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Laser Cutting of HDPE Nano Clay Composites Polymers

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Abstract

This paper presents an experimental study into the influence of the laser beam cutting parameters on the surface quality for HDPE nano clay composites polymer. The main cutting parameters are laser beam, cutting speed and the ratio of nano clay composites polymer. The surface quality are metal removal rate, heat affected zone, kerf width and dross. Thermo-gravimetric analysis (TGA),Dynamic mechanical thermal analysis (DMTA)and Shore D Hardness tests are performed to assess the stability of HDPE nanoclay composites .Experiments are carried out according to Taguchi method and the results are explained according to grey relational method .Best cutting conditions are determined. Results revealed that the beneficial effect of adding nanoclay composites into HDPE polymer.

Keywords: Laser beam. Nanoclay composites, Kerf width. Dross, Heat affected zone Metal removal rate, HDPE.

1. Introduction

Several attempts have been made to study the performance characteristics of cutting polymers by laser beam as follows:

Zhou and Mahdavian [1] studied the effect of laser power and cutting speed on the cutting depth when cutting polymethylmethacrylate (PMMA) by using CO_2 laser. It was found the effect of cutting speed has more significant on cutting depth than laser power and the cutting depth decreasing exponentially with cutting speed. Also, it was that a single optimized set for the input cutting parameters is not always at high laser beam power. F. Caiazzoa et al. [2] examined the effect of laser beam power, cutting velocity, focusing lens, assistant gas pressure and workpiece thickness on the certain performance characteristics ,kerf widths, the melted transverse area, the melted removal rate and surface roughness for three polymeric materials, polyethylene (PE), polypropylene (PP), and polycarbonate (PC) using CO_2 laser. It was found the single optimized set for the input cutting parameters is not always at high cutting velocity and high laser beam power. Also, cutting speed has proved to be more significant when cutting plastic than those found when cutting the ferrous and nonferrous metals. Furthermore, the degree of polymer ability to operate using CO_2 laser cutting for the three types of polymer was arranged respectively: polycarbonate (PC) high, polypropylene (PP) medium-high, and polyethylene (PE) lower.

Al-Sulaiman et al. [3] studied cutting capability to cutting carbon/carbon multi-lamelled plain-weave structure using CO_2 laser beam. They found that the kerf width was significantly affected by laser power and particles orientation. Also, the heat generated also transmits with the direction of the fiber. Davim et al. [4] estimated the effect of cutting speed and laser power on surface roughness, dimensional accuracy and heat affected zone (HAZ) for two-dimensional irregular polymethylmethacrylate. It was found that the heat affected zone (HAZ) increases with increase of laser power but decreases without any dross in the cutting bottom with increase of cutting speed. While, the surface roughness increase with a decrease of laser power and increase of cutting speed. In another study *Davim* et al. [5] investigated the effect of laser processing parameters on HAZ and burr characteristics of PMMA, PC, PP and thermoset plastics. The considered input parameters are laser power, cutting speed and assist gas pressure, were varied randomly resulting in a total of 59 experiments. The HAZ for all three types of polymers exhibit similar pattern as the earlier study suggested [4]. They observed that laser cutting workability of PMMA was very high, PC was high, PP was medium and reinforced thermoset plastic was low. Herzog (2008) et al. [6] showed that the both of heat effects and static strength were significantly affected by the Nd: YAG and CO_2 laser tube.

Lau et al. [7] showed that the laser beam and electric discharge (ED) machining have effective tool in cutting composite materials over than many nontraditional machining methods. The greater depth of cut can be obtained by increasing the pulse energy during pulsed Nd-YAG laser cutting of metal matrix composites, carbon fibre composites and ceramic composites. It was found the material removal rate (MRR) was faster in pulsed Nd-YAG laser beam than the electric discharge (ED). Also they proved that the excimer laser better than the Nd-YAG laser in case of surface damage.

Eltawahni et al. [8] examined the effect of laser beam power, feed speed and focal point position on upper and lower kerf width and surface roughness when cutting Ultra-high-molecular-weight polyethylene (UHMWPE) using CO_2 laser. It was found the upper and lower kerf width ratio was significantly affected by the three input cutting parameter. Also found the best surface roughness when located the laser focal point at a distance from the surface is equal to half the thickness of the cut material. Their results confirmed the influence of input factors on the ratio between upper kerf and lower kerf. It was also proved that the best surface quality could be obtained when the focal point is located in middle of the work piece thickness.Riveiro et al. [9] studied the effect of laser cutting parameter namely continuous wave and pulse mode on the output performance characteristics namely surface quality and heat affected zone (HAZ) when cutting carbon fiber reinforced plastics (CFRP) by using CO_2 laser beam. It was found the surface quality improved when used continuous wave mode and the heat affected zone (HAZ) decrease by reduce the power and increasing cutting velocity.

