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ORIGINAL CONTRIBUTION

Development of Nylon Based FDM Filament for Rapid Tooling Application

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Abstract There has been critical need for development of cost effective nylon based wire to be used as feed stock filament for fused deposition modelling (FDM) machine. But hitherto, very less work has been reported for development of alternate solution of acrylonitrile butadiene styrene (ABS) based wire which is presently used in most of FDM machines. The present research work is focused on development of nylon based wire as an alternative of ABS wire (which is to be used as feedstock filament on FDM) without changing any hardware or software of machine. For the present study aluminium oxide (Al_2O_3) as additive in different proportion has been used with nylon fibre. Single screw extruder was used for wire preparation and wire thus produced was tested on FDM. Mechanical properties i.e. tensile strength and percentage elongation of finally developed wire have been optimized by Taguchi L9 technique. The work represented major development in reducing cost and time in rapid tooling applications.

Keywords Screw extruder machine · Fused deposition modelling · Nylon · Al_2O_3

Introduction

As a matter of fact, the new market realities require faster product development and reduced time to meet market demands (like: higher quality, greater efficiencies, cost reductions and an ability to meet environmental and recycling objectives) [1–3]. To reduce the product development time and cost of manufacturing, new technology of rapid prototyping (RP) has been developed [2]. Fused deposition modelling (FDM) is one of the RP technology which works on an "additive" principle where material in form of layers is extruded out of nozzle tip [3]. A plastic filament or metal wire is unwound from a coil and material is supplied to an extrusion nozzle [4]. Presently FDM fabricate parts are used for design verification, form and fit checking and patterns for casting processes and medicine application [5]. New materials for FDM are needed to increase its application domain especially in RT and rapid manufacturing (RM) areas [5]. A key requirement for any material to be used in FDM is compatibility of material with existing FDM setup without changing functional hardware/software of machine. Apart from compatibility, mechanical properties of material are also important to explore its industrial applications [6]. The development of alternative materials considering polymer, plastic, metal and composite made it a tough job as requirements of feed stock filament as well as FDM machine are very specific [7]. The literature review reveals that very less has been reported on development of feedstock filament other than ABS for FDM [5–8]. In previous reported studies feedstock filament was developed using iron powder and ABS powder in proportion of 10 % iron powder and 90 % ABS powder by volume with an aim to improve mechanical and thermal properties of filament wire [5]. Whereas, in another development process metal–polymer elements were chosen in varying volume fractions of metal powder as 5, 10, 20, 30 and 40 % for producing appropriate feed stock filament for FDM [6]. The results of these studies highlights that iron and copper powders as short fibre fillers were used because of good mechanical and thermal properties, as well as their capabilities of mixing and surface bonding with polymers [4]. Twin-screw extruder, with a screw diameter of

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34 mm and L:D ratio of 34 and single screw extruder with a screw diameter of 30 mm and length of 800 mm were used to develop FDM filament (The diameter of the filament was controlled to fall in the range of 1.75–1.90 mm). Some studies highlighted that glass fibres were used to significantly improve the strength of an ABS filament at the expense of reduced flexibility and handle-ability [7].

Almost all reported literature highlights metal based composites with ABS combination that has been suggested for FDM feedstock filament [5–10] and no alternative to ABS has been explored in detail. The present research paper presents the development of nylon based wire as alternative of ABS material and composite material Al_2O_3 as matrix reinforcement for filament of FDM. The aim is to develop the new composite with desirable mechanical properties for RT applications and to study properties like tensile strength and percentage elongation of the wire formed.

Experimentation

In any development work, the most important task is to obtain maximum realistic information with the minimum number of well-designed experiments and factors affecting output of process, which must be optimised using Design of Experiments (DoE). Taguchi L9 OA has been used to design final control log of experimentation for the present study. Development of FDM feedstock filament wire has been carried out on single screw extruder as shown in Fig. 1.

In the present research work, pilot experimentation, as shown in Table 1, has been conducted with an aim of selection of optimum input levels and nylon–Al_2O_3 used in granular form. Nylon granules (as shown in Fig. 2) was mixed with varying proportion of Al_2O_3 and then processed on extruder machine under controlled processing parameters. Based on pilot experimentations, levels of

