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Analysis and optimization of machining parameters of laser cutting for polypropylene composite

A Deepa, K Padmanabhan and P Kuppan
School of Mechanical Engineering, VIT University, Vellore - 632014, Tamil Nadu, India.

E-mail: deepa.a@vit.ac.in

Abstract. Present works explains about machining of self-reinforced Polypropylene composite fabricated using hot compaction method. The objective of the experiment is to find optimum machining parameters for Polypropylene (PP). Laser power and Machining speed were the parameters considered in response to tensile test and Flexure test. Taguchi method is used for experimentation. Grey Relational Analysis (GRA) is used for multiple process parameter optimization. ANOVA (Analysis of Variance) is used to find impact for process parameter. Polypropylene has got the great application in various fields like, it is used in the form of foam in model aircraft and other radio-controlled vehicles, thin sheets (~2-20μm) used as a dielectric, PP is also used in piping system, it is also been used in hernia and pelvic organ repair or protect new herrnis in the same location.

1. Introduction

A composite is the mixture of two or more material which may or may not be similar and have distinct interface between them resulting into the superior property of the materials used. There are two phases, discrete and continuous, discrete phase is distributed into continued one. In self-reinforced composite discrete and the continuous phase is same. The properties, geometry and architecture of the constituent element decide the property of the material. They are classified on the basis of physical and chemical properties of matrix phase, for example polymer matrix, ceramic matrix and metal matrix. They are also classified on the basis of reinforced material into particle, short fibre, and continuous fibre.

Self-reinforced composites are a new family of composite material, where the polymer matrix is reinforced by highly oriented polymer fibres. The basis of all SRPC techniques is to set a suitable processing window, which exploits the difference in the melting temperature (Tm) of the reinforcement and the matrix. The wider the processing window, cheaper the processing can be. This temperature difference can be widened in various ways, such as using fibres of different orientation [1]. Fibre-reinforced plastic is a composite material comprising a polymer matrix reinforced with fibres. The fibres are usually fibre glass, carbon, or aramid, while the polymer is usually a thermosetting plastic.

Optimisation of roughness and removal rate have been performed earlier[2] and [3] on mild steel using taguchi method in advance machining process i.e. laser cutting, by this we come to know about the smoothness of material after laser cutting. Investigation of Multi-Objective optimisation of various laser cutting parameters [4] was done which gave the various parameters of laser like power, pressure, machining speed, etc. used in machining process; this helped in selecting the appropriate parameter for laser cutting.

1.1. Laser Machining:

Laser machining involves laser for cutting purpose, beam is generated by stimulating a lasing material by electric discharge or lamps within closed container, and it is reflected internally and escapes as a beam of monochromatic light. This is unconventional way of machining. Depending upon the material thickness kerf width could be as small as 0.004 inches. The parallel ray of laser light often ranges from 0.06-0.08 inches. In the present work the considered parameters are the laser power and maching speed of CO_2 laser. Advantage of using laser machining is it has easier work holding as compared to other mechanical devices. It also gives smooth finish to the material. After cutting this process have heat affected zone, which may slightly vary the material property, variation in the temperature was analysed [3] using taguchi method, which shows that there are few mechanical properties which changes after the machining using laser.