Chuan and Choudhury [10] studied the effect single and multiple pass modes on glass fibers reinforced polyester when cutting by CO_2 laser. It was found the surface quality improved when apply single pass mode and the kerf width was least possible width when apply multiple pass mode.

Schneider et al. [11] proved that when decreasing time between passes in multiple pass modes the heat affected zone (HAZ) intensity will increase during cutting fiber reinforced thermoplastic polymers. M.M.Noor et al. [12] studied the effect of laser cutting parameter including the laser beam power, cutting velocity and standoff distance on the surface roughness during the machining of acrylic sheets by used 30 watt pulsed CO_2 laser beam. Moreover, Box-Behnken design based on Response surface method (RSM) to minimize the number of experiments and to develop the first and second order regression equation to relate between the input process parameters and the output surface roughness response was employed. It was concluded that the effect of standoff distance has more significant on HAZ than all input cutting parameters, followed by the laser beam power and cutting speed. Some defects such as burning, melting and wavy surface which may causes less strength in the material has been was observed. Choudhurya and Shirley [13] cutting three polymeric materials polypropylene (PP), polycarbonate (PC) and polymethylmethacrylate (PMMA) by CO_2 laser is investigated with the aim of evaluating the effect of the main input laser cutting parameters (laser power, cutting speed and compressed air pressure) on laser cutting quality. The output quality characteristics examined were heat affected zone (HAZ), surface roughness and dimensional accuracy. Twelve sets of tests were carried out for each of the polymer based on the central composite design. Predictive models have been developed by response surface methodology (RSM). First-order response models for HAZ and surface roughness were presented. It was found that the responses models are representing by a linear function. It has been observed that PMMA has less HAZ, followed by PC and PP. For surface roughness, PMMA has better cut edge surface quality than PP and PC.

Although RSM showed some success in formulating the mathematical relationships between multiple input and optimized response variables using a sequence of designed experiments [14, 15] as previously indicated the problem becomes more complicated and challenging if more output parameters are considered with higher number of samples. Additionally, multi-objective optimization techniques have proved useful at determining the optimized set of process parameters by taking into consideration all measured cutting characteristics. For instance, due to limitation of single-objective optimization of Taguchi method, Dubey and Yadava [16] resorted to principal component analysis with orthogonal array to determine the multi-objective optimization of Nd: YAG laser cutting of nickel-based super alloy sheet.

In a different study, Pandey and Dubey [17] combined Taguchi method with fuzzy logic theory to optimize multiple responses. The set of optimized parameters were determined based on the highest fuzzy multi-response performance index.

Grey rational analysis (GRA), as a discrete statistical analysis was proposed by Deng [18], to optimize process parameters based on multiple laser cut quality characteristics of different thermoplastics is employed. Use of GRA was demonstrated useful for multiple-objective optimization in laser joining of similar [19] and dissimilar [20] materials, aimed at achieving high joint strength [21] with reduced HAZ. Since laser cutting is similar to laser joining in nature, GRA has proven to be effective in laser cutting of materials [22-24]. Ayob Karimzad Ghavidel et al. [25] studied the effect of carbon nanotubes on laser cutting of injection molded multi-walled carbon nanotubes/poly methyl methacrylate (MWCNT/PMMA) composite. Also, the influence of processing parameters on laser cutting of MWCNT/PMMA nanocomposites is investigated in this study. Designs of experiments are performed using full factorial method. Variable input factors are considered as MWCNT wt. %, laser power and feed rate. Output parameters are heat affected zone (HAZ), the average kerf width, and the taper kerf of the samples. Continuous wave CO_2 laser is used in the cutting process of the samples. Experiments analysis are performed using analysis of variance method. Regarding the HAZ, results show that the most effective parameters are feed rate and the amount of the carbon nanotubes. High available carbon nanotube percentage causes approximately 50% decrease in the HAZ. Findings also clearly showed that average kerf width is influenced by the three variable input factors. The tapering kerf is also significantly depended on the percentage of the carbon nanotube.

S. Nagesh1et al. [31] studied the effect of two types of Nano fillers, namely carbon black and nickel nanopowder on laser cutting of vinylester/glass nanocomposites. Designs of experiments are performed using orthogonal array technique. Variable input factors are considered as Nano fillers wt. %, constant laser power 400 W, Air pressure and Scan speed. Output parameters are top and bottom kerf widths and the surface roughness. Continuous wave CO_2 laser is used in the cutting process of the samples 3 mm thick. Experiments analyses are performed using grey relational analysis method. It was found the scanning speed was the most influencing factor on the top and bottom kerf widths. Also as scanning speed increase the both of kerf widths reduced. Also was found the surface roughness significantly affected by the addition of Nano fillers. For linear cut profile, it was found the influence of nickel nanopowder was much greater than that of carbon black. For curved cut profile, it was found the Output parameters significantly affected by the Scanning speed for both types of the Nano fillers. Also It was concluded the higher air pressure is preferred for nickel nanopowder, and lower air pressure is preferred for carbon black. And it was found the addition of nickel nanopowder 4 wt % to polymer composite produced uniform distribution of smaller globules of char, and hence, the fibers were fully protected.

