Experimental Investigation on Mechanical Behavior and Parameters of FDM Printed Carbon Fiber PLA & Carbon Fiber PET-G

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Abstract: Micro Air Vehicles are the logical successors to modern aircraft and advancements in automated technology. In recent years, the use of Micro Air Vehicles (MAV) and Unmanned Aerial Vehicles (UAV) are playing important roles in different applications. It is used in many aspects of military and civil broadly, such as aerial photogrammetry, warzone, reconnaissance, attack missions, surveillance of pipelines, and interplanetary exploration and so on. The current trend in aircraft structural design is to use composite materials as primary structural elements. The main objective of this work is to analysis of Mechanical behavior of 3D printed composite materials Carbon Fiber PLA and Carbon Fiber Reinforced PET-G parts by varying various 3D- printing parameters like Printing Speed (mm/sec), Infill Density (%), and Layer Height (microns). Various tests such as Tensile Test, Compression test and Flexural test and are performed to determine failure characteristics of Carbon Fiber PLA and Carbon Fiber Reinforced PET-G materials. Optimization techniques like Taguchi and Taguchi Grey Relational Analysis are also applied to know the printing parameters influence on the mechanical properties of the printed part in order to obtain how parts can be manufactured (printed) to achieve improved mechanical properties. The ANOVA also carried out to know the percentage contribution of printing parameters.

***Index Terms* – 3D Printing, Fused Deposition Modelling (FDM), Polylactide(PLA), Polyethylene Terephthalate (PET-G).**

I. INTRODUCTION:

In recent years, the biodegradable composites draw many attentions in aerospace applications (MAV), as the increasingly serious environmental pollution problems caused by thermosetting composites. Mohanty et al. (2000) reviewed the application of biopolymers and considered that the biopolymers offer environmental benefits including biodegradability, renewability and less greenhouse gas emissions. Polylactide (PLA) & Polyethylene Terephthalate (PET-G) is a kind of biodegradable materials derived from renewable resource and possesses good mechanical properties, which makes it promising an ecologically friendly material for composite applications. At least one species of bacteria in the genus Nocardia can degrade these materials with an esterase enzyme. Japanese scientists have isolated a bacterium Ideonella sakaiensis that possesses two enzymes which can break down these into smaller pieces that the bacterium can digest. A colony of I. sakaiensis can disintegrate a plastic film in about six weeks.

3D printing method is widely investigated in processing the thermoplastic resin of PLA & PETG due to the good characteristics of strong operation, low cost and no need of tooling or mold. The printing techniques of polymer materials mainly include the Stereo Lithography Apparatus (SLA) and Fused Deposition Modelling (FDM). The Fused Deposition Modelling is the low cost printing device and thermoplastic materials are a better choice for industrial production. Various devices and parts have been printed by the FDM.

II. FUSED DEPOSITION MODELING

In this project we are using FDM technology which is one of the most widely used rapid prototyping systems in the world. FDM is today the second most common commercial layered manufacturing system. The main reasons of its increasing popularity and use have been its reliability, safe and simple fabrication process, low cost of material and the availability of a variety of thermoplastics. Ever since the first FDM system was launched in early 1990s, the Stratasys Inc.USA has been marketing improved FDM systems on a regular basis. However, research has also been going on in universities and research institutions around the world to increase its applications, to develop new materials and to improve the FDM process. The FDM method forms three-dimensional objects from computer generated solid or surface models like in a typical RP process. Models can also be derived from computer tomography scans, magnetic resonance imaging scans or model data created from 3D object digitizing systems. The FDM 2000 system is shown in Figure

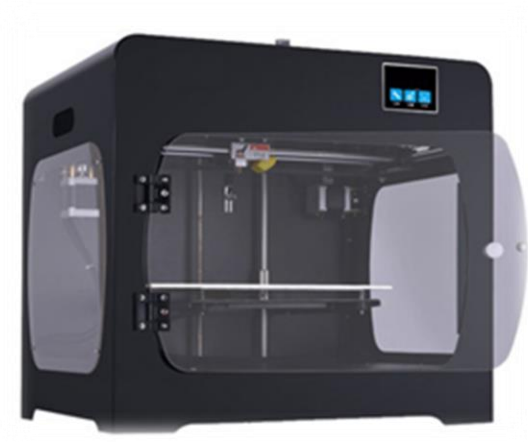

Fig. 1 3D Printing FDM Machine

Details of Pramaan 200 3D-Printer:

Build Volume	200 mm x 200 mm x 200 mm
Display	Digital
Input Format	G Code, STL
Operation Mode	Automatic
Size	38 cm x 37 cm x 48 cm
Voltage(V)	220 V
Build	Aluminium Extrusions
Cover	Powder Coated Sheet Metal Frame
Resolution	100 - 300 microns
Printable Materials	PLA, ABS, Nylon, TPU, Composites etc.
Number of Nozzles	1
Interface	Touch Screen
Connectivity	USB, SD Card, Ethernet, Wi-Fi

WORKING PRINCIPLE:

The FDM system consists of the main 3-D Modeller unit, slicing software and a workstation. The process starts with the creation of a part with a CAD) system as a solid or surface model. The model is then converted into a .STL tile and sent to the FDM slicing software. There, the STL file is sliced into thin cross sections of a desired resolution, creating a .SLC file. Supports are created if required by the geometry and sliced as well. The sliced model and supports are converted into a .SML tile that contains actual instruction codes for the FDM machine.

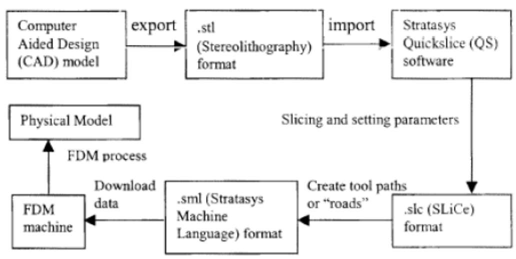

Fig. 2 Working Process Cycle

The filament softens and melts inside the liquefier to a temperature just above its melting point. The molten polymer is extruded out of a nozzle at the end of the liquefier. 37 The positive force required for this extrusion is small and is provided by the rollers driving the incoming filament. A continuous positive displacement is provided in this manner.

