Additive Manufacturing by FDM using ABS/MMT as Feedstock

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Abstract

Mont MorinoliteNanoclay (MMT) reinforced in Acrylonitrile Butadiene Styrene (ABS) has evoked interest of researchers for development of packaging materials. This paper deals with parametric optimisation of fused deposition modelling (FDM) specimens. ABS/MMT specimens were prepared via soften mixing and extruded as filaments for producing FDM specimens. Parametric study was performed considering layer thickness, shell thickness and infill density as parameters. Tensile, flexural and impact strengths of the FDM specimens were determined. All the three parameters of FDM influenced all the three responses. However, Grey Relational Analysis showed significant influence of shell thickness.

Keywords: *ABS/MMT,Fused Deposition Modelling, Grey Relational Grade, ANOVA*

1.0 Introduction

Rapid Prototyping (RP) is a fabrication technique for developing 3D models based on Computer Aided Design (CAD) of physical parts. RP is used to develop products based on the scaled down dimensions to fully developed product. It is widely used in automobile industries for manufacturing automobile parts to cut down production time and production cost of manufacturing the components [1-5]. Usage of RP is growing in medical applications such as organ and tissue building, anatomy modelling, customized prosthetics and implant fabrication [6-11]. FDM is used for development of concept models, manufacturing of tools, end-use parts and functional prototypes [12-14]. Thermoplastics used in FDM include polylactic acid (PLA), polycaprolactone (PCL), acrylonitrile-butadiene-styrene (ABS), polylactic acid (PLA), polystyrene (PS), polypropylene (PP), and polycarbonate (PC) [15-18]. Addition of nanoparticles in FDM feedstock enhances mechanical and electrical properties of 3D printed parts [19-22].

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Nanofillers such as short glass fibres, carbon fibres, nanoclay and carbon black are explored for FDM feedstock. Incorporation of nanofillers increases the viscosity of the materials, which influences the printability of nanocomposite filament. Most common of the mixing methods is melt extrusion [23-25]. Among reinforcing materials, short fibre reinforced with ABS has greater porosity in 3D printed composites than those of the compression moulded. Sithiprumnea et.al.reported that graphene nanoplatelets compounded in 4 wt. % ABS improved its mechanical properties[26]. Sun et al. observed that PC/clay improved tensile strength [27]. Chamil et al.reported that ABS in PLA at 100% infill density resulted in Young's modulus of 1538 MPa [28]. Sajjad et al.reportedhighest tensile strength with 2 wt. % nanoclay and highest hardness with 4 wt. % nanoclay in ABS/MMT [29]. Priyanka et al.reported that ABS/cloisite 30B showed improvement in torsional, axial and impact properties and hence the potential of the materials for application of external orthotic devices [30]. Venkatesh et al. reported preparation of PP/organomodifiednanoclay with and without compatibilizer and improvement in storage modulus with increase in nanoclay content from 3 to 9 wt. % [31]. Nevin et al. reported carbon fibre/ PA6 increased in tensile strength [32]. Nikzad et al. reported that ABS/Fe and ABS/Cu with metal nanopowderupto 40 vol. % was carried out to study their viscoelastic properties [33]. Li et al. reported that ABS /HNO_3 treated short carbon fibres showed improvement in tensile modulus and tensile strength [34]. Basavaraj et. al.reported influence of thickness of layer, shell thickness and on FDM of nylon[35]. Singh et al. reported 5wt. % of Al_2O_3/Nylon showed high tensile strength [36]. Feng et al. observed that good interfacial adhesion between RCF/nylon6 resulted in significant improvement in tensile strength [37]. Francis et al. reported ABS/polymer-layered silicate (PLS) improved mechanical strength of FDM parts [38].

Review of Literature indicates that several authors performed studies to improve surface roughness, mechanical properties and dimensional accuracy of FDM components. Also parametric studies are reported on the influence of layer thickness, air gap, orientation of part build, raster angle, and raster width on FDM parts. Latest FDM machines have provision for optimising the feed stock and hence the properties of FDM components by selecting the best parametric combination of shell thickness, infill density and layer thickness. It provides scope for extended study and parametric optimization of FDM components. Software Cura with Slic3r was used in the present research to set constant parameters namely speed, print temperature, bed temperature and varying parameters namely infill density, shell thickness, layer thickness to achieve lower consumption of material and improved strength. Efforts for improving properties of ABS by dispersing fillers showed promising results.