According to the above arguments, several studies on cutting polymeric materials by laser beam have been reported in the literatures review. However, cutting nanocomposites polymeric materials is still few and not considered in the literatures [25 and 31]. Therefore, the main target of the present work is to study the ability of cutting nano clay polymeric composites materials by laser beam. The HDPE was selected due to its wide applications all fields of engineering like, biomedical applications; drug delivery system, biosensor devices, tissue engineering, cosmetics etc. The influence of laser beam parameters, laser power and cutting speed, besides the nanoclay ratios on the quality of machined surfaces are investigated. The considered quality of machined surface are metal removal rate, kerf width, heat affected zone and dross. Through Taguchi method the number of experiments was determined and the best cutting conditions were determined by using grey relational analysis (GRA).

2. Experimental Investigations

The experimental work is carried out on high density polyethylene (HDPE) polymer with nanoclay composite materials and fabricated in the sheet form of 3mm thickness. This polymeric material is widely used in the manufacturing industries and has wide applications in optics, vehicles, electrical engineering appliances, office equipment, medicine, air crafts, boats, and sports industries. Also, this material has some problems in especially in cutting with traditional and nontraditional cutting techniques [26, 27].

The engineering plastic polymer High Density Polyethylene (HDPE) is used for preparation of nanocomposites material. Nanoclay of (25-30 wt. % methyl dihydroxyethyl hydrogenated tallow ammonium chloride) was used. The HDPE polymer and Nanoclay materials are mixed by melt blending technique in a bra bender plastic order lab station mixer attached with PL-2000 controller unit as shown in Fig. 1.
The content of nanoclay was 0, 1, 3and 5wt %. In order to produce nanocomposites material (test specimens) sheets, plastic mold with dimension of 175x80x3 mm is used.

Fig.1 Bra Bender Plasticorder device.

Three tests were performed on the specimens. They are:

1- Thermo-gravimetric analysis (TGA).
2- Dynamic mechanical thermal analysis (DMTA).
3- Hardness test.

All experiments were performed using laser machine consisting of a 130W pulsed CO_2 laser (sharp laser cutting machine model CF90) and a two axes CNC-controlled table with work volume 1x1 m as shown in Fig. 2.

Fig.2 Sharp CO_2 Laser Machine

The 16 experiments have been carried out with three input parameters and four levels for each as indicated in Table 1.The number of experiments are determined according to Taguchi method [17,19and28]. The 16 experiments and their actual values are reported in Table2.

Table 1.Cutting parameters and their levels

Factors		Level 1	Level 2	Level 3	Level 4
W	Laser Power (W)	72	84	102	120
S	Speed (mm/sec)	2	4	6	7
N	Ratio of Nano-clay %	0%	1%	3%	5%

The cut quality characteristics of interest in LBC are kerf width (KW), heat affected zone (HAZ), dross inclusion and metal removal rate (MRR) which indicated by Fig.3.

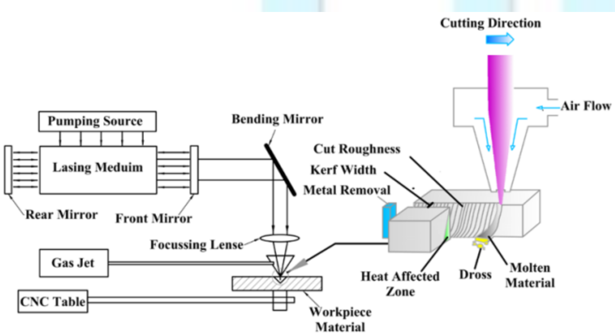

Fig.3 Principale of Laser Cutting and Cutting Zone

The kerf width and heat affected zone measurements were done by used computerized optical microscope of different magnifications Model Nemesis 9500 in the image plane as shown in Fig.4.