It fabricates parts by extruding molten thermoplastic material or wax through a small „nozzle to form a thin bead or road that is deposited in a predetermined pattern to complete each build layer, bonding the extrudate to adjacent and previously deposited roads. The most common build material used with FDM systems is P400 ABS plastic and it is available in several stock colours, including white, red, blue, green, yellow and black. Inside the flying extrusion head, the filament is melted into liquid above its melting temperature by a resistant heater. The head traces an exact outline of each cross-section layer of the part. As the head moves horizontally in X and Y axes the thermoplastic material is extruded out a nozzle by a precision pump. The material solidifies in 1/10 second as it is directed on to the workplace. After one layer is finished, the extrusion head moves up a programmed distance in Z direction for building the next layer. Each layer is bonded to the previous layer through thermal heating. The designed object is fabricated as a three-dimensional part based solely on the precise deposition of thin layers of the extrudate. The deposition path and parameters for every layer are designated depending on the material used, the fabrication conditions, the applications of the designed part and the preferences of the designer. The processing parameters of filling each layer depend on the earlier inputs into the slicing software. These include the FDM head speed, the roller speed, the slice interval and the direction of deposition within each layer. Once built, the supports are removed after part building by breaking them away from the object.

III. MATERIAL SELECTION:

The material selection is the most important thing for printing, because we have different materials. The material has different working materials based on their properties.

There are different technologies that are used in 3D printing and so there are various material that are used in this process. Some printers support around 170 different types of material for printing .tis can broadly be categorized into four important heads.

- Plastic
- Powder
- Resins
- Other material

III.I PLASTIC

The FDM printers use thermoplastic filament which is heated till the melting point and then the molten plastic is placed layer by layer to form the model. These printers tend to use the following materials: Carbon reinforced PET-G, Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Soft PLA, Polyvinyl Alcohol Plastic, and Polycarbonate. The right selection of the machining material is the most important aspect to take into consideration in processes related to the FDM process. From the observation and from the literature review printed material that has been selected is Polylactic Acid (PLA) & Carbon reinforced PET-G.

III.II CARBON FIBER POLYLACTIC ACID (PLA)

PLA has an aliphatic backbone with and polar carbon-oxygen bonds, which allows it to form a semi-crystalline structure. The crystalline structure and methyl (CH_3) pendant group imparts strength to polymer, but also makes it brittle. The polar bonds in PLA can make it susceptible to water absorption which can cause issues because water can partially breakdown PLA causing it to become even more brittle.

III.III PLA Technical Specifications & Properties:

Flexural Strength: 88.8 MPa
- Melting Temperature: >155°C
- Tensile Strength: 61.5MPa
- Heat Deflection: N/A
- Heat Resistance: 110ºC
- Impact Strength: 30.8[kJ/m^2]
- Elongation at Break: 6%
- Standard Tolerance: +/-0.05mm
- Minimum Wall Thickness: 0.0197mm - 0.5 mm
- Extruded Temperature: 160°C-220°C
- Shore Hardness: 85A
- Density: 1.25 g/cm^3
- Thermal Conductivity: 0.13 W/m-K

III.IV CARBON FIBER REINFORCED PET-G

When 3D printer filament like PLA, PETG are reinforced with carbon fiber the result is an extremely stiff and rigid material with relatively little weight, very good ductility, impact resistance and higher strength than PLA Carbon Fiber. Such compounds shine in structural applications that must withstand wide variety of end-use environments.

III.V PREPARING CAD MODEL FOR THE SPECIMENS TO BE PRINTED:

In the project we are going to analyze the strength of the objects printed with PLA & Carbon reinforced PET-G material, by varying various process parameters of 3D-printing machine. To analyze their mechanical strengths the objects has to undergo Tensile, Compressive & Flexural tests. To perform these tests the objects has to be printed as per the ASTM standards design required for these tests. So first the objects called as specimens, CAD model has to be designed using any of the designing software and they are to be printed.

III. VI DESIGN OF CAD MODEL

Using the design package CATIA V5 the specimens were designed as per the ASTM Standards. CAD model for tensile test: Tensile Test Specimens were designed in CATIA V5, a rectangular block with 12.7mmX 12.7mm X 25.4mm following ASTM D695standards for plastics. CAD model for Compressive test: Compression Test Specimens were designed in CATIA V5, a rectangular block with 12.7mmX 12.7mm X 25.4mm following ASTM D695standards for plastics. CAD model for Flexural test: Flexural Test Specimens were designed in CATIA V5 with 127mm X 12.7 mm X 6.4 mm following ASTM D790 standards for plastics.

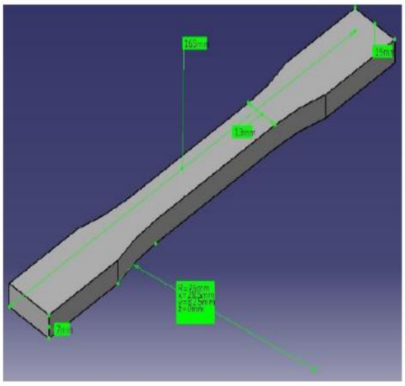

Fig. Tensile Specimen

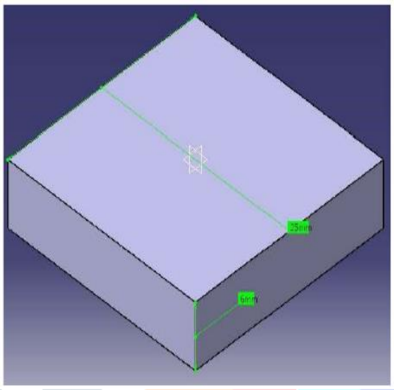

Fig. Compression Specimen

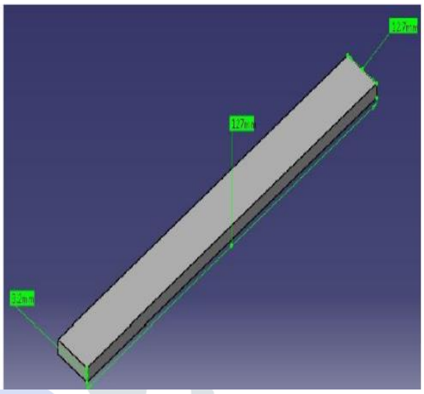

Fig. Flexural Specimen

IV. SELECTION OF PROCESS PARAMETERS

From the Ishikawa cause effect and based on the literature review the input process parameters selected for the present experimentation of FDM were as follows:

INPUT PROCESS PARAMETERS

Input Parameter	Level 1	Leve l 2	Level 3
Print Speed(mm/sec)	60	80	100
Infill Density(%)	40	60	80
Layer Height(microns)	100	200	300

Table No: 1 Process Parameters and their levels

IV. I DESIGN OF EXPERIMENT

A 9 run experiment is selected based on Taguchi‘s technique by the information from the **above table Process Parameters and their levels,** the L9 orthogonal array was created by using the MINITAB 17 software.