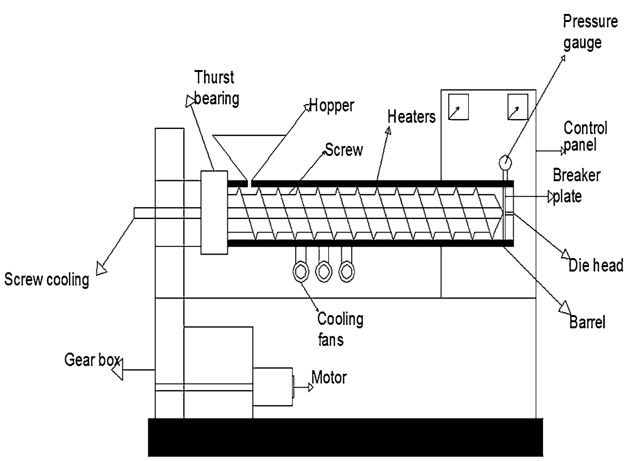

Fig. 1 Schematic of single screw extruder machine

Fig. 2 Nylon granules

Table 1 Results of pilot experimentation

S. no.	Barrel temperature (°C)	Screw speed (RPM)	Vol.% of Al_2O_3 in nylon	Tensile strength (Kg/mm^2)	Elongation (%)
1	170	15	2.5	14.85	11.4
2	180	25	5	41.81	27.8
3	185	30	7.2	30.69	17.2
4	190	35	10	30.24	28.1

Table 2 Input parameters

Barrel temperature (°C)	Screw speed (RPM)	Vol.% of Al_2O_3 in nylon
180	25	5
185	30	7.5
190	35	10

Table 3 Control log of experimentation

S. no.	Barrel temperature (°C)	Screw speed (RPM)	Vol.% of Al_2O_3 in nylon
1	180	25	5
2	180	30	7.5
3	180	35	10
4	185	25	7.5
5	185	30	10
6	185	35	5
7	190	25	10
8	190	30	5
9	190	35	7.5

input parameters as shown in Table 2 were selected and mechanical properties were optimized.

A total of 27 experiments were conducted and each experiment was conducted thrice under unchanged input levels to reduce experimental error. The control log of experimentation is given in Table 3. Figure 3 shows the finally developed wire. Mechanical tests were performed on the developed wire and compared with standard ABS wire supplied by manufacturer (OEM) thereafter.

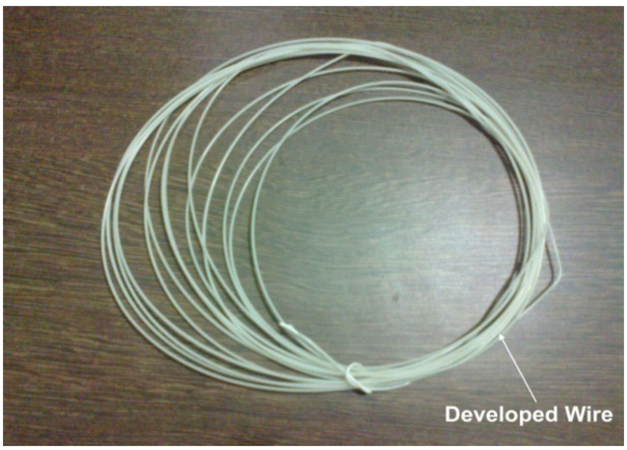

Fig. 3 Developed wire

Table 4 Standard ABS wire average results

Tensile strength (Kg/mm^2)	Elongation (%)
2.24	6

Results and Discussion

The results obtained by final experimentation were analyzed by using signal to noise (S/N) ratio analysis. Results obtained from standard ABS wire are given in Table 4. All tests were conducted on universal tensile testing machine under controlled environment as per ASTM-D638 standard.

Tensile Strength

Observations from experiments conducted are shown in Table 5, whereas Fig. 4a–c shows the variation of S/N ratio and tensile strength with respect to barrel temperature, screw head speed and percentage proportion of Al_2O_3 in nylon. Table 6 shows the S/N response for tensile strength. From Table 5, it was observed that the strength of developed wire was uniformly obtained at different positions of a long wire due to homogeneous mixing of alumina with nylon.

Percentage Elongation

Table 7 shows the results for elongation and Fig. 5a–c show the variation of S/N ratio and percentage elongation with respect to input variables, whereas, Table 8 shows the S/N response to percentage elongation data.

The percentage contribution of different process variables in tensile strength and percentage elongation are represented by 3D Pie charts in Fig. 6. These results are valid for 95 % confidence level. It should be noted that in commercially used FDM machines, the operation cost is around 2.74×10^5 US\$/m^3 with ABS filament. The major part of this cost is attributed to patented ABS wire material. With this new development of nylon based filament, this cost is reduced to 0.7506×10^5 US\$/m^3 with flexibility of improved/controlled mechanical properties for tailor made RT/RM applications.