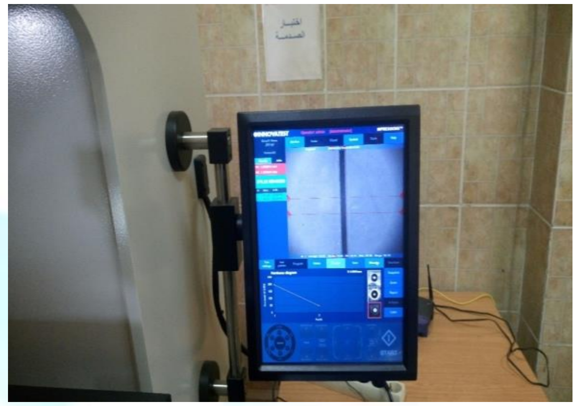

Fig.4 Computerized Optical Microscope Device (Nemesis 9500).

While, the simplest and accurate method for measuring the dross is by using the digital micrometer, type Starrett, Model No. 734.

Table 2 16 Test conditions

	Factors		
	W	S	N
No	Laser Power (Watt)	Speed (mm/sec)	Ratio of Nano-clay %
1	72	2	0
2	72	4	1
3	72	6	3
4	72	7	5
5	84	2	1
6	84	4	0
7	84	6	5
8	84	7	3
9	102	2	3
10	102	4	5
11	102	6	0
12	102	7	1
13	120	2	5
14	120	4	3
15	120	6	1
16	120	7	0

Also, Workpieces are weighted before and after cutting using sensitive balanced instrument with an accuracy of 0.0001g .to determine metal removal rate.

Grey relational analysis is used for optimization of multi performance characteristics. Then overall grey relational grade is determined by averaging the grey relational coefficient corresponding to selected responses [29, 18-20, 22-24, 30]

Table 3 Experimental results for output parameters

	Factors			Experimental results			
	W	S	N				
No	Laser Power (Watt)	Speed (mm/sec)	Ratio of Nano-clay %	MRR (g/min)	KW(mm)	HAZ(mm)	D(mm)
1	72	2	0	0.0840	0.4059	0.1432	0.6990
2	72	4	1	0.2160	0.3648	0.1363	0.1378
3	72	6	3	0.3480	0.3412	0.1701	0.2385
4	72	7	5	0.4560	0.3249	0.1724	0.001
5	84	2	1	0.1080	0.4018	0.1537	0.5328
6	84	4	0	0.2220	0.3915	0.1281	0.1083
7	84	6	5	0.3480	0.3532	0.1939	0.001
8	84	7	3	0.4620	0.4084	0.1527	0.1685
9	102	2	3	0.1260	0.4425	0.2017	0.4745
10	102	4	5	0.2940	0.3990	0.2105	0.001
11	102	6	0	0.3420	0.4075	0.1319	0.1943
12	102	7	1	0.4440	0.4995	0.1434	0.2525
13	120	2	5	0.1680	0.4015	0.2912	0.001
14	120	4	3	0.2580	0.5189	0.2632	0.2595
15	120	6	1	0.4500	0.4786	0.1466	0.2112
16	120	7	0	0.4200	0.3703	0.1258	0.3287

3. Results and Discussion

The results of Thermo-gravimetric (TG) and Dynamic mechanical thermal (DMT) revealed an improving of thermal stability against degradation and improving the dynamic properties (storage modulus). Moreover, an increasing in shore D hardness of about 15.4% was obtained

3.1 Effect of cutting parameters on metal removal rate

Table 3 shows the experimental results of 16 performed tests for output parameters at different cutting conditions.

In order to understand the effect of cutting parameters on metal removal rate for HDPE nano clay composites polymer, it is important to plot the cutting variables

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against the mean value of metal removal rate as shown in Figs. (5-7). From Fig.5&6, it is clearly shown that as the laser power and cutting speed increases the metal removal rate increases. Moreover, Fig.7 shows as the metal removal rate increase as nano clay ratio rose from 0% to 1% and it's dropped up to 3% and increase thereafter.