Steps involved in creating L9 Orthogonal Array using MINITAB 17

1. Open the MINITAB 17 window, then an empty worksheet will be displayed.

2. Go to STAT > DOE > Taguchi > Create Taguchi Design

3. Then select 3 -level design, number of factors 3 and enter factors (Print Speed (mm/sec), Infill Density (%), and Layer Height (microns)) and their levels. Then the required orthogonal array was displayed as in the Table: 3.3

S.No	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	60	40	100
2	60	60	200
3	60	80	300
4	80	40	200
5	80	60	300
6	80	80	100
7	100	40	300
8	100	60	100
9	100	80	200

Table No: 2 Experimental Design created by MINITAB 17 for PLA & Carbon reinforced.

IV.II 3D Printing Specimens:


Tensile Specimen


Flexural Specimen


Compression Specimen

V. OPTIMIZATION OF PROCESS PARAMETERS

SINGLE VARIABLE OPTIMIZATION (TAGUCHI METHOD)

Taguchi's method is systematic and experimentally designed to find the main process parameters and will locate a good combination of process parameters to improve the output quality by using the experiments of Orthogonal Array. In this method each experimental value is converted to Signal to Noise ratio and is defined as the deviation between the experimental value and ideal value.

V.I Process parameters optimization by Taguchi Design of Experimentation

Process parameters are optimized using Taguchi Design by Using the MINITAB 17. In this Means and S/N ratios for all response parameters were calculated. Then response table for each response parameter was created to find out the optimum level of experiment for each parameter i.e., Tensile Strength, Flexural Strength, Compressive Strength.

S.No	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Ultimate Tensile Strength (N/mm^2)	S/N Ratio of UTS	Flexural Strength (N/mm^2)	S/N Ratio of FS	Compressive Strength (N/mm^2)	S/N Ratio of CS
1	60	40	100	17.118	24.66906	141.41	43.009602	13.15	22.3778545
2	60	60	200	15.26	23.671091	152.77	43.680762	16.93	24.5715999
3	60	80	300	20.26	26.132789	110.7	40.882952	17.16	24.691864
4	80	40	200	14.916	23.473047	141.74	43.029849	13.87	22.8434077
5	80	60	300	26.304	28.400436	135.33	42.627882	33.05	30.3834293
6	80	80	100	21.961	26.833042	62.67	35.941194	23.64	27.4729494
7	100	40	300	18.068	25.138202	91.43	39.221774	15.04	23.5472665
8	100	60	100	19.465	25.785088	57.85	35.246067	20.6	26.2790308
9	100	80	200	16.659	24.432979	131.28	42.363971	23.25	27.3273383

Table No:3 Signal to Noise Ratios for Tensile Strength, Flexural Strength, and Compressive Strength for PLA material

VI. Taguchi Analysis: Tensile Strength, Flexural Strength and Compressive Strength VS Print Speed (PS), Infill Density (ID), Layer Height (LH) for **PLA material**

	S/N Ratios			Means		
Level	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	24.82	24.43	25.76	17.55	16.7	19.51
2	**26.24**	**25.95**	23.86	21.06	20.34	15.61
3	25.12	25.8	**26.56**	18.06	19.63	21.54
Delta	1.41	1.53	2.7	3.51	3.64	5.93
Rank	3	2	1	3	2	1

Table No: 4 Response Table for Ultimate Tensile Strength (N/mm2) (Mean and S/N ratios) (Larger is better criteria) (PLA Material)

VI. II Confirmation Test for Tensile Strength

The final step in verifying the improvement in Tensile strength was done by conducting experiments using optimal conditions. The confirmation experiment was conducted at the optimum setting of process parameters namely Printing speed at level 2(80m/s), Infill Density level 2 (60%), Layer Height level 3(300microns) and the Tensile strength observed to be 24.89 **N/mm2**, which was around the confidence interval of the predicted Tensile Strength 25.16 **N/mm2**.

	S/N Ratios			Means		
Level	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	**42.28**	**41.13**	35.59	131.74	116.59	60.26
2	40.53	40.52	**43.02**	113.25	115.32	141.93
3	38.94	39.73	40.91	93.52	101.55	112.49
Delta	3.34	1.4	7.43	38.22	15.04	81.67
Rank	2	3	1	2	3	1

Table No: 5 Response Table for Flexural Strength (N/mm2) (Mean and S/N ratios) (Larger is better criteria) (PLA Material)

VI.III Confirmation Test for Flexural Strength:

The final step in verifying the improvement in Flexural strength was done by conducting experiments using optimal conditions. The confirmation experiment was conducted at the optimum setting of process parameters namely Printing speed at level 1(60m/s), Infill Density level 1 (40%), Layer Height level 2(200microns) and the Flexural strength 52

Observed to be 162.91N/mm2, which was around the confidence interval of the predicted optimal Flexural strength 173.93 N/mm2.

	S/N Ratios			Means		
Level	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	24.63	23.2	**26.88**	17.05	14.46	22.12
2	**26.9**	**27.08**	24.91	23.52	23.53	18.02
3	25.72	26.5	26.21	19.63	21.35	21.75
Delta	2.27	3.88	1.96	6.48	9.07	4.11
Rank	2	1	3	2	1	3

Table No: 6 Response Table for Compression Strength (N/mm2) (Mean and S/N ratios) (Larger is better criteria) (PLA Material)

VI. IV Confirmation Test for Compressive Strength

The final step in verifying the improvement in compressive strength was done by conducting experiments using optimal conditions. The confirmation experiment was conducted at the optimum setting of process parameters namely printing speed at level 2 (80m/s), infill density level 2 (60%), layer height level 1(100microns) and the compressive strength observed to be 28.633n/mm2, which was around the confidence interval of the predicted optimal compressive strength 26.913 n/mm2.

The experimental results were analyzed with the Analysis Of Variance (ANOVA), which is used to know the design parameters percentage contribution towards the Tensile Strength, Flexural Strength & Compressive Strength

S.No	Print Speed (mm/sec)	Infill Density (%)	Layer Height (Microns)	Ultimate Tensile Strength (N/mm^2)	S/N Ratio of UTS	Flexural Strength (N/mm^2)	S/N Ratio of FS	Compression Strength (N/mm^2)	S/N Ratio of CS
1	60	40	100	25.244	28.0431634	34.94	30.86645801	13.118	22.35735253
2	60	60	200	20.005	26.0227711	36.47	31.23871527	15.792	23.96874271
3	60	80	300	34.629	30.788799	29.96	29.53083618	20.979	26.43569566
4	80	40	200	28.481	29.0911047	28.41	29.06942467	9.993	19.99391775
5	80	60	300	27.059	28.6462349	29.18	29.30170575	15.936	24.04758642
6	80	80	100	29.466	29.3864237	32.78	30.31217898	22.143	26.9047292
7	100	40	300	1.98	5.93330381	26.27	28.38920146	9.728	19.76047124
8	100	60	100	30.03	29.5511066	27.6	28.81818164	16.767	24.48910729
9	100	80	200	31.174	29.8758506	34.83	30.83906949	26.026	28.30814851