2. Literature Review

Polypropylene [PP] has relatively slippery i.e. “low energy surface” that means that many common glues will not form adequate joint. The additionally present methyl group improves mechanical properties and increase the thermal resistance, but chemical resistance decreases, the properties depend on the molecular weight and its distribution. Thermal expansion of polypropylene is very large [5]. PP has the property of anisotropy and is non-homogeneous and hence they are difficult to machine using traditional machining methods. Teti explains about the basic introduction to composites and their classifications like PMC, MMC, CMC composites and problems faced during their machining and the influence of various cutting tools in
their machining and the different tool wear mechanisms arises during machining of each type which depends on fibre orientation and volume fraction of both matrix and reinforcement phases, these two strongly determine the strength and mechanical properties of composites [6]. The problems are mainly due to their non-homogeneity and orientation of fibres. Morgan, Weager, Hare and Bishop [2009] studied about the SRPC and aimed at achieving the efficient and cost-effective manufacturing process while maintaining the highest mechanical properties the material can offer. Hot Compaction is a method by which highly oriented polymer tapes are very accurately heated [±0.5°C]. This heating allows approximately 10% of the polymer tapes to melt. With the application of pressure this molten polymer flows throughout the lattice work of tapes to form a continuous matrix. The sheet is then cooled while still under pressure to solidify the matrix.
The properties of the phases used may vary and makes difficulty in machining [7]. The energy required to melt the fibre or to vaporize them is higher to that require to melt or vaporize polymer matrix and also thermal conductivity of fibre is very much higher than polymer matrix. The temperature distribution across the depth of the work-piece that is machined using Laser assisted machining [LAM] is studied. Ti-6Al-4V alloy is the material considered for this, because Titanium alloys has a wide range of applications in automotive as well as aerospace industries. They have high strength to weight ratio and can withstand heavy temperatures. Due to its high strength, conventional machining is low productivity process. At particular values of laser power, scanning speed and spot size the alloy will reach its melting-point; hence those values are not desirable for LAM. This result help in selecting the optimum laser parameters for LAM.The application of the CO_2 laser cutting process for polyethylene [PE] in different thicknesses ranging from 2 to 10 mm are investigated. Laser power, cutting speed, type of focussing lens, pressure and flow of the covering gas, thickness of the samples are the process parameters examined. Kerf widths, melted transverse area, the melted volume with time and the surface roughness on the cutting edges were parameters measured. Optimisation of parameters was done using Taguchi method, analysis done using main plots and ANOVA.

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3. Experimental Detail

3.1 Work Material

Polypropylene matrix and fibre sheets are taken in the sizes of 50cmx50cm. For each set of sample preparation three reinforcements and two matrix sheets are used and reinforcements are placed in between the matrix sheets of following properties shown in Table 1.

Table 1. Properties of Polypropylene.

Property	Value
Density(g/cm^3)	0.910
Melting point(°C)	160
Modulus of Elasticity(GPa)	0.9-1.1
Electrical Resistivity(Ω/Cm)	10^{16}-10^{18}
Co-efficient of Thermal Expansion(M/M·°C)	72-90

3.2. Experimental Setup and Experimental Procedure

The final fabricated sheet has properties better than those of individual components. The fabrication method used for Self-reinforced composites is hot compaction method in which the commercially available polypropylene sheet and fibre material are taken and cut in to required dimensions i.e. 500mm x 500mm. Sandwiching is done layer by layer as shown in figure 1.

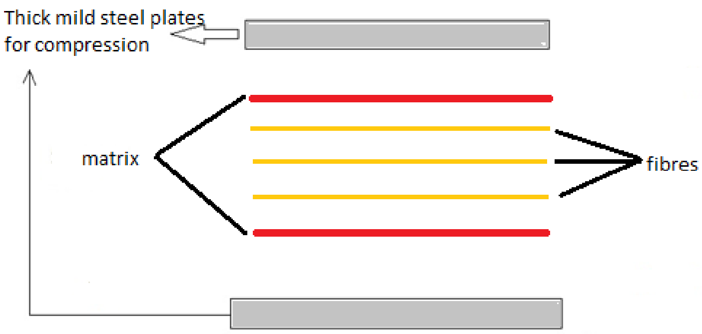

Figure 1. Stacking Sequence

The whole arrangement is kept inside the electric oven and heated till 190°c and waited for one hour exactly, and then the setup is allowed to cool for 16-18 hours. Later it is taken out. The edges are machined for proper dimensions and to achieve even composition of matrix and fibre edges. The specimens are machined using LAM [Laser assisted machining] having parameters shown in Table 2. Specimens were machined according to ASTM standards as mentioned in Table 3.Tensile, flexural tests and hardness tests were done and mechanical properties were obtained.

Table 2. Experimental Setup Details.

Machine Parameters	Value
Machine Type	LASER
Machine Power used	1000 W
Material	Polypropylene
Material Thickness	2mm
Type of Gas	Co2
Nozzle Diameter	1.7mm
Lens Focal Length	7.5”
Nozzle Stand Off	0.60mm

Table 3. Codes and Standards of Specimen.