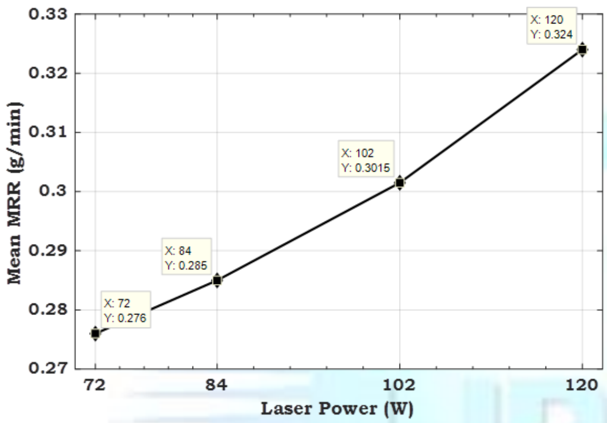

Fig. 5 Effect laser power on metal removal rate

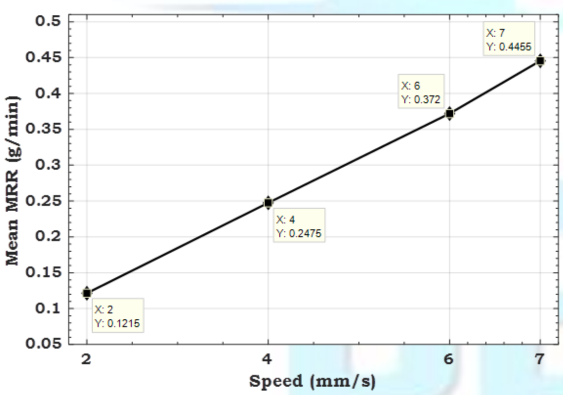

Fig.6 Effect of cutting speed on metal removal rate

3.2 Effect of cutting parameters on kerf width

The relationship between the laser cutting parameters and the resultant kerf width are illustrated in Figs (8-10). From Fig.8, it is clearly shown that the kerf width increase as power rose from 72 W to 102 W and its approximating constant thereafter. Also, from Fig.9, it is clearly shown that the kerf width increase as speed rose from 2 mm/s to 4 mm/s and it's dropped up to 6 mm/s and increase thereafter

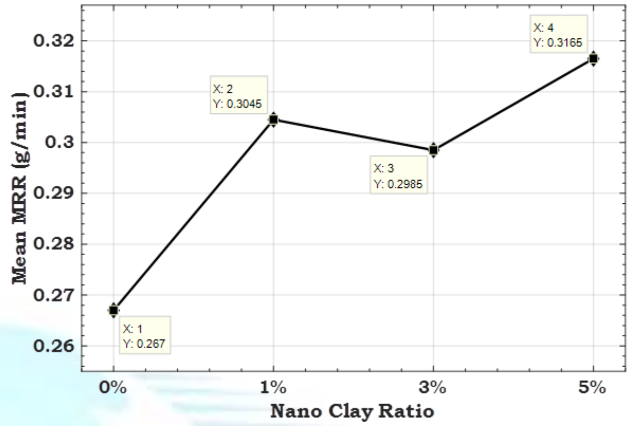

Fig.7 Effect of nano clay ratio on metal removal rate

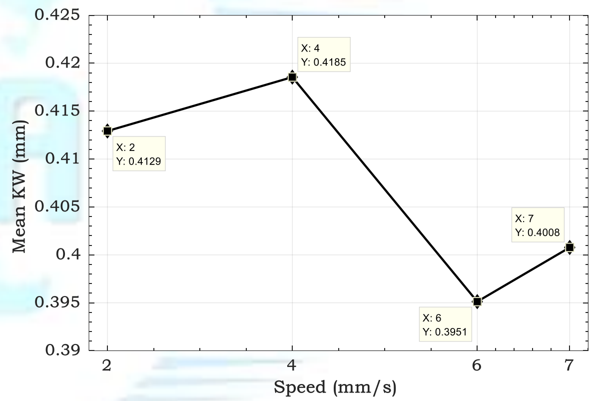

Fig.9 Effect of cutting speed on kerf width

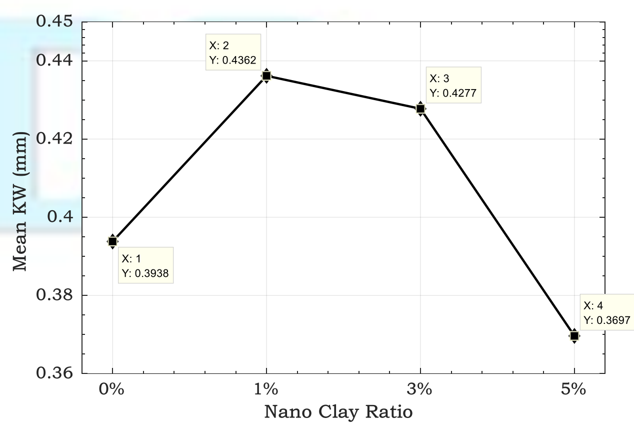

Fig.10 Effect of nano clay ratio on kerf width

Moreover, from Fig.10, it is noticed that the kerf width increase as nano clay ratio rose from 0% to 1% and it's dropped thereafter.

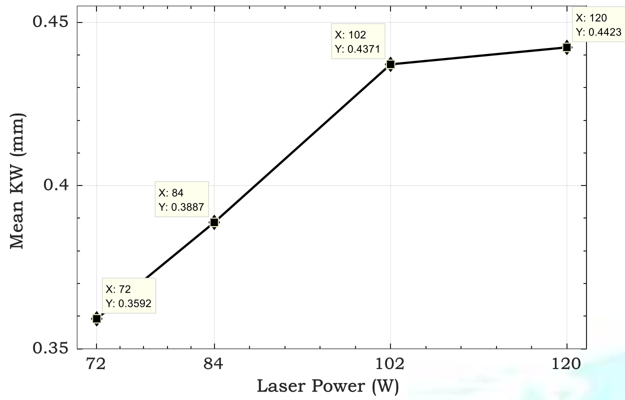

Fig.8 Effect of laser power on kerf width.

