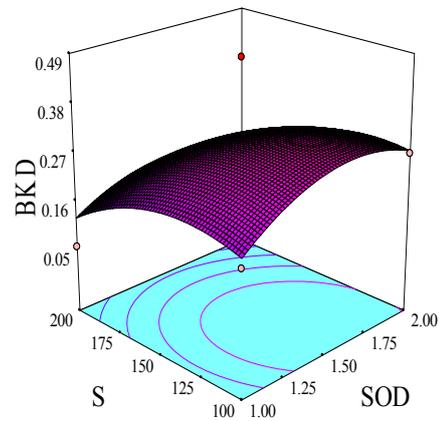


Figure 12. 3-D Surface plot for variation of BKD as a function of S and SOD

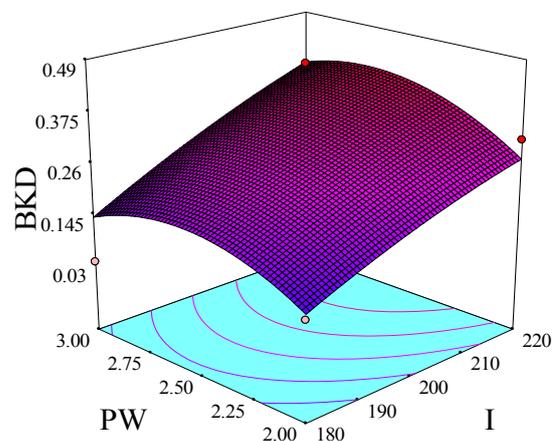


Figure 13. 3-D Surface plot for variation of BKD as a function of PW and I

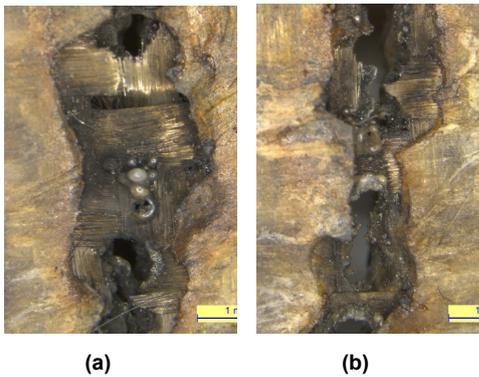


Figure 14 (a-b). Deposited epoxy resin

5. CONCLUSION

In the study, an attempt has been made to cut a 2.34 mm thick Kevlar-29, Basalt and Glass fiber based hybrid FRP composite laminate by using a pulsed Nd:YAG laser beam. Grey relational analysis has been employed for the single index optimization of top and bottom kerf deviations. Following conclusions are drawn from this study:

1. Hand layup technique has been successfully employed to fabricate a hybrid composite laminate with three different fibers as reinforcement.
2. Geometrical quality of laser cut has been quantified in terms of the top kerf deviation (TKD) and bottom kerf deviation (BKD).
3. A grey relation analysis approach has been used for a single index optimization of multiple kerf quality characteristics.
4. The optimum setting of laser cutting parameters has been obtained by employed GRA approach are lamp current at 200 Amp; pulse width at 2 ms; standoff distance at 1 mm; compressed air pressure at 8 kg/cm² and cutting speed at 200 mm/min.
5. The top and bottom kerf deviation have considerably improved up to 18.64 % and 10.34 %, respectively at the optimum combination of laser parameters. Moreover, an overall improvement of 14.50 % in responses was registered by employed GRA technique.
6. In this study, it was also observed that the specific properties of constituent fibers with polymer matrix phase have also significantly affected the kerf deviations at the top and bottom side of the cut.

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**ОПТИМИЗАЦИЈА ОДСТУПАЊА РЕЗА КОД
РЕЗАЊА ПУЛСНИМ Nd:YAG ЛАСЕРОМ
ХИБРИДНОГ КОМПОЗИТНОГ ЛАМИНАТА
ПРИМЕНОМ GRA**

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Циљ истраживања је одређивање оптималног нивоа главних параметара резања ласером у циљу постизања прецизне и квалитетније геометрије резања при резању новог хибридног FRP композитног ламината на бази базалта, стакла и кевлара 29. Извршено је укупно 42 експеримента са ламинатом дебљине 2,34 мм применом пулног Nd:YAG ласера са напајањем од 250 W. Извор светла, ширина импулса, растојање од материјала, притисак компримованог ваздуха и брзина резања су одабрани за променљиве параметре ласерског резања. Применом греј релационе анализе издвојен је индекс оптимизације истовремено за горњи и доњи део реза. Валидација оптималних решења је извршена упоређивањем резултата експеримената, при чему је утврђено значајно побољшање. Такође је утврђено да је растојање од материјала најутисајнији параметар код одступања како горњег тако и доњег дела реза.