Type of test	Standard and Code	Specimen dimensions(mm)	Parameter obtained
Tensile test	ASTM D3039	Length=250,Width=25& Thickness=2	Tensile Strength
Bending test	ASTM D790	Length=125,Width=25& Thickness=2	Flexural Strength

3.3. Machining parameters and their levels of machining

Selecting the machining parameter for the laser was one of the very important steps; improper selection may result into damage of work piece or many other problems. As the machining speed and power both are one of the very important factors to be considered while machining, whereas gives good surface finish. The problem of parameter selection does not completely depend on the machining controls rather it also depends on the material used. The selected parameter and their levels are shown in Table 4.

Table 4. Process Parameters and their Levels.

Symbol	Control Factor	Level 1	Level 2	Level3
B	Power(W)	800	900	1000
A	Speed(mm/min)	360	420	480

4. Analysis of Results

The specimens were machined using Laser cutting by varying machining parameters like machining speed and laser power. Specimens were machined according to ASTM standards. Tensile, Flexural and Shore Hardness tests were performed.

Table 5. Polypropylene experimental Results.

Specimen Number	Machining Speed (mm/min)	Laser Power (W)	Hardness	Maximum Flexural Stress(Mpa)	UTS (GPa)
PPL-1	360	800	44.17	42.32	0.017

PPL-2	360	900	42.67	38.87	0.014
PPL-3	360	1000	42.83	33.19	0.016
PPL-4	420	800	44	32.26	0.018
PPL-5	420	900	41.17	30.33	0.02
PPL-6	420	1000	39.5	23.26	0.021
PPL-7	480	800	44.67	45.1	0.021
PPL-8	480	900	44.83	44.33	0.022
PPL-9	480	1000	41.83	40.16	0.022

Table 6. Signal to Noise Ratio Results.

Specimen Number	Machining Speed (mm/min)	Laser Power (W)	Signal to Noise Ratio		
			Hardness	UTS (GPa)	Maximum Flexural Stress (Mpa)
PPL-1	360	800	32.9025	-35.3910	32.5309
PPL-2	360	900	32.6025	-37.0774	31.7923
PPL-3	360	1000	32.6350	-35.9176	30.4201
PPL-4	420	800	32.8691	-34.8945	30.1733
PPL-5	420	900	32.2916	-33.9794	29.6374
PPL-6	420	1000	31.9319	-33.5556	23.7722
PPL-7	480	800	33.0003	-33.5556	33.0835
PPL-8	480	900	33.0314	-33.1515	32.9340
PPL-9	480	1000	32.4298	-33.1515	32.0759

Hardness, UTS and Maximum Flexural Stress for each factor i.e. machining speed and Laser power at each level i.e. level 1, level 2 and level 3 was obtained and results were summarized in Table 5. The quality investigated in the study was "Larger-the-better'' owing to the fact that high surface hardness, UTS and maximum flexural stress represents material with good mechanical properties as mentioned in Table 6.

4.1. Main Effects Plots

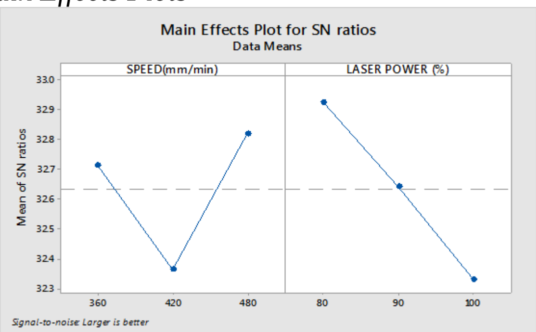

Figure 2. Hardness (PP)

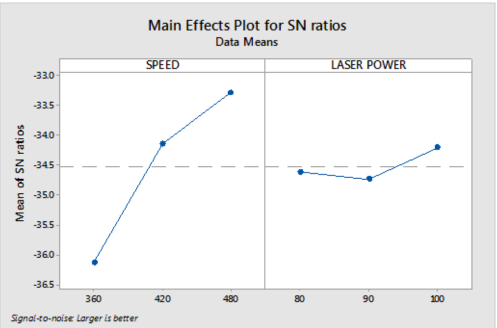

Figure 3. UTS (PP)