3.3 Effect of cutting parameters on heat affected zone

To understand the influence of cutting parameters on heat affected zone for HDPE nano clay composites polymer, it is important to draw the cutting variables against the mean value of heat affected zone as shown in Figs (11-13).

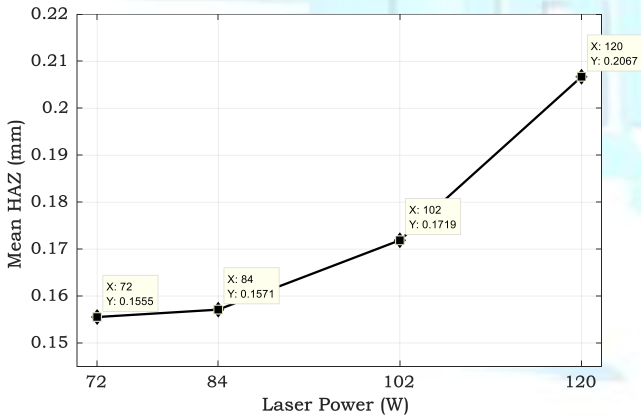

Fig.11 Effect of laser power on heat affected zone.

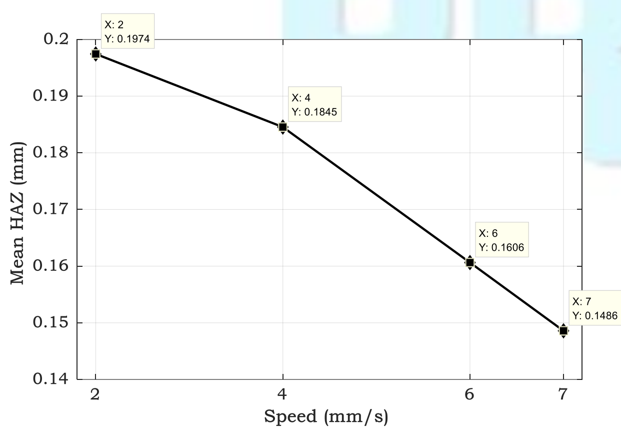

Fig.12 Effect of speed on heat affected zone.

From Fig.11, it is clearly shown that the heat affected zone approximately constant as power rose from 72 W to 84 W and increase thereafter. Also, from Fig.12, It is clearly shown that an increase of the cutting speed the heat affected zone dropped.

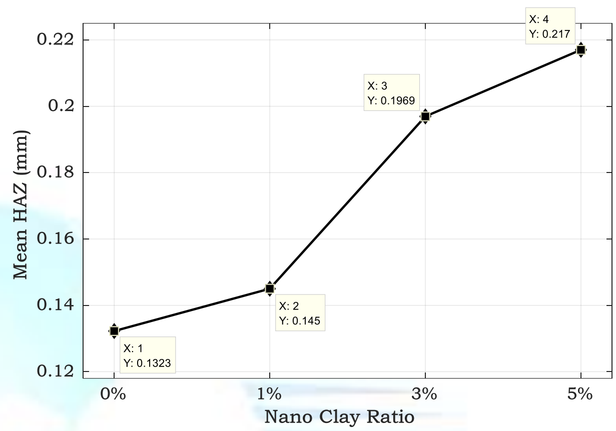

Fig.13 Effect of nano clay ratio on heat affected zone.

Moreover, from Fig.13, it is noticed that when increasing the Nano Clay Ratio the heat affected zone increases.

3.4 Effect of cutting parameters on dross

In order to understand the effect of cutting parameters on dross for HDPE nano clay composites polymer, it is important to plot the cutting variables against the mean value of dross as shown in Figs. (14-16).

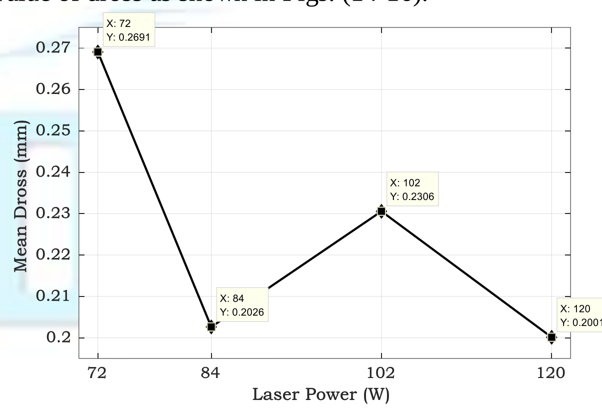

Fig.14 Effect of laser power on dross

From Fig.14, it is clearly shown that the dross dropped as power rose from 72 W to 84 W and increase up to 102 W and decrease thereafter.

