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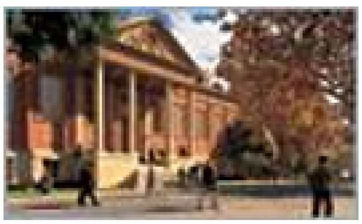

Mechanical, thermal and melt flow of aluminum-reinforced PA6/ABS blend feedstock filament for fused deposition modeling

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Abstract

Purpose – This study aims to highlights the mechanical, thermal and melting behavior compatibility of aluminum (Al)-reinforced polyamide (PA) 6/ acrylonitrile butadiene styrene (ABS)-based functional prototypes prepared using fused deposition modeling (FDM) from the friction welding point of view. Previous studies have highlighted the use of metallic/non-metallic fillers in polymer matrix for preparations of mechanically improved FDM feedstock filaments and functional prototypes. But hitherto, very less has been reported on fabrication of functional prototypes which fulfill the compatibility of two polymers for joining/welding-based applications. The compatibility of two dissimilar polymers enables the friction welding for maintenance applications.

Design/methodology/approach – The twin screw extrusion process has been used for mechanical mixing of metallic reinforcement in polymer matrix, and final blend of reinforced polymers in the form of extruded feed stock filament has been used on FDM for printing of functional prototypes (for friction welding). The methodology involves melt flow index (MFI) investigations, differential scanning calorimetry (DSC) investigations for thermal properties, tensile and hardness testing for mechanical properties and photo micrographic investigations for metallurgical properties on extruded samples.

Findings – It was observed that the reinforced ABS and PA6 polymers have better compatibility in the terms of similar melt flow, thermal properties and can lead to the better joint efficiency with friction welding.

Originality/value – In the present work composite feed stock filament composed of ABS and PA6 with reinforcement of Al powder has been successfully developed for preparation of functional prototype in friction welding applications.

Keywords FDM, Thermal properties, ABS,

Paper type Research paper

1. Introduction

Fused deposition modeling (FDM) technology has evolved since the late 1980's with development of a series of FDM equipment such as FDM Titan, FDM Dimension, FDM Vantage, FDM Maxum, FDM 3000 and FDM Prodigy Plus over the last four decades, (Bakar *et al.*, 2010). Many researchers have worked on the development of feedstock filament for FDM, and it has been ascertained that besides cost factor, the mechanical/metallurgical properties of prototypes can also be improved. Some researchers have reported use of Nylon6 matrix reinforced by Fe metal fillers for development of polymer composites as a direct rapid tooling (Masood and Song, 2004). The screw extrusion process was used for preparations of FDM feedstock filament comprising ABS with iron (Fe) powder as filler. In that study, 10 per cent Fe powder (by weight) was reinforced with ABS matrix, which contributed for better mechanical properties as compared to the virgin ABS filament (Nikzad *et al.*, 2007).

Another study has been conducted to understand the optimal part deposition orientation for FDM process by considering two objectives, namely building time and average part surface roughness (Thrimurthulu *et al.*, 2004). Further investigations were made to examine the thermal and mechanical properties of ABS polymer matrix with metal powder filler. Fe/ABS and copper (Cu)/ABS were mixed mechanically and extruded though the screw extruder machine.

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The results of the study highlighted the effect of filler percentage on the elongation of functional prototypes (Nikzad *et al.*, 2011). There are many obstacles in the development of FDM feedstock wire such as composition should have a relative melt flow index, a uniform mix of the filler is required and there should be uniformity of the extruded filament as well. Researchers have introduced a non-conventional extrusion process named as extruder deposition process (EDP), which uses a numerically controlled mechanism to build components (Reddy *et al.*, 2007). The previous studies also reveal the influences of input process variables such as: chamber temperature, nozzle temperature and road gap on bond strength and surface finish (Singh *et al.*, 2017). Reinforcement of metallic and non-metallic fillers leads to the improvement in mechanical and morphological characteristics of the polymer matrix as well as polymer compatibility for joining and mixing (Cai *et al.*, 2017; Puyvelde *et al.*, 2001; Banerjee *et al.*, 2017). Some studies explained the application of polymer blends with carbon fiber or other metallic/nonmetallic fillers for biomedical and dental applications (Bonon *et al.*, 2016; Finotti *et al.*, 2017). Dissimilar polymer-based materials often face a problem in mixing with each other or their compatibility. Some researchers have studied the effect of metallic and non-metallic compounds at micron or nano-size level to enhance the compatibility, mixing and thermal stability (Chen *et al.*, 2016; Faker *et al.*, 2008; Hamad *et al.*, 2015; Ma and Yang, 2008; Nguyen *et al.*, 2016; Maroufkhani *et al.*, 2017). Single screw extrusion process for polymeric material often produces a feedstock filament with certain defects like: porosity and non-uniform mixing. So for this reason the twin screw extrusion or reactive extrusion process emerged as commonly used technique to overcome these defects (Russo *et al.*, 2007; Rached *et al.*, 2008; Hansch *et al.*, 2012; Fard and Anderson, 2013; Domenech *et al.*, 2013; Wang *et al.*, 2016). Besides mechanical mixing of polymer matrix with fillers, the chemical mixing in controlled chemical proportion offers a better blend of polymer matrix concerning thermal, mechanical and metallographic properties. The chemical mixing reduces the porosity and improves the packing factors (Na *et al.*, 2002; Li *et al.*, 2004; Sung *et al.*, 2005; Reyes-Labarta *et al.*, 2006; Stark and Jaunich, 2011). Some researchers studied the effect of thermal aging, refinement of grain size, reducing porosity level and outlined that improved mechanical properties can be achieved by using thermal aging process (Marcilla *et al.*, 2001; Mourad, 2010). Friction welding technique originally came into existence to join similar metallic pieces only (Taylor *et al.*, 1989). But later on, much research tested the feasibility of friction welding for dissimilar metals such as steel–aluminum, steel–copper and aluminum–magnesium cylindrical piece (Yilbas *et al.*, 1995; Kostka *et al.*, 2009). Researchers in the present era aim to weld dissimilar polymers. Some studies have reported the mechanism of friction welding for dissimilar polymeric material such as ABS and high-density polyethylene (HDPE) (Gao *et al.*, 2015). Recently, the use of different tools and techniques to explain the effect of tool pin profile, a heating assisted tool and effects of particulate on tensile properties have been highlighted (Patel *et al.*, 2016; Banjare *et al.*, 2016; Yeh and Hsu, 2016; P. *et al.*, 2017).