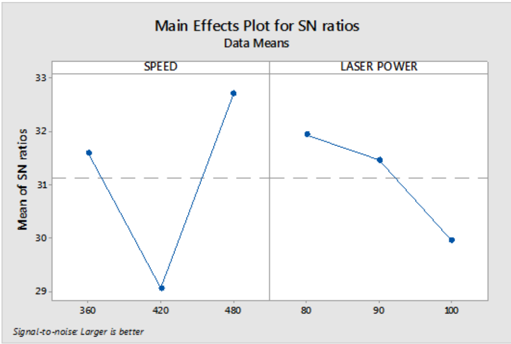

Figure 4. Main Effects Plot for Maximum Flexural Stress (PP)

Figure2 shows the combination of laser parameters and their level A_3B_1 yields the optimum quality characteristic i.e. cutting speed of 480 mm/min and laser power of 800W gives optimal hardness of the material. Figure3 shows the level A_3B_3 i.e. machining speed of 480 mm/min and laser power of 1000W gives optimal UTS for the material. Figure 4 shows the level A_3B_1 i.e. machining speed of 480 mm/min and laser power of 800W gives optimal maximum flexural stress for the material.

4.2. Results of ANOVA

Table 7. Hardness Anova Results.

Source	DF	Adj SS	Adj MS	% Influence
Speed(Mm/Min)	2	8.012	4.006	31.53
Laser Power (%)	2	12.56	6.282	49.43
Error	4	4.848	1.201	
Total	8	25.42		

Table7 shows the results of ANOVA for hardness. The percentage contribution of each parameter was calculated. It can be seen from the table that the percent contribution of the parameter i.e. Laser power to hardness is maximum (49.43%). The percentage contribution of speed is 31.53%. Thus, based on, ANOVA analysis the optimal combination of laser parameters is A_3B_1 i.e. machining speed of 480 mm/min and laser power of 800W.

Table 8. UTS Anova Results.

Source	DF	Adj SS	Adj MS	%Influence
Speed(Mm/Min)	2	0.000056	0.000028	84.8
Laser Power (%)	2	0.000002	0.000001	3.04
Error	4	0.000008	0.000002	
Total	8	0.000066		

Results of ANOVA from Table8, shows that the percentage contribution of speed is maximum (84.84%). The percentage of laser power is very less (3%). Thus, based on ANOVA analysis the optimal combination of laser parameters is A_3B_3 i.e. machining speed of 480 mm/min and laser power of 1000 W.

Table 9. Maximum Flexural Stress Anova Results.

Source	DF	Adj SS	Adj MS	%Influence
Speed(mm/Min)	2	328.721	164.361	76.4
Laser Power (%)	2	95.148	47.574	22.11
Error	4	6.391	1.598	
Total	8	430.260		

Table 9 predicts the results of ANOVA for maximum flexural stress. It is observed that the percentage contribution of speed is more (76.39%). The percentage of laser power is less (22.11%). Thus, based on ANOVA analysis the optimal combination of laser parameters is A_3B_1 i.e. machining speed of 480 mm/min and laser power of 800 W.

4.3. Multi Objective Optimization Using Grey Relational Analysis

In our case, the problem has three performance characteristics that need to be maximized by choosing appropriate processing conditions. They are: Shore D Hardness, UTS and Maximum Flexural Stress. In such cases, the problem is converted into a single objective problem using grey relational analysis. The grey relational analysis deals with ranks and not with real value of the grey relational grade.

4.3.1. Formulation of the Problem

The response values from the experiment are converted to signal to noise ratio values, analysis is done on these S/N ratio values. Hardness, UTS and Maximum Flexural Stress are all larger the better performance characteristic, the optimized qualitative characteristic of interest is estimated and expressed as

$$\text{S/N Ratio}= -\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}} \text{.............} \quad (1)$$

Where y_{ij}= noticed response values

i=1, 2 ...up to n; j=1, 2 ...up to k

n= number of replica

During grey relational analysis, to streamline the raw data for investigation, data processing is implemented first. Normalization means transforming single data input evenly and scale it to a standard range. In this analysis, linear rationalisation of S/N ratio is done from 0 to 1. Y_{ij} is interpreted as Z_{ij} by using the equation to elude the effect of nullifying different values and to reduce the impact of variability.

$$Z_{ij} = \frac{y_{ij} - Miny_{ij}}{Maxy_{ij} - Miny_{ij}} \dots\dots\dots\dots\dots .(2)$$

The above normalization equation is applied for larger-the-better comparison.