Also, from Fig.15, it is clearly shown that the dross dropped as speed rose from 2 mm/s to 4 mm/s and increase thereafter. Moreover, from Fig.16, it is noticed that dross decrease as nano clay ratio rose from 0% to 1% and approximate constant up to 3% and dropped thereafter.

3.5 Percentage contribution of cutting parameters on output parameters

From Fig.17 it is noticed that the influence of speed has the greatest effect (93.5 %). Hence, the speed is the most significant parameter affecting the metal removal rate however; the other factors have no significant effect (2.0543 % – 2.0474 %).

The percentage of error caused by machine inaccuracy is of 2.3677%.Also, the Percentage contribution of each cutting parameters on kerf width indicates that the influence of power has the greatest effect (42.5%). Hence, the power is the most significant parameter affecting the kerf width followed by nano clay ratio (.254 %), however the speed factor has no significant effect (3.1%). The percentage of error caused by machine inaccuracy is of 29 %.

Moreover, the Percentage contribution of each cutting parameter on heat affected zone showed that the influence of nano clay ratio has the greatest effect (56.10%). Hence, the nano clay ratio is the most significant parameter affecting the (HAZ) followed by power (19.2%) and speed (16.8), however the percentage of error caused by machine inaccuracy is of 7.90 % .

It is clearly showed that the influence of nano clay ratio has the greatest effect (44.3%). Hence, the nano clay ratio is the most significant parameter affecting the dross followed by speed (36%) however the power factor has no significant effect (2 %). The percentage of error caused by machine inaccuracy is of 17.7%.

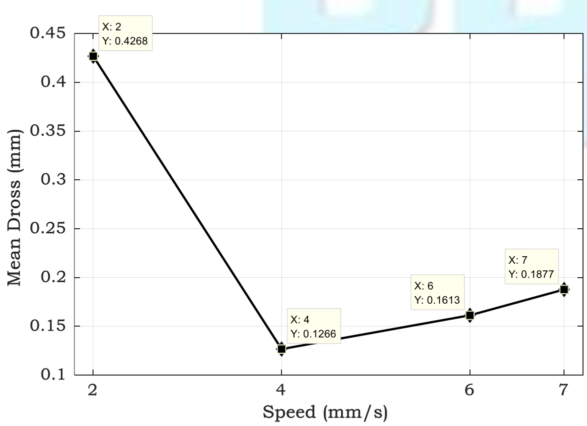

Fig.15. Effect of cutting speed on dross.

3.6 Grey relational analyses (multi response optimization)

From Table 4 the cutting parameters set of experiment no. 4 has the highest grey relation grade. Therefore the best cutting conditions for HDPE are as follows:
Laser Power = 72 W
Speed =7 mm/s
Nano-clay Ratio = 5 %

3.7 Best level of laser cutting parameters

From Fig. 18 and Table 5, one has concluded the optimum parameter levels are: Laser power is 0.6951 (level 1), cutting speed is 0.7667 (level 4) and nano clay ratio is 0.7143 (level 4).

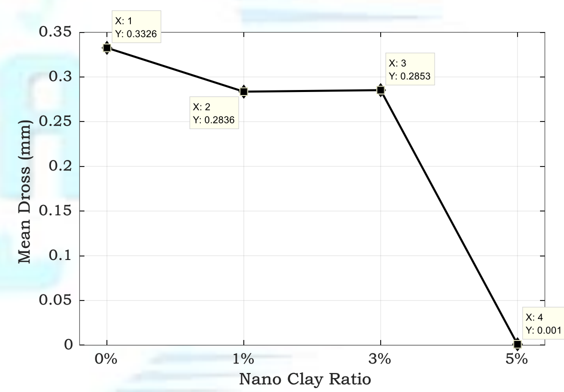

Fig.16 Effect of nano clay ratio on dross

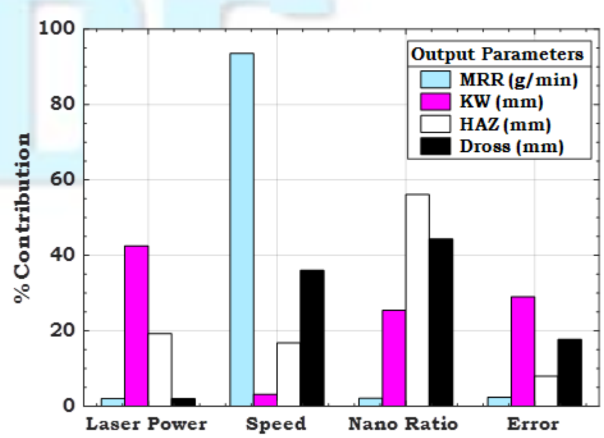

Fig.17 Percentage contribution of cutting parameters on output parameters

The higher grey relational grade from each level of factor shows that the optimum level. It is concluded that the optimum parameters level for laser power, cutting speed and Nano-clay ratio is level 1 (72 W), level 4 (7 mm/s), and level 4 (5%) respectively