2.0 Experimental Details

2.1 Materials and processes

ABS with tradename Sinkral®F322 supplied by Versalis S.P.A. (Mantova, Italy) was used in this research. The polymer softens at 14 cm^3/10 min (@220 ^{0}C/10 kg) and has a density of 1.04 g/cm^3 [31].ALDRICH 682624-500G, MMT, surface modified with 35 to 45% dimethyl dialkyl (C14-C18) amine, manufactured from Nanocor, batch #04005HJ, Sigma Aldrich MMT, was used [32].

2.2 Fabrication of FDM feedstock

ABS in pellet form was mixed with MMT in a blender. ABS/ MMT was dried for two hours at 60^{o}C to 80^{o}C. The dried ABS/MMT was passed through a single screw extruder at 120^{o}C to 220^{o}C, through several heated chambers for melting and mixing. The melt mix was pulled out of a die of fixed dimensions. A laser diameter gauge was used to ensure 1.75 mm diameter of the filament. Finally, the filament was wrapped for spool refills. The filaments were vacuum sealed to avoid moisture ingress.

3.0 Experimental Investigation Acrylonitrile Butadiene Styrene (ABS) with MMT Filler

ABS with MMT filler was fabricated in fused deposition machine as per ASTM standard dimensions. The fabrication was conducted depending upon the design of experiment with the help of Taguchi L_9 orthogonal array. The experimental plan of L_9 orthogonal array and responses for tensile, flexural and impact strength were tabulated in table 1.

3.1 Calculations for ANOVA

ANOVA was performed in order to investigate the influence of process parameters such as layer height, shell thickness and infill density for tensile, flexural and impact strength response of ABS with MMT. The strategy of pooled sum of errors was considered and the results of ANOVA are analyzed most influencing factor responses of ABS. Influence of the parameter was investigated using ANOVA at 95% confidence level using MINITAB 16 version. The assessment was made using F and P distributions [21].

Table 1. Experimental Investigation ABS with MMT nanofiller- L_9 Orthogonal Array

Sl No.	Layer Thickness (mm)	Shell thickness (mm)	Infill density (%)	2.5%			5%			7.5%			10%		
				UTS	FS	IS	UTS	FS	IS	UTS	FS	IS	UTS	FS	IS
1.	0.1	0.5	20	15.92	38.23	41.83	26.41	68.21	24.60	31.58	94.14	19.68	24.03	99.40	29.52
2.	0.1	1	30	24.09	54.96	31.98	27.36	63.45	44.29	26.47	83.51	29.52	24.83	93.70	44.29
3.	0.1	1.5	40	20.05	52.34	22.14	35.21	79.65	51.67	34.56	104.26	27.06	28.52	120.80	49.21
4.	0.2	0.5	30	12.52	36.45	46.75	23.65	47.71	29.52	27.59	86.41	41.83	23.69	76.60	46.75
5.	0.2	1	40	19.92	37.82	49.21	28.23	53.21	46.75	32.45	97.23	49.21	32.54	84.30	41.83
6.	0.2	1.5	20	24.56	68.48	63.97	32.74	92.54	59.05	23.62	78.35	56.59	24.53	78.90	59.05
7.	0.3	0.5	40	10.12	32.34	44.29	29.73	79.15	34.44	27.27	86.37	39.37	36.82	110.00	46.75
8.	0.3	1	20	23.14	63.78	41.83	24.24	54.59	39.37	20.85	70.19	44.29	29.34	105.00	29.52
9.	0.3	1.5	30	20.34	61.36	44.29	28.95	85.42	41.83	24.74	82.74	49.21	30.54	90.60	39.37

UTS – Ultimate Tensile Strength (MPa), FS – Flexural Strength (MPa), and IS- Impact Strength (KJ/m^2)

3.2 Grey relational Analysis for ABS strengthened with MMT

The grey theory method applies small samples random improbability to solve some problems in systems that are complex in nature and have incomplete information [34]. Generally, two kinds of systems are present namely white system and black system. A system having adequate amount of information is white system and a system having completely unknown information is black system. The grey system has limited information that lies between the white and black system [35]. Grey Relational Analysis (GRA) is a normalization process to solve difficult multi-performance characteristics.