Table 5 Tensile strength results

S. no.	Barrel temperature (°C)	Screw speed (RPM)	Vol.% of Al_2O_3 in nylon	Tensile strength (Kg/mm^2)		
				L1	L2	L3
1	180	25	5	16.82	15.65	16.18
2	180	30	7.5	34.24	31.33	32.11
3	180	35	10	41.81	40.95	41.12
4	185	25	7.5	10.69	9.46	9.84
5	185	30	10	8.06	8.13	7.94
6	185	35	5	22.47	19.85	20.32
7	190	25	10	9.71	8.98	8.28
8	190	30	5	16.21	16.14	15.21
9	190	35	7.5	11.96	11.81	11.72

L1, L2 and L3 are three repetitions of experiment conducted as per Table 3

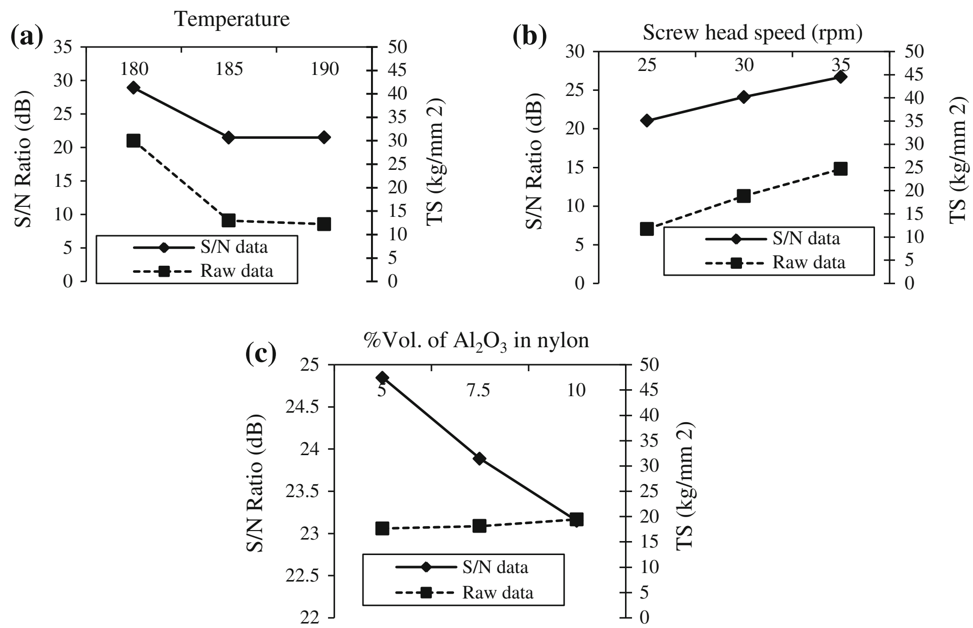

Fig. 4 Variation of S/N ratio and tensile strength w. r. t. **a** barrel temperature, **b** screw head speed and **c** vol. proportion (%) of Al_2O_3 in nylon

Table 6 S/N response to tensile strength data

L1	L2	L3	Sum reci.	S/N ratio	Avg.
16.82	15.65	16.18	0.003812	24.18794	16.21667
34.24	31.33	32.11	0.000947	30.23554	32.56
41.81	40.95	41.12	0.000587	32.31655	41.29333
10.69	9.46	9.84	0.010084	19.96355	9.996667
8.06	8.13	7.94	0.015462	18.10748	8.043333
22.47	19.85	20.32	0.002313	26.35737	20.88
9.71	8.98	8.28	0.012531	19.02013	8.99
16.21	16.14	15.21	0.003989	23.99135	15.85333
11.96	11.81	11.72	0.007147	21.45879	11.83

Table 7 Percentage elongation results

S. no.	Barrel temperature (°C)	Screw speed (RPM)	Vol.% of Al_2O_3 in nylon	Elongation (%)		
				L1	L2	L3
1	180	25	5	15.4	15.3	15.3
2	180	30	7.5	27.8	27.6	27.7
3	180	35	10	27.6	27.3	27.2
4	185	25	7.5	10.3	10.1	10.2
5	185	30	10	11.7	11.6	11.7
6	185	35	5	17.1	17	16.8
7	190	25	10	7	6	6
8	190	30	5	18.2	18	18.1
9	190	35	7.5	7.6	7.5	7.5