Table 5 Average grey relational grade by factor levels

		Average grey relational grade by factor level			
Factors		Level 1	Level 2	Level 3	Level 4
W	Laser Power (W)	0.6951*	0.6709	0.6094	0.6133
S	Speed (mm/sec)	0.5080	0.6172	0.6968	0.7667*
N	Ratio of Nano-clay %	0.6594	0.6391	0.5760	0.7143*

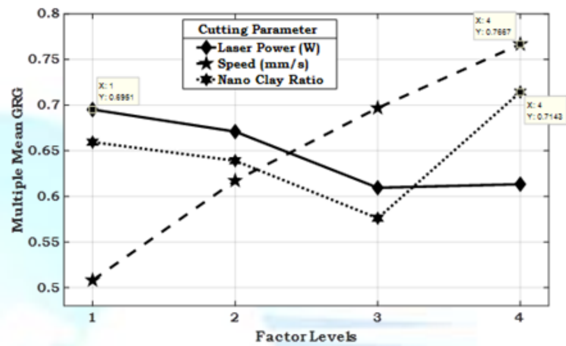

Fig. 18 Grey relational grade v/s factor levels

Table 4 Grey relational grades at equal weighting factor

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	Factors			Grey relational grade at equal weighting factor					
	W	S	N	25%	25%	25%	25%		
No	Laser Power (Watt)	Speed (mm/sec)	Ratio of Nano-clay %	MRR	KW	HAZ	Dross	γj	Order
1	72	2	0	0.3333	0.5449	0.8262	0.3333	0.5094	14
2	72	4	1	0.4345	0.7085	0.8873	0.7184	0.6872	7
3	72	6	3	0.6238	0.8561	0.6512	0.5951	0.6815	9
4	72	7	5	0.9692	1.0000	0.6396	1.0000	0.9022	1
5	84	2	1	0.3481	0.5578	0.7477	0.3962	0.5125	13
6	84	4	0	0.4406	0.5929	0.9729	0.7648	0.6928	5
7	84	6	5	0.6238	0.7741	0.5484	1.0000	0.7366	4
8	84	7	3	1.0000	0.5374	0.7546	0.6757	0.7419	3
9	102	2	3	0.3600	0.4520	0.5214	0.4243	0.4394	16
10	102	4	5	0.5294	0.5669	0.4940	1.0000	0.6476	11
11	102	6	0	0.6117	0.5401	0.9313	0.6436	0.6817	8
12	102	7	1	0.9130	0.3571	0.8245	0.5812	0.6690	10
13	120	2	5	0.3913	0.5588	0.3333	1.0000	0.5708	12
14	120	4	3	0.4809	0.3333	0.3757	0.5745	0.4411	15
15	120	6	1	0.9403	0.3869	0.7990	0.6241	0.6876	6
16	120	7	0	0.8182	0.6812	1.0000	0.5157	0.7538	2

4. Conclusions

From the obtained experimental results the following conclusions can be drawn for the HDPE nano clay composites polymer:

Single objective optimization

1. The maximum metal removal rate was obtained by setting the power at 120 watt, cutting speed at 7 mm/s and additive 5% nano clay ratio.
2. The minimum kerf width was obtained at laser power 72 watt, cutting speed at 6 mm/s and additive 5% nano clay ratio.
3. The minimum heat affected zone value was obtained at laser power 72 Watt, cutting speed at 7 mm/s and using the pure HDPE without any additions to the nano-clay ratios.
4. The optimal combination of cutting parameters to minimize the dross value is by setting the power level at 120 watt followed by 84 watt, cutting speed at 4 mm/s, and additive 5% nano clay ratio.

ANOVA analysis

1. The speed is the most significant parameter affecting metal removal rate however; the other factors have no significant effect.
2. The power is the most significant parameter affecting kerf width followed by nano clay ratio; however the speed factor has no significant effect.
3. The nano clay ratio is the most significant parameter affecting the (HAZ) followed by power and speed.
4. The nano clay ratio is the most significant parameter affecting the dross followed by speed; however the power factor has no significant effect.

Grey analysis

The all cut qualities are largely optimized at high cutting speed 7 mm/s, low laser power 72 watt and additive 5% nano clay ratio.

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