Considering the smaller the Better criteria, the normalised values are given as:

$$x_j(\mathrm{m}) = \frac{\max y_j(\mathrm{m}) - y_j(\mathrm{m})}{\max y_j(\mathrm{m}) - \min y_j(\mathrm{m})} \ldots\ldots (1)$$

Where $x_j(m)$ gives the response after grey relation generation, Max $x_j(m)$ and Min $x_j(m)$ are the highest and lowest value of m^{th} response.

$$\xi i(m) = \frac{\Delta\mathrm{min} + \Psi\Delta\mathrm{max}}{x_j(\mathrm{m}) - \Psi\Delta\mathrm{max}} \ldots\ldots\ldots\ldots\ldots (2)$$

The grey relation coefficient $\xi_i(m)$ is calculated using equation (3), Where $\Delta_{Min,}\, \Delta_{Max}$ corresponds to the minimum and maximum value of $x_j(m)$.

The GRG (Grey relational grade) is analysed as:

$$\gamma_i = \frac{1}{n}\sum_{m=1}^{n}\left(\xi_i(m)\right) \ldots\ldots\ldots\ldots\ldots.\ldots. (3)$$

Here *n* represent the responses. $\xi_i(m)$ correspond to the GRC (grey relation coefficient). γ_I corresponds to the GRG (grey relation grade).

Equation (1) to (3) was used to calculate the response of grey relation grade and order.

Table 2. ANOVA calculation for ABS 2.5% with MMT 97.5%

Source	DOF	UTS				Flexural Strength				Impact Strength			
		SS	MS	F_{Test}	P	SS	MS	F_{Test}	P	SS	MS	F_{Test}	P
Layer Thickness	2	6.96	3.48	3.85	0.20	40.83	20.42	0.64	0.61	683.6	341.8	4.10	0.19
Shell Thickness	2	168.7	84.4	93.2	0.01	973.3	486.7	15.2	0.06	17.51	8.75	0.10	0.90
Infill Density	2	30.51	15.3	16.8	0.05	392.6	196.3	6.12	0.14	187.1	93.53	1.12	0.47
Error	2	1.81	0.95			64.18	32.09			166.8	83.40		
Total	8	208.0				1471				1055			
$F_{Test\ 2,8} = 4.46$													

Individual ANOVA analysis of flexural strength and UTS shows that infill density and shell thickness were significant parameters. Table 2 shows that any of the parameters doesn’t influences the impact strength. The Degree of Freedom (DOF), Sum of Square (SS), and Mean Sum of Square (MS) are evaluated in ANOVA tables.

Table 3. Grey Relational evaluation for ABS 2.5% reinforced with MMT 97.5%

EXPT No.	Grey Relational Grade of UTS, FS and IS			Overall Relational Grade	Grey Relational Order
L1	0.0506	0.0385	0.0540	0.0477	7
L2	0.1043	0.0602	0.0439	0.0695	3
L3	0.0684	0.0553	0.0370	0.0536	6
L4	0.0417	0.0370	0.0609	0.0465	8
L5	0.0676	0.0381	0.0651	0.0570	5
L6	0.1111	0.1111	0.1111	0.1111	1
L7	0.0370	0.0341	0.0572	0.0428	9
L8	0.0928	0.0859	0.0540	0.0776	2
L9	0.0701	0.0769	0.0572	0.0681	4

Table 4. Response for GRA of ABS 2.5% with 97.5% MMT

Process Parameter	Layer Thickness	Shell Thickness	Infill Density
Level 1	0.0569	0.0457	0.0788
Level 2	0.0715	0.068	0.0614
Level 3	0.0628	0.0776	0.0511
Max-Min	0.0146	0.0319	0.0277
Order	3	1	2
Mean value of grey relational grade = 0.0247			

Table 3. shows the grey relational grade for tensile, flexural and impact strength of ABS with MMT. Based on ranking order obtained using GRA it is concluded that experiment set no 6 has higher rank order. Hence the overall optimized values are 0.1111. Rank order obtained based on grey relational grade on table 4, shell thickness has more influence on tensile, flexural and impact strength of ABS with MMT followed by infill density and layer thickness.