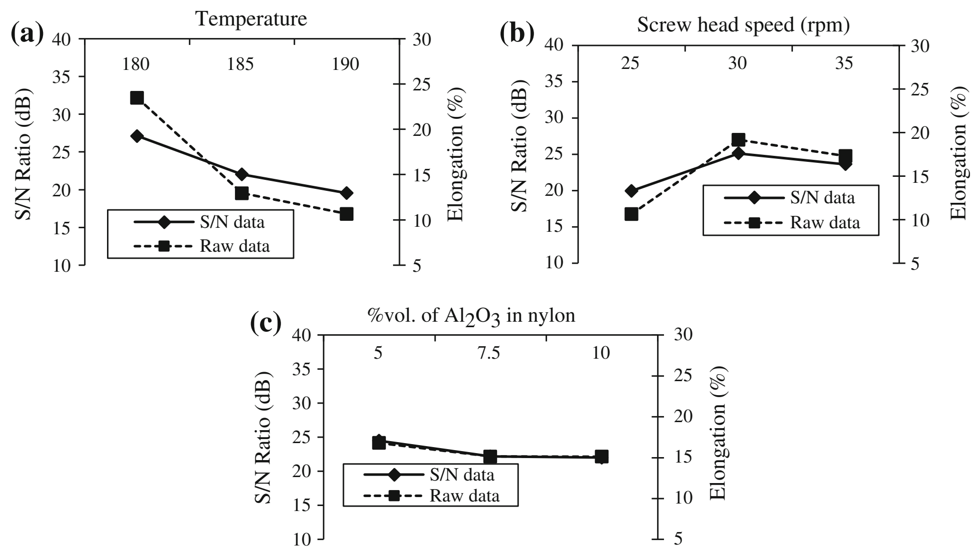

Fig. 5 Variation of S/N ratio and percentage elongation w. r. t. **a** barrel temperature, **b** screw head speed and **c** vol. proportion (%) of Al_2O_3 in nylon

Table 8 S/N response to percentage elongation data

L1	L2	L3	Sum reci.	S/N ratio	Avg.
15.4	15.3	15.3	0.004253	23.71261	15.33333
27.8	27.6	27.7	0.001303	28.84948	27.7
27.6	27.3	27.2	0.001335	28.74394	27.36667
10.3	10.1	10.2	0.009614	20.17117	10.2
11.7	11.6	11.7	0.007347	21.33872	11.66667
17.1	17	16.8	0.003474	24.59122	16.96667
7	6	6	0.025321	15.96515	6.333333
18.2	18	18.1	0.003053	25.15331	18.1
7.6	7.5	7.5	0.017623	17.53924	7.533333

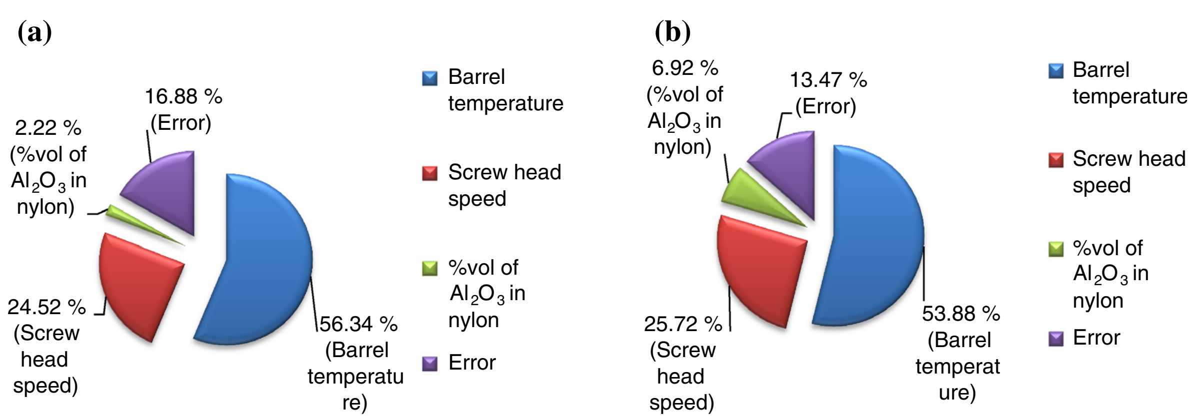

Fig. 6 Pie charts showing percentage contribution of various parameters **a** tensile strength and **b** percentage elongation

Conclusions

The outcome of present research work outlines the possibilities of alternative feedstock filament of FDM. However, precise control is required at each level of development process inclusive of testing. The flexible filaments of the new material have been successfully produced and processed in the existing FDM setup. Mechanical properties like tensile strength and percentage elongation has been increased significantly. The main conclusions are summarized as follows:

1. Nylon based feed stock filament for FDM machine has been developed and composite material provide good mechanical properties as compared to the conventional filament used.
2. It has been observed that tensile strength was maximum when, 5 % proportion of Al_2O_3 is mixed in nylon, barrel temperature being kept at 180 °C and screw head speed being 35 rpm. Similarly, in case of percentage elongation, optimized settings are at barrel temperature of 180 °C, screw head speed of 30 rpm and Al_2O_3 proportion 5 %.
3. Percentage contribution of different input parameters for tensile strength is: barrel temperature-56.34 %, screw head speed-24.52 % and Al_2O_3 proportion-2.22 %. In case of percentage elongation, contribution of different input parameters is: barrel temperature-53.88 %, screw head speed-25.72 % and Al_2O_3 proportion-6.92 %.

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