Table No: 7 Signal to Noise Ratios for Tensile Strength, Flexural Strength, and Compressive Strength for PETG material

VI. V Taguchi Analysis: Tensile Strength, Flexural Strength and Compressive Strength VS Print Speed (PS), Infill Density (ID), Layer Height (LH) for PETG material:

	S/N Ratios			Means		
Level	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	28.28	21.02	**28.99**	26.63	18.57	28.25
2	**29.04**	28.07	28.33	28.34	25.7	26.55
3	21.79	**30.02**	21.79	21.06	31.76	21.22
Delta	7.25	8.99	7.2	7.27	13.19	7.02
Rank	2	1	3	2	1	3

Table No: 8 Response Table for Ultimate Tensile Strength (N/mm2) (Mean and S/N ratios) (Larger is better criteria) (PETG Material)

VI.VI Confirmation Test for Tensile Strength

The final step in verifying the improvement in Tensile strength was done by conducting experiments using optimal conditions. The confirmation experiment was conducted at the optimum setting of process parameters namely Printing speed at level 2(80m/s), Infill Density level 3 (80%), Layer Height level 1(100microns) and the Tensile strength observed to be 36.82 N/mm2, which was around the confidence interval of the predicted optimal Tensile Strength 37.64N/mm2.

	S/N Ratios			Means		
Level	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	**30.55**	29.44	30	33.79	29.87	31.77
2	29.56	29.79	**30.38**	30.12	31.08	33.24
3	29.35	**30.23**	29.07	29.57	32.52	28.47
Delta	1.2	0.79	1.31	4.22	2.65	4.77
Rank	2	3	1	2	3	1

Table No: 9 Response Table for Flexural Strength (N/mm2) (Mean and S/N ratios) (Larger is better criteria) (PETG Material)

VI. VII Confirmation Test for Flexural Strength

The final step in verifying the improvement in Flexural strength was done by conducting experiments using optimal conditions. The confirmation experiment was conducted at the optimum setting of process parameters namely Printing speed at level 1(60m/s), Infill Density level 3 (80%), Layer Height level 2(200microns) and the Flexural strength 58

Observed to be 35.28 N/mm2, which was around the confidence interval of the predicted optimal Flexural strength 37.22 N/mm2.

	S/N Ratios			Means		
Level	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	**24.25**	20.70	**24.58**	16.63	10.95	**17.34**
2	23.65	24.17	24.09	16.02	16.17	17.27
3	24.19	**27.22**	23.41	**17.51**	**23.05**	15.55
Delta	0.61	6.51	1.17	1.48	12.10	1.80
Rank	3	1	2	3	1	2

Table No: 10 Response Table for Compressive Strength (N/mm2)(Mean and S/N ratios) (Larger is better criteria) (PETG Material)

VI. VIII Confirmation Test for Compressive Strength

The final step in verifying the improvement in compressive strength was done by conducting experiments using optimal conditions. The confirmation experiment was conducted at the optimum setting of process parameters namely printing speed at level 1 (60m/s), infill density level 3 (80%), layer height level 1(100microns) and the compressive strength observed to be 24.35 n/mm2, which was around the confidence interval of the predicted optimal compressive strength 23.56 n/mm2.

The experimental results were analyzed with the Analysis Of Variance (ANOVA), which is used to know the design parameters percentage contribution towards the Tensile Strength, Flexural Strength & Compressive Strength.

VII. ANOVA CALCULATION FOR TENSILE STRENGTH, FLEXURAL STRENGTH AND COMPRESSIVE STRENGTH FOR PLA & PETG:

The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence. Study of ANOVA table for a given analysis helps to determine which of the parameters need control .The ANOVA for material removal rate, surface roughness, and wire wear ratio was generated using the MINITAB.

VII.I ANOVA for Tensile Strength (PLA):

Source	DF	SS	MS	F	% of Contribution
Print Speed	2	3.325	1.663	0.60	16.64
Infill Density	2	4.235	2.117	0.81	21.195
Layer Height	2	11.534	5.767	4.10	57.724
Residual Error	2	0.887			4.441
Total	8	19.981			100

Table No: 11 ANOVA for Tensile Strength (PLA)

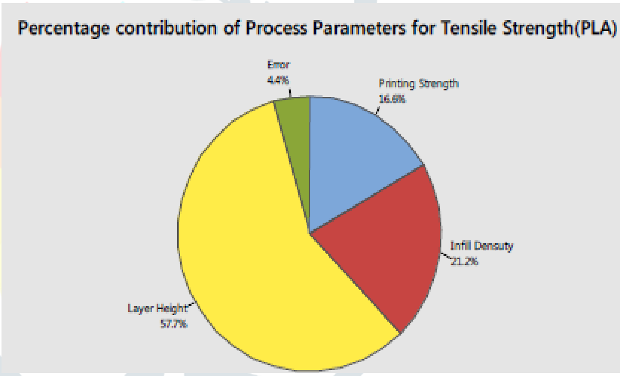

Fig: 4.1 % Contribution of Tensile Strength (PLA)

VII.II ANOVA for Flexural Strength (PLA):

Source	DF	SS	MS	F	% of contribution
Print Speed	2	19.31	9.655	0.94	23.91
Infill Density	2	6.247	3.123	0.25	7.73
Layer Height	2	37.16	18.579	2.56	46.02
Residual Error	2	18.013			22.34
Total	8	80.73			100

Table No: 12 ANOVA for Flexural Strength (PLA)

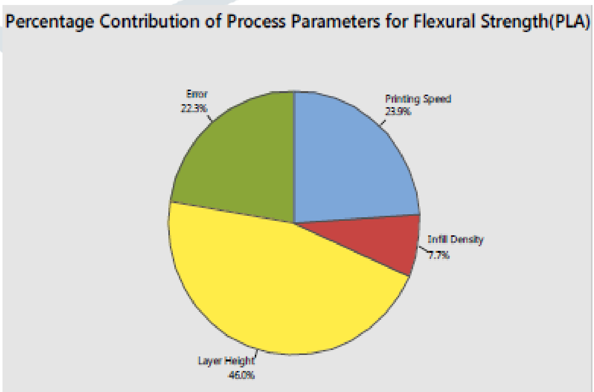

Fig: 4.2 % Contribution of Flexural Strength (PLA)

VII.III ANOVA for Compressive Strength (PLA):

Source	DF	SS	MS	F	% of Contribution
Print Speed	2	13.88	6.941	1.04	25.78
Infill Density	2	30.40	15.198	3.89	56.46
Layer Height	2	2.251	1.286	0.15	4.77
Residual Error	2	6.985			12.99
Total	8	53.836			100