Table 5.ANOVA calculation for ABS 5% with MMT 95%

Source	DOF	UTS				Flexural Strength				Impact Strength			
		SS	**MS**	**F_{Test}**	**P**	**SS**	**MS**	**F_{Test}**	**P**	**SS**	**MS**	**F_{Test}**	**P**
Layer Thickness	2	6.51	3.25	0.69	0.59	115.6	57.80	0.24	0.80	69.93	34.96	0.66	0.60
Shell Thickness	2	64.90	32.45	6.92	0.12	1326.3	663.10	2.81	0.26	704.04	352.02	0.63	0.13
nfill Density	2	31.32	15.66	3.34	0.23	66.8	33.40	0.14	0.87	49.76	24.88	0.47	0.68
Error	2	9.38	4.69			472.2	236.1			106.24	53.12		
Total	8	112.12				1980.9				929.96			
$F_{Test\ 2,8} = 4.46$													

Individual ANOVA for UTS shell thickness was significant. Flexural and impact strengths revealed that none of the parameter has influenced (Table 5).

Table 6. Grey Relational analysis for ABS 5% reinforced with MMT 95%

EXPT No.	Grey Relational Grade of UTS, FS and IS			Overall Relational Grade	Grey Relational Order
L1	0.0440	0.0533	0.0371	0.0448	7
L2	0.0471	0.0484	0.0599	0.0518	6
L3	0.1111	0.0705	0.0778	0.0865	2
L4	0.0370	0.0370	0.0410	0.0383	9
L5	0.0503	0.0403	0.0649	0.0518	5
L6	0.0778	0.1111	0.1111	0.1000	1
L7	0.0570	0.0696	0.0458	0.0575	4
L8	0.0383	0.0413	0.0519	0.0438	8
L9	0.0533	0.0843	0.0556	0.0644	3

Table 7. Response for GRA of ABS 2.5% with 97.5% MMT

Process Parameter	Layer Thickness	Shell Thickness	Infill Density
Level 1	0.061	0.0469	0.0629
Level 2	0.0634	0.0492	0.0515
Level 3	0.0552	0.0836	0.0653
Max-Min	0.0082	0.0367	0.0138
Order	3	1	2
Mean value of grey relational grade = 0.0195			

Table 6 shows the grey relational grade for tensile, flexural and impact strength of ABS with MMT. Based on ranking order obtained using GRA it is concluded that experiment set no 6 has higher rank order. Hence the overall optimized values are 0.0100. Rank order obtained based on grey relational grade on table 7, shell thickness has more influence on tensile, flexural and impact strength of ABS with MMT followed by infill density and layer thickness.

Table 8.ANOVA calculation for ABS 7.5% with MMT 92.5%

Source	**DOF**	**UTS**				**Flexural Strength**				**Impact Strength**			
		SS	**MS**	**F_{Test}**	**P**	**SS**	**MS**	**F_{Test}**	**P**	**SS**	**MS**	**F_{Test}**	
Layer Thickness	2	65.20	32.6	3.00	0.25	303	151	2.71	0.3	946.2	473.1	37	0.02
Shell Thickness	2	7.42	3.71	0.34	0.74	51.79	25.9	0.46	0.7	178.9	89.43	7.0	0.12
Infill Density	2	64.39	32.2	2.97	0.25	375.5	187	3.36	0.2	5.38	2.69	0.2	0.82
Error	2	21.70	10.8			111.7	55.8			25.55	12.78		
Total	8	158.7				842.0				1156			
$F_{Test\ 2,8} = 4.46$													

The ANOVA analysis of flexural, UTS, and impact strengths revealed that infill density, shell thickness, and layer thickness have not influence the characteristics (Table 8).

Table 9. Grey Relational analysis for ABS 7.5% reinforced with MMT 92.5%

EXPT No.	Grey Relational Grade of UTS, FS and IS			Overall Relational Grade	Grey Relational Order
L1	0.0774	0.0697	0.0370	0.0614	4
L2	0.0510	0.0501	0.0450	0.0487	8
L3	0.1111	0.1111	0.0427	0.0883	1
L4	0.0551	0.0543	0.0617	0.0570	6
L5	0.0850	0.0787	0.0794	0.0810	2
L6	0.0428	0.0441	0.1111	0.0660	3
L7	0.0538	0.0542	0.0575	0.0552	7
L8	0.0370	0.0370	0.0667	0.0469	9
L9	0.0457	0.0491	0.0794	0.0580	5

Table 10. Response for GRA of ABS 7.5% with 92.5% MMT

Process Parameter	Layer Thickness	Shell Thickness	Infill Density
Level 1	0.0661	0.0579	0.0581
Level 2	0.068	0.0589	0.0546
Level 3	0.0534	0.0708	0.0748
Max-Min	0.0146	0.0129	0.0202
Order	2	3	1
Mean value of grey relational grade = 0.0159			

Table 9 shows the grey relational grade for tensile, flexural and impact strength of ABS with MMT. Based on ranking order obtained using GRA it is concluded that experiment set no 3 has higher rank order. Hence the overall optimized values are 0.0883. Rank order obtained based on grey relational grade on table 10, infill density has more influence on tensile, flexural and impact strength of ABS with MMT followed by layer thickness and shell thickness.