The estimation of GRC is done to express the relationship between the optimal and actual streamlined experimental results. The GRC is expressed as

$$\gamma\big(x_o(k), x_i(k)\big) = \frac{\Delta min + \varepsilon\Delta max}{\Delta_{0i}(k) + \epsilon\Delta max} \dots\dots\dots\dots .(3)$$

X_o (k) represents the response progression, whereas x_o (k) is considered to be unity, k=1, 2, up to m; x_i (k) represents the precise correlation.

Equal weightage is given all parameters considered in this analysis, hence ε (Distinguishing coefficient) value is considered as 0.5.

Grey Relational Grade (GRG) is carried out for each performance distinctive by taking mean of corresponding GRC values. The GRG can be represented as:

$$\gamma(x_{0,}x_i) = \frac{1}{m}\sum_{i=1}^{m}\gamma(x_o(k), x_i(k)) \dots\dots\dots\dots(4)$$

Where j is the component of the GRG for the j^th analysis and k represents the number of executed characteristics. GRG approach derives a single response optimization solution for a multi response situation using this objective.

4.3.2. Grey Relational Analysis Results

Table 10. GRG Values for PP Samples.

Specimen Number	Speed (mm/min)	Laser Power (W)	Hardness	GRC UTS (GPa)	Maximum Flexural Stress(Mpa)	GRG
PPL-1	360	800	0.361594	0.53789	0.356146	0.418543
PPL-2	360	900	0.450486	1	0.392005	0.614164
PPL-3	360	1000	0.4388	0.628597	0.482204	0.516534
PPL-4	420	800	0.369717	0.473473	0.503022	0.448737
PPL-5	420	900	0.604486	0.387862	0.555054	0.515801
PPL-6	420	1000	1	0.357892	1	0.785964
PPL-7	480	800	0.33974	0.357892	0.333333	0.343655
PPL-8	480	900	0.333333	0.333333	0.339212	0.335293
PPL-9	480	1000	0.524746	0.333333	0.377414	0.411831

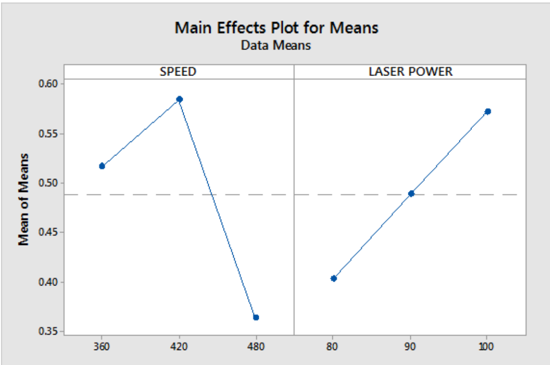

Figure 5. Main Effects Plot for GRG

Table10 shows the combination of laser parameters and their level A_2B_3 yields the optimum quality characteristic as predicted in figure5. i.e. Machining speed of 420 mm/min and laser power of 1000W gives optimal mechanical properties of the material.

5. Conclusion

Level A_3B_1 yields the optimum quality characteristic i.e. machining speed of 480 mm/min and laser power of 800W gives optimal hardness of the material as the difference of hardness values of orthogonal array for A_3B_1 and A_3B_2 after normalization is negligible. Level A_3B_3 yields the optimum quality characteristic i.e. machining speed of 480 mm/min and laser power of 100W gives optimal UTS of the material. Level A_3B_1 yields the optimum quality characteristic i.e. machining speed of 480 mm/min and laser power of 800W gives optimal maximum flexural stress of the material. Level A_2B_3 yields the optimum quality characteristic i.e. machining speed of 420 mm/min and laser power of 1000W gives optimal mechanical properties of the material.

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