Table No: 13 ANOVA for Compressive Strength (PLA)

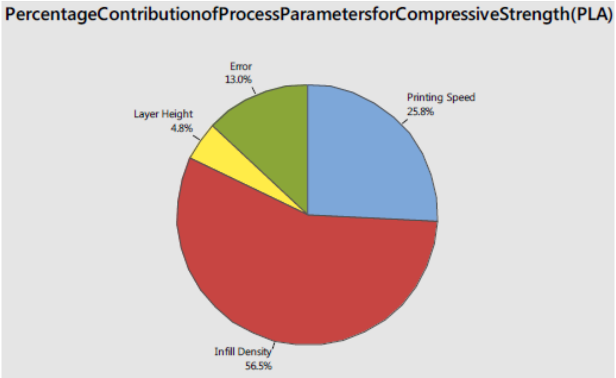

Fig: 4.3 % Contribution of Compressive Strength (PLA)

Source	DF	SS	MS	F	% of Contribution
Print Speed	2	86.80	43.40	0.39	11.63
Infill Density	2	261.5	130.73	1.62	35.03
Layer Height	2	80.62	40.31	0.36	10.80
Residual Error	2	317.4			42.54
Total	8	746.32			100

Table No: 14 ANOVA for Tensile Strength (PETG)

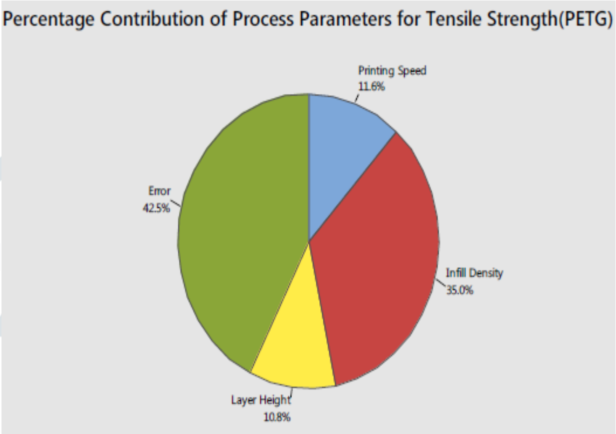

Fig: 4.4 % Contribution of Tensile Strength (PETG)

ANOVA for Flexural Strength (PETG):

Source	DF	SS	MS	F	% of Contribution
Print Speed	2	31.59	15.80	1.24	29.22
Infill Density	2	10.56	5.280	0.32	9.76
Layer Height	2	35.77	17.89	1.48	33.09
Residual Error	2	30.17			27.93
Total	8	108.09			100

Table No: 15 ANOVA for Flexural Strength (PETG)

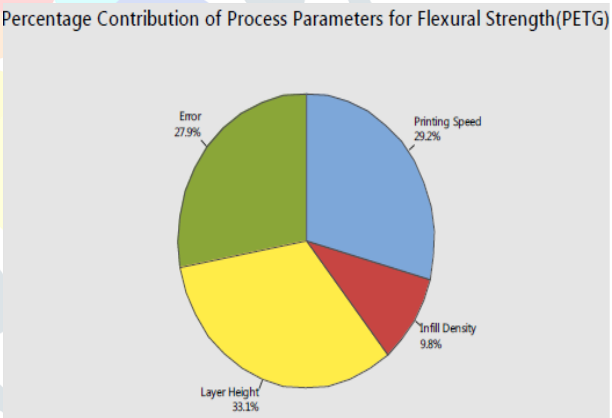

Fig: 4.5 % Contribution Flexural Strength (PETG)

ANOVA for Compressive Strength (PETG):

Source	DF	SS	MS	F	% of Contribution
Print Speed	2	3.336	1.688	0.004	1.22
Infill Density	2	221.11	110.556	30.67	91.08
Layer Height	2	6.195	3.097	0.08	2.55
Residual Error	2	12.102			5.15
Total	8	242.743			100

Table No: 16 ANOVA for Compressive Strength (PETG)

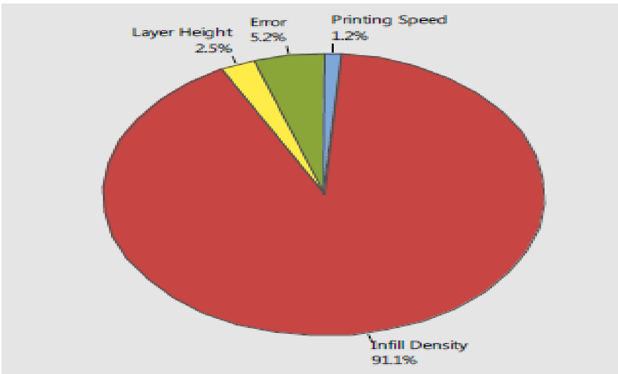

Fig: 4.6 % Contribution of Compressive Strength (PETG)

MULTI VARIABLE OPTIMIZATION (GREY RELATIONAL ANALYSIS)

Since optimizing multiple output qualities of a process requires the calculation of overall S/N ratios and may not optimize the multiple output qualities simultaneously by using the Taguchi's method. Therefore a Grey Relational Analysis (GRA) is recommended and used to integrate and optimize the multiple qualities of a process.

FOR PLA:

Exp. No	NORMALIZED SEQUENCES			DEVIATION SEQUENCES		
	TS	FS	CS	TS	FS	CS
1	0.1933	0.8803	0	0.8067	0.1197	1
2	0.0302	1	0.1899	0.9698	0	0.8101
3	0.4692	0.5567	0.2015	0.5308	0.4433	0.7985
4	0	0.8837	0.0361	1	0.1163	0.9639
5	1	0.8162	1	0	0.1838	0
6	0.6186	0.0507	0.5271	0.3814	0.9493	0.4729
7	0.2767	0.3537	0.0949	0.7233	0.6463	0.9051
8	0.3944	0	0.3743	0.6006	1	0.6257
9	0.1530	0.7735	0.5075	0.847	0.2265	0.4925

Table No: 17 Results for Comparability and Deviation Sequences

Exp.No	PRINT SPEED	INFILL DENSITY	LAYER HEIGHT	Grey Relational Coefficient			Grey relational grade
				TS	FS	CS	
1	80	80	100	0.3826	0.8068	0.3334	0.5076
2	100	60	100	0.3401	1	0.3816	0.5739
3	60	40	100	0.4850	0.5300	0.3850	0.4667
4	100	80	200	0.3334	0.8112	0.3415	0.4953
5	80	40	200	1	0.7312	1	0.9104
6	60	60	200	0.5672	0.3449	0.5139	0.4753
7	60	80	300	0.4087	0.4361	0.3558	0.4002
8	80	60	300	0.4542	0.3334	0.4441	0.4105
9	100	40	300	0.3711	0.6882	0.5037	0.521