Table 11. ANOVA calculation for ABS 10% with MMT 90%

Source	DOF	UTS				Flexural Strength				Impact Strength			
		SS	MS	F_{Test}	P	SS	MS	F_{Test}	P	SS	MS	F_{Test}	P
Layer Thickness	2	70.97	35.48	12.00	0.07	1098.82	549.41	7.91	0.11	187.10	93.50	0.71	0.58
Shell Thickness	2	1.70	0.85	0.29	0.77	8.98	4.49	0.06	0.93	187.10	93.50	0.71	0.58
Infill Density	2	83.86	41.93	14.18	0.06	494.52	247.26	3.56	0.21	66.00	33.00	0.25	0.80
Error	2	5.91	2.95			138.95	69.47			263.70	131.90		
Total	8	162.45				1741.26				703.90			

Individual ANOVA for UTS revealed that layer thickness and infill density were significant and flexural strengths only layer thickness was significant (Table 11). The analysis shows that any of parameters studied have not influence the impact strength.

Table 12. Grey Relational analysis for ABS 10% reinforced with MMT 90%

EXPT No.	Grey Relational Grade of UTS, FS and IS			Overall Relational Grade	Grey Relational Order
L1	0.0377	0.0564	0.0370	0.0437	9
L2	0.0393	0.0499	0.0556	0.0483	7
L3	0.0491	0.1111	0.0667	0.0756	2
L4	0.0370	0.0370	0.0606	0.0449	8
L5	0.0673	0.0419	0.0513	0.0535	4
L6	0.0387	0.0384	0.1111	0.0627	3
L7	0.1111	0.0746	0.0606	0.0821	1
L8	0.0519	0.0648	0.0370	0.0513	5
L9	0.0568	0.0470	0.0476	0.0505	6

Table 13. Response for GRA of ABS 10% with 90% MMT

Process Parameter	Layer Thickness	Shell Thickness	Infill Density
Level 1	0.0559	0.0569	0.0526
Level 2	0.0537	0.051	0.0479
Level 3	0.0613	0.0629	0.0704
Max-Min	0.0076	0.0119	0.0059
Order	2	1	3
Mean value of grey relational grade = 0.0084			

Table 12 shows the grey relational grade for tensile, flexural and impact strength of ABS with MMT. Based on ranking order obtained using GRA it is concluded that experiment set no 7 has higher rank order. Hence the overall optimized values are 0.0821. Rank order obtained based on grey relational grade on table 13, shell thickness has more influence on tensile, flexural and impact strength of ABS with MMT followed by layer thickness and infill density

4.0 Conclusion

- ABS with MMT procedure parameters showed importance with Shell thickness 2.5%,5 % and 10% infill density of 7.5% from the response of GRA.

- The ABS with numerous MMT values of nanofillers are used in the FDM to manufacture the specimen and envisioned the UTS, Flexural Strength and Impact strength. The factors inclusive of layer thickness, shell thickness and infill density had been numerous to estimate the UTS, Flexural and Impact strength. The ABS with 2.5, 5, 7.5 and 10 % of MMT have been used to estimate the characteristics of the materials.
- The UTS, Flexural energy and Impact strength of ABS with 2.5 % MMT nanofillers are anticipated that Flexural strength is 68.48 MPa in layer thickness of 0.2 mm, 1.5 mm and 20 % infill density. The better Impact energy is completed as 63.97 KJ/m^2 in 20 % infill density, 1.5 mm shell thickness, and 0.2 mm layer thickness.
- ABS with 5 % MMT nanofillers are estimated, as proven inside the Table 1. The ABS with 5 % MMT nanofillers have better UTS of 35.21 MPa in 40 % infill density, 1.5 mm shell thickness and 0.1 mm layer thickness.
- ABS with 7.5 % MMT nanofillers are predicted, because the higher UTS is performed as 32.45 MPa in 40 % infill density, 1 mm shell thickness and 0.2 mm layer thickness.
- The UTS, Flexural and Impact strength of ABS with 10 % MMT nanofillers are envisioned, as the higher UTS is carried out as 36.82 MPa in 40 % infill density, 0.5 mm shell thickness and 0.3 mm layer thickness.

References

01. D B Short, A Sirinterlikci, P Badger, B Artieri, Environmental, health, and safety issues in rapid prototyping, *Rapid Prototyping Journal*, 12, 1-9, 2015

02. T Rayna, L Striukova, from rapid prototyping to home fabrication: How 3D printing is changing business model innovation, *Technological Forecasting and Social Change*, 102, 214-224, 2016

03. N Li, Y Li, S Liu, Rapid prototyping of continuous carbon fiber reinforced polylactic acid composites by 3D printing, *Journal of Materials Processing Technology*, 238, 218-225, 2016

04. I F Ituarte, S Chekurov, J Tuomi, J E Mascolo, A Zanella, P Springer, J Partanen, Digital manufacturing applicability of a laser sintered component for automotive industry: a case study, *Rapid Prototyping Journal*, 24 (7), 1203-1211, 2018

05. G Dwivedi,S K Srivastava, R K Srivastava, Analysis of barriers to implement additive manufacturing technology in the Indian automotive sector, *International Journal of Physical Distribution & Logistics Management*, 2017, 47 (10), 972-991, 2017

06. N Brusco, M Andreetto, L Lucchese, S Carmignat, G M Cortelazzo, Metrological validation for 3D modelling of dental plaster casts, *Medical Engineering & Physics*, 29, 954–966, 2007

07. M N AAPatara, T Komeda, C Y Low, J Mahmud, System integration and control of finger orthosis for post stroke rehabilitation, *Materials and Design*, 15, 756 – 765, 2014

08. E Debarre, P Hivart, D Baranski, P Déprez, Speedy skeletal prototype production to help diagnosis in orthopaedic and trauma surgery, *Methodology and examples of clinical applications*, *Orthopaedics & Traumatology: Surgery & Research*, 98, 597-602, 2012

09. I F Ituarte, S Chekurov ,J Tuomi, J E Mascolo, A Zanella, P Springer, J Partanen, Digital manufacturing applicability of a laser sintered component for automotive industry: a case study, *Rapid Prototyping Journal*, 24 (7), 1203-1211, 2018

10. Q Peng, Z Tang, O Liu, Z Peng, Rapid prototyping-assisted maxillofacial reconstruction, *Annals of medicine*, 47(3), 186-208, 2015

11. R Singh, R Kumar, I Mascolo, M Modano, On the applicability of composite PA6-TiO2 filaments for the rapid prototyping of innovative materials and structures, *Composites Part B: Engineering*, 143, 132-140, 2018

12. J Zhang,B Yang, F Fu, F You, X Dong, M Dai, Resistivity and its anisotropy characterization of 3D-printed acrylonitrile butadiene styrene Copolymer (ABS)/carbon black (CB) composites, *Applied Sciences*,7,20-31, 2017

13. Y G Zhou, J R Zou, H H Wu, B P Xu, Balance between bonding and deposition during fused deposition modeling of polycarbonate and acrylonitrile-butadiene-styrene composites, *Polymer Composites*, 41(1), 60-72, 2020

14. M L Shofner, K Lozano, F J Rodriguez-Macias, E V Barrera, Nanofiber-reinforced polymers prepared by fused deposition modelling, *Journal of Applied Polymer Science*, 89, 3081-3090, 2003

15. H Nevin, H Mehrdad, Deposition direction-dependent failure criteria for fused deposition modelling polycarbonate,*Rapid Prototyping Journal,* 20, 221-227, 2014

16. D W Hutmacher, T Schantz, I Zein, K W Ng,S H Teoh, K C Tan, Mechanical properties and cell cultural response of polycaprolactone scaffolds designed and fabricated via fused deposition modelling, *Journal of Biomedical Materials Research,* 55, 203-216, 2001

17. H S Ramanath, C K Chua, K F Leong, K D Shah, Melt flow behaviour of poly-ε-caprolactone in fused deposition modelling, *Journal of Materials Science: Materials in Medicine,* 19, 2541-2550, 2008