Table No: 18 Results for Grey Relation Coefficient and Grey Relational Grades

Taguchi Analysis for Grey Relational Grade for PLA:

	S/N Ratios			Means		
Level	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	-5.777	-6.649	-6.695	0.5161	0.4677	0.4645
2	**-4.460**	**-4.457**	-5.530	0.6270	0.6316	0.5301
3	-7.117	-6.248	**-5.130**	0.4439	0.4877	0.5924
Delta	2.6528	2.191	1.565	0.1831	0.1639	0.1280
Rank	1	2	3	1	2	3

Table No: 18 Response Table for Mean and Signal to Noise Ratios (Larger is better) of Grey Relational Grade

PETG:

Exp. No	NORMALIZED SEQUENCES			DEVIATION SEQUENCES		
	TS	FS	CS	TS	FS	CS
1	0.7125	0.85	0.1673	0.2875	0.15	0.8327
2	0.5520	1	0.2994	0.448	0	0.7006
3	1	0.3617	1	0	0.6383	0
4	0.8116	0.2098	0.0130	0.1884	0.7902	0.987
5	0.7681	0.2852	0.0808	0.2319	0.7148	0.9192
6	0.8418	0.6382	0.6130	0.1582	0.3618	0.387
7	0	0	0	1	1	1
8	0.8591	0.1303	0.3475	0.1409	0.8697	0.6525
9	0.8941	0.8392	0.8047	0.1059	0.1608	0.1953

Table No: 19 Results for Comparability and Deviation Grey Relational Grades

Exp.No	PRINT SPEED	INFILL DENSITY	LAYER HEIGHT	Grey Relational Coefficient			Grey relational grade
				TS	FS	CS	
1	80	80	100	0.6349	0.7692	0.3751	0.5930
2	100	60	100	0.5274	1	0.4164	0.6479
3	60	40	100	1	0.4392	1	0.8130
4	100	80	200	0.7263	0.3875	0.3362	0.4834
5	80	40	200	0.6831	0.4115	0.3523	0.4823
6	60	60	200	0.7596	0.5801	0.5636	0.6344

Table No: 20 Results for Grey Relation Coefficient and Sequences

According to performed experimental design, it is clearly observed from Table, that the _FDM parameters setting of experiment no 9 has the highest Grey Relation Grade. Thus, the twelve experiment gives the best multi-performance characteristics among the 9 experiments. To find out the optimum level of WEDM parameters, calculate the average grey relational grade for each factor level using Taguchi Design of Experiment in Minitab 17.

Taguchi Analysis for Grey Relational Grade for PETG:

	S/N Ratios			Means		
Level	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)	Print Speed (mm/sec)	Infill Density (%)	Layer Height (microns)
1	**-3.369**	-6.78	-4.689	0.6846	0.4699	0.5846
2	-5.533	-5.226	**-4.130**	0.5334	0.5522	0.6327
3	-5.807	**-2.685**	-5.891	0.5422	0.7381	0.5429
Delta	2.438	4.112	1.761	0.1513	0.2682	0.0898
Rank	2	1	3	2	1	3

Confirmation test at optimal parameter level obtained From Grey Relational Analysis

The final step in verifying the improvement in response variables was done by conducting experiments using optimal conditions. The confirmation experiment was conducted at the optimum setting of process parameters namely Printing Speed level 1(60m/s), Infill Density level 3(80%), Layer Height level 2(200microns). Therefore the values of UTS = 32.50N/mm2, FS=35.23N/mm2, CS= 26.23N/mm2.

ANOVA for Grey Relational Grade for PLA & PETG:

Source	DF	SS	MS	F	% of Contribution
Print Speed	2	0.05104	0.02552	1.13	27.36
Infill Density	2	0.04798	0.02399	1.04	25.72
Layer Height	2	0.02457	0.01228	0.46	13.17
Residual Error	2	0.06295			33.75
Total	8	0.18654			100

Table No: 21 ANOVA for Grey Relational Grade (PLA)

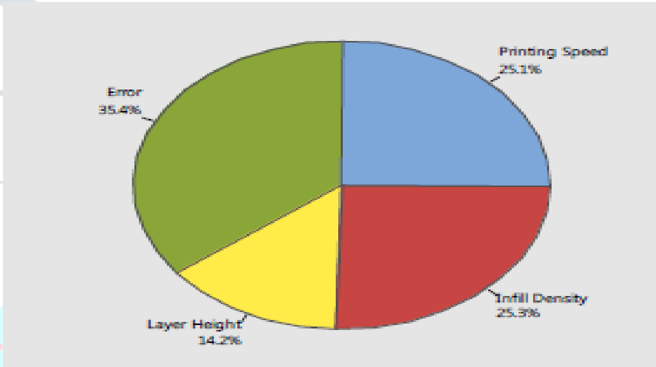

Fig: 4.4 % Contribution of Grey relational grade (PLA)

Source	DF	SS	MS	F	% of Contribution
Print Speed	2	0.04325	0.02162	0.95	24.14
Infill Density	2	0.11325	0.05662	5.16	63.22
Layer Height	2	0.01213	0.006063	0.22	6.77
Residual Error	2	0.01049			5.87
Total	8	1.7871			100

Table No: 22 ANOVA for Grey Relational Grade (PETG)

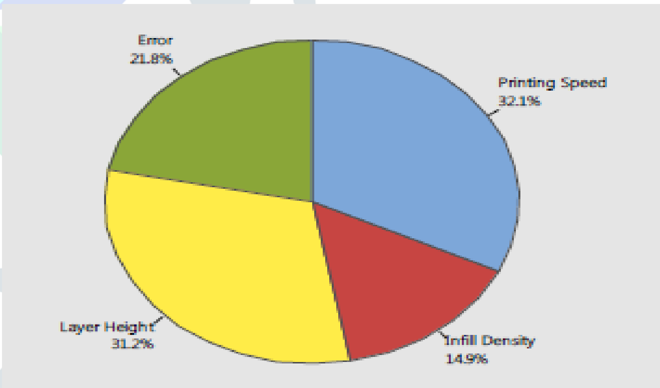

Fig: 4.5 % Contribution of Grey relational grade (PETG)

RESULTS AND DISCUSSIONS:

After printing the 9 specimens for PLA & Carbon reinforced PET-G specimens with various process parameters of range printing speed (mm/sec) (60, 80, 100), Infill Density (%) (40, 60, 80) and Layer height (microns) (100, 200, 300), the mechanical tests like Tensile, Flexural and Compressive Tests were performed. Optimization techniques also implemented to optimize the process parameters.