18. J H Shim, J Y Won, S J Sung, D H Lim, W S Yun, Y C Jeon, J B Huh, Comparative efficacies of a 3D-printed PCL/PLGA/β-TCP membrane and a titanium membrane for guided bone regeneration in beagle dogs, *Polymers,* 7, 2061-2077,2015

19. R D Farahani, M Dube, Printing polymer nanocomposites and composites in three dimensions, *Advanced Engineering Materials*, 20 (2), 1700539-1700547, 2017

20. U Kalsoom, P N Nesterenko, B Paull, Recent developments in 3D printable composite materials. *RSC Advances*, 6, 60355-60371, 2016

21. S J Leigh, R J Bradley, C P Purssell, D R Billson, D A Hutchins, A Simple, low-cost conductive composite material for 3D printing of electronic sensors, *PLOS ONE*, 7, 49365-49370,2012

22. J T Muth, DM Vogt, R L Truby, Y Menguç, D B Kolesky, R J Wood, J A Lewis, Embedded 3D printing of strain sensors within highly stretchable elastomers, *Advanced Materials*, 26, 6307-6312, 2014

23. P Parandoush, D Lin, A review on additive manufacturing of polymer-fiber composites, *Composite Structures,* 182,36-53, 2017

24. R D Farahani, M Dubé, D Therriault, Three-dimensional printing of multifunctional nanocomposites: manufacturing techniques and applications, *Advanced Materials*, 28, 5794-5821,2016

25. W Zhong, F Li, Z Zhang, L Song,Z Li, Short fiber reinforced composites for fused deposition modelling, *Materials Science and Engineering: A,*301, 125-130, 2001

26. S Dul, L Fambri, A Pegoretti, Fused deposition modelling with ABS–graphene nanocomposites. *Composites Science and Technology*, 85, 181–191, 2016

27. S Suin, S Maiti, N K Shrivastava, B B Khatua, mechanically improved and optically transparent polycarbonate/clay nanocomposites using phosphonium modified organoclay, *Materials and Design*, 54, 553–563, 2014

28. C Abeykoon, P Sri-Amphorn, A Fernando, Optimization of fused deposition modelling parameters for improved PLA and ABS 3D printed structures, *International Journal of Lightweight Materials and Manufacture*, 3,284-297, 2020

29. S M Shishavan, TAzdast, S R Ahmadi, Investigation of the effect of nanoclay and processing parameters on the tensile strength and hardness of injection molded Acrylonitrile Butadiene Styrene–organoclay nanocomposites, *Materials and Design*, 58, 527–534, 2014

30. P Singh, A K Ghosh, Torsional, tensile and structural properties of acrylonitrile–butadiene–styrene clay nanocomposites, *Materials and Design*, 55, 137-145, 2014

31. G S Venkatesh, A Deb, A Karmarkar, S SChauhan, Effect of nanoclay content and compatibilizer on viscoelastic properties of montmorillonite/polypropylene nanocomposites, *Materials and Design*, 37, 285-291, 2012

32. N G Karsli, A Aytac, Tensile and thermomechanical properties of short carbon fiber reinforced polyamide 6 composites, *Materials and Design*, 51, 270-275, 2013

33. M Nikzad, S H Masood, I Sbarski, Thermo-mechanical properties of a highly filled polymeric composites for Fused Deposition Modeling, *Materials and Design*, 32, 3448-3456, 2011

34. J Li, C L Cai, The carbon fiber surface treatment and addition of PA6 on tensile properties of ABS composites, *Current Applied Physics*, 11, 50-54, 2011

35. C K Basavaraj, M Vishwas, Studies on Effect of Fused Deposition Modelling, Process Parameters on Ultimate Tensile Strength and Dimensional Accuracy of Nylon, *Material Science and Engineering*, 149, 82-90, 2016

36. R Singh, S Singh, Development of Nylon Based FDM Filament for Rapid Tooling Application. *Journal of Manufacturing processes*, 95, 103–108, 2014

37. N Feng, X Wang, D Wu, Surface modification of recycled carbon fiber and its reinforcement effect on nylon 6 composites: Mechanical properties, morphology and crystallization behaviors, *Current Applied Physics*, 13, 2038-2050, 2013

38. V Francis, P K Jain, Experimental investigations on fused deposition modelling of polymer-layered silicate nanocomposite, *Virtual and Physical Prototyping*, 11, 109-121, 2016