ULTIMATE TENSILE, FLEXURAL AND COMPRESSIVE STRENGTHS

5.1.1 Ultimate Tensile Strength

• For PLA the Ultimate Tensile Strength found to be 26.304 N/mm2 at ultimate load of 2.4 KN for the specimen Printing Speed – 80mm/sec, Infill Density-60%, Layer Height- 300 microns.

• For Carbon reinforced PET-G the Ultimate Tensile Strength found to be 34.629 N/mm2 at ultimate load of 2.94 KN for the specimen Printing Speed – 60mm/sec, Infill Density-80%, Layer Height- 300 microns.

Flexural Strength

• For PLA the Flexural Strength found to be 152.77 N/mm2 at ultimate load of 240 N for the specimen Printing Speed – 60mm/sec, Infill Density-60%, Layer Height- 200 microns.

• For Carbon reinforced PET-G the Ultimate Tensile Strength found to be 36.47 N/mm2 at ultimate load of 57.5 KN for the specimen Printing Speed – 60mm/sec, Infill Density-60%, Layer Height- 200 microns.

5.1.3Compressive Strength

• For PLA the Compressive Strength found to be 33.05 N/mm2 at ultimate load of 10.8 KN for the specimen Printing Speed – 80mm/sec, Infill Density-60%, Layer Height- 300 microns.

• For Carbon reinforced PET-G the Compressive Strength found to be 26.026 N/mm2 at ultimate load of 8.68 KN for the specimen Printing Speed – 100mm/sec, Infill Density-80%, Layer Height- 200 microns.

Main Effect Plots for Printing Process Parameters Vs Ultimate Tensile, Flexural and Compressive Strengths:

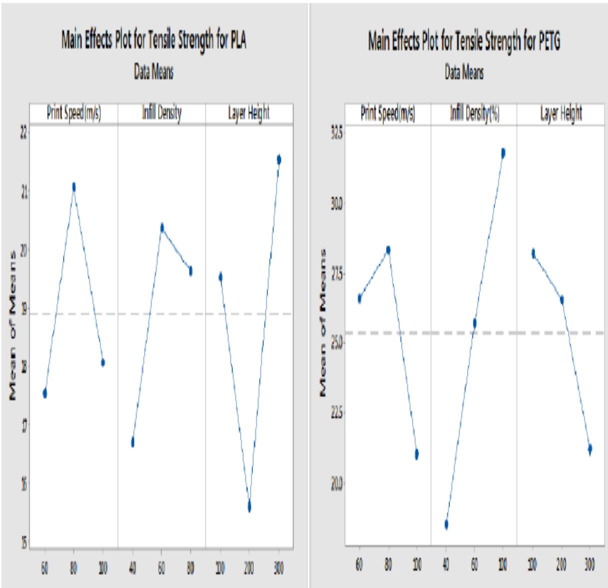

Fig. 5.1 Graph of Printing Parameters v/s Tensile Strength

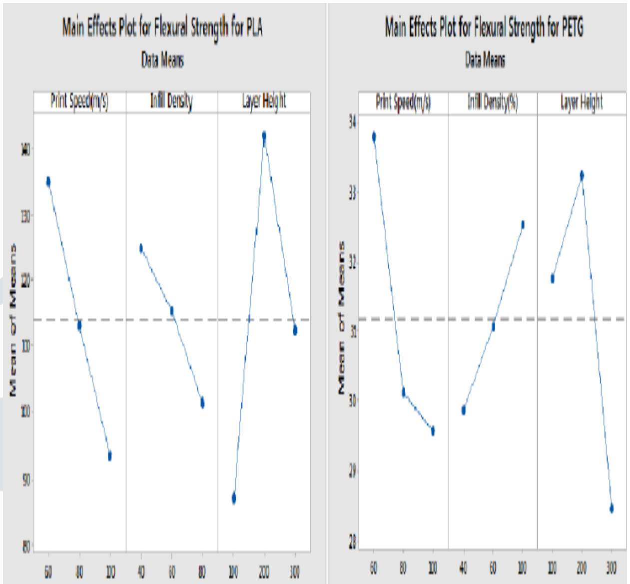

Fig. 5.2 Graph of Printing Parameters v/s Flexural Strength

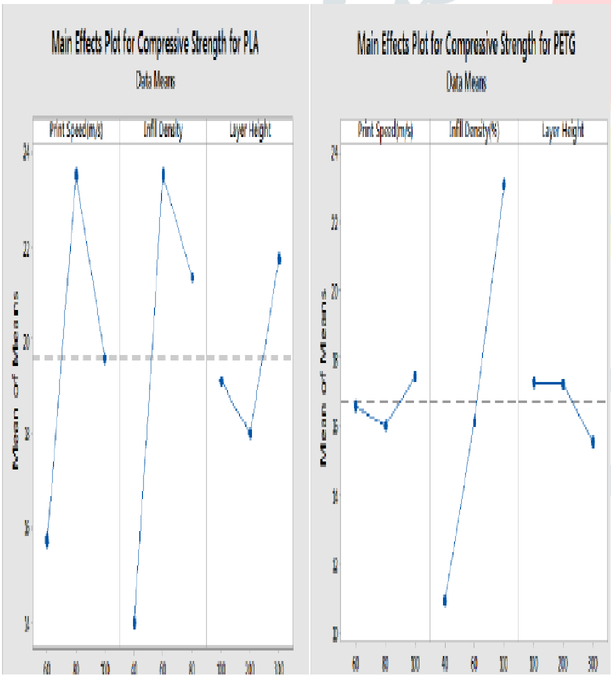

Fig. 5.3 Graph of Printing Parameters v/s Compressive Strength

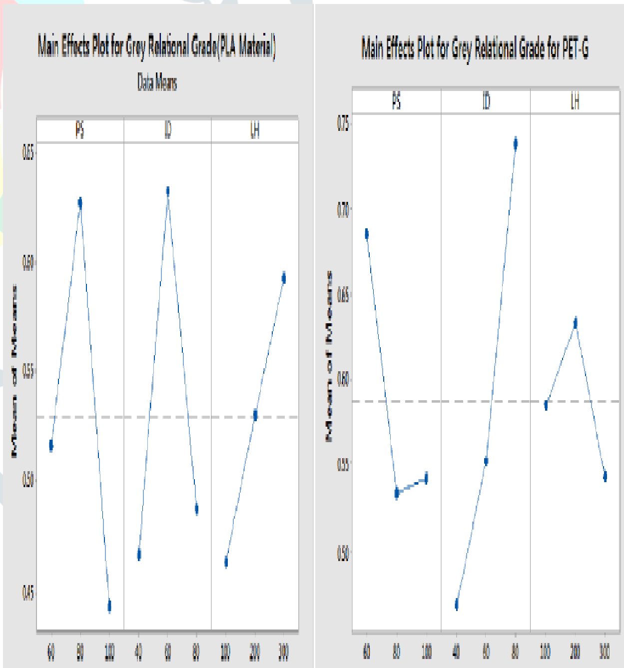

Fig. 5.4 Graph of Printing Parameters v/s Grey Relational Grade (GRG)

PREDICTED RESULTS AND CONFIRMATION TEST RESULTS OBTAINED FROM TAGUCHI AND GREY RELATIONAL ANALYSIS:

Optimization		Optimum Level	Predicted	Confirmation Test
Taguchi Analysis of Design	Tensile Strength	Printing Speed=80mm/sec Infill Density= 60% Layer Height= 300microns	25.16 N/mm^2	24.89 N/mm^2
	Flexural Strength	Printing Speed=60mm/sec Infill Density= 40% Layer Height= 200microns	173.93 N/mm^2	162.91 N/mm^2
	Compressive Strength	Printing Speed=100mm/sec Infill Density= 60% Layer Height= 200microns	26.913 N/mm^2	28.633 N/mm^2

Optimization	Predicted Grey Relational Grade	Optimal Level Of Parameters	Confirmation Test For: Tensile Strength	Flexural Strength	Compressive Strength
Grey Relational Analysis	0.9104	Printing Speed=80mm/sec Infill Density= 60% Layer Height= 300microns	26.928 N/mm^2	123.27 N/mm^2	31.25 N/mm^2

Table No: 5.1 Results obtained from Taguchi Analysis and Taguchi Grey Relational Analysis for PLA

Optimization		Optimum Level	Predicted	Confirmation Test
Taguchi Analysis of Design	Tensile Strength	Printing Speed=80mm/sec Infill Density= 80% Layer Height= 100microns	37.64 N/mm^2	36.82 N/mm^2
	Flexural Strength	Printing Speed=60mm/sec Infill Density= 80% Layer Height= 200microns	37.22 N/mm^2	35.28 N/mm^2
	Compressive Strength	Printing Speed=60mm/sec Infill Density= 80% Layer Height= 100microns	23.56 N/mm^2	24.35 N/mm^2

Optimization	Predicted Grey Relational Grade	Optimal Level Of Parameters	Confirmation Test For: Tensile Strength	Flexural Strength	Compressive Strength
Grey Relational Analysis	0.8130	Printing Speed=60mm/sec Infill Density= 80% Layer Height= 200microns	32.5 N/mm^2	35.23 N/mm^2	26.23 N/mm^2

Table No: 5.2 Results obtained from Taguchi Analysis and Taguchi Grey Relational Analysis for Carbon Reinforced PET-G

From the Taguchi Analysis for the PLA material optimal parameter level for Ultimate Tensile Strength is Printing Speed 80 mm/sec, Infill Density 60%, Layer height 300microns and at this level the Ultimate Tensile strength is found to be 24.89 N/mm2. While the optimal parameter level obtained for Flexural Strength is Printing Speed 60 mm/sec, Infill Density 40%, Layer height 200microns and at this level the Flexural strength is found to be 162.91 N/mm2While the optimal parameter level obtained for Compressive Strength is Printing Speed 100 mm/sec, Infill Density 60%, Layer height 200microns and at this level the Compressive Strength is found to be 28.633 N/mm2. From the Grey Relational Analysis, it was found that the optimal parameter level Speed 80 mm/sec, Infill Density 60%, Layer height 300microns. The confirmation test was carried out at this level then observed the following results: Ultimate Tensile Strength 26.928 N/mm2, Flexural strength 123.27 N/mm2 and Compressive Strength 31.25 N/mm2. From the Taguchi Analysis for the Carbon Reinforced PET-G material optimal parameter level for Ultimate Tensile Strength is Printing Speed 80 mm/sec, Infill Density 80%, Layer height 100microns and at this level the Ultimate Tensile strength is found to be 36.82 N/mm2. While the optimal parameter level obtained for Flexural Strength is Printing Speed 60 mm/sec, Infill Density 80%, Layer height 200microns and at this level the Flexural strength is found to be 35.28 N/mm2, While the optimal parameter level obtained for Compressive Strength is Printing Speed 60 mm/sec, Infill Density 80%, Layer height 100microns and at this level the Compressive Strength is found to be 24.35N/mm2. From the Grey Relational Analysis, it was found that the optimal parameter level Speed 60mm/sec, Infill Density 80%, Layer height 100microns. The confirmation test was carried out at this level then observed the following results: Ultimate Tensile Strength 32.5 N/mm2, Flexural strength 35.23 N/mm2 and Compressive Strength 26.23 N/mm2.

CONCLUSIONS:

Materials with high strength to weight ratio like Carbon Fiber composite materials are used to manufacture light weight parts which can be used to produce MAV‘s and also to replace some parts in other beneficiary industries. The experiments were conducted to analyze the mechanical properties of 3D-printed specimens with Carbon Fiber PLA and Carbon Fiber Reinforced PET-G and optimization was done to optimize the different machining parameters like Printing Speed, Infill Density and Layer Height of FDM machine. From Taguchi and Grey Relational Analysis it can be concluded that:

- For the Ultimate Tensile Strength applications Carbon fiber reinforced PET-G has better results.
- For the Flexural and Compressive Strength Carbon Fiber PLA has better results.
- Overall Carbon Fiber PLA can be concluded as the suitable material to prepare MAV vehicles.
- The optimal set of printing parameters for **Carbon Fiber PLA** is

Taguchi Analysis: Tensile Strength-Printing Speed=80mm/sec, Infill Density= 60%, Layer Height= 300microns Flexural Strength-Printing Speed=60mm/sec, Infill Density= 40%, Layer Height= 200microns Compressive Strength-Printing Speed=100mm/sec, Infill Density= 60%, Layer Height= 200microns **Taguchi Grey Relational Analysis:** Printing Speed=80mm/sec, Infill Density= 60%, Layer Height= 300microns

- The optimal set of printing parameters for **Carbon Fiber reinforced PET-G** is

Taguchi Analysis:

Tensile Strength-Printing Speed=80mm/sec, Infill Density= 80%, Layer Height= 100microns

Flexural Strength-Printing Speed=60mm/sec, Infill Density= 80%, Layer Height= 200microns Compressive Strength-Printing Speed=60mm/sec, Infill Density= 10%, Layer Height= 200microns **Taguchi Grey Relational Analysis:** Printing Speed=60mm/sec, Infill Density= 80%, Layer Height= 200microns

 From ANOVA analysis:

From ANOVA it can be concluded that Layer Height is the most influential parameter on Tensile Strength, Printing Speed and Layer Height are the influential parameters for Flexural strength, Infill Density is the influential parameter for Compressive Strength. By considering all these observations and conclusions one can develop the MAV vehicles according to the usage.

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