The literature review reveals that the use of thermoplastics with metallic and non-metallic fillers improves the rheological, mechanical, thermal and morphological properties. Some limited studies have been conducted to highlight the use of fillers to improve the polymer compatibility for joining/welding applications. There is research gap to fabricate the functional prototypes, which fulfill the compatibility of two polymers in terms of joining/welding. The compatibility of two dissimilar polymers enables friction welding for maintenance and structural applications. So in this present work, an attempt has been made to join (by friction welding) two dissimilar thermoplastic materials (namely, ABS and PA6) by maintaining melt flow, thermal, mechanical and morphological properties at similar/compatible levels, which were prepared as functional prototypes using the FDM process.

2. Materials and methods

The purpose of the present study is to develop feedstock filament for FDM of two different polymer composites that must be compatible with each other based upon thermal, mechanical, melt flow and morphological properties. Commercial-grade ABS (Grade- EX58) and PA6 (Grade- PX99848) were selected for preparation of composite feedstock filament subsequently undergoing twin screw extrusion. Table I shows the melting point of market grade ABS (Grade- EX58) and PA6 (Grade- PX99848) tested using DSC.

2.1 Material selection

ABS and PA6 have dissimilar material characteristics based upon their mechanical, chemical, metallurgical and thermal behaviors. These thermoplastic materials have significant difference in their melt flow index (MFI), specific heat capacity, chemical resistivity, melting point, mechanical strength etc. (Table II).

In this study, ABS and PA6 thermoplastic polymeric materials were selected because these materials have wide applications. ABS and PA6 are used in fabrication of automobile parts, pipelines, gas tanks and are used in many civil engineering applications. Both possess good tensile properties and can withstand severe environmental conditions such as humidity, corrosive/erosive environment. The melting point of ABS is considered to be heterogeneous in nature because of its amorphous nature, but its melting range can be considered in between 190 and 220°C, which varies according to different commercial grades of ABS.

2.2 Methods of producing feedstock filament

There are a variety of screw extrusion processes available to extrude feedstock filament for FDM. Single screw extrusion is a conventional process for producing feedstock filament but defects such as tiny pores, blow holes, non-mixing are the major problems associated with this process. Twin-screw extrusion

Table I Melting point evaluated for selected grade of polymers

Materials	Melting point (°C)
ABS	190.55
PA6	223.29

Table II Mechanical, chemical and thermal properties of ABS and PA6, (Kang *et al.*, 1997; Harris *et al.*, 1996; Kudva *et al.*, 1998; Fu and Lauke, 1998; Hale *et al.*, 1999)

Properties	ABS	PA6
Tensile strength (kgf/mm^2)	3.52-5.27	4.22-16.88
Flexural strength (kgf/mm^2)	189.88-267.24	274.27-773.59
Chemical resistance	Poor to fair	Good to excellent
Glass transition temperature (°C)	105	46
Melting point(°C)	No true melting (amorphous)	215°C
Chemical formula	$(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$	$(C_6H_{11}NO)_n$
Density(g/cm^3)	0.9-1.53	1.08
Specific heat capacity(J/kg.K)	1,300	1,600

emerged as an advanced technique for producing feedstock filament free from defects. It ensures mixing, shearing, cooling, heating, compressing, transporting, shaping, pumping, etc. with a very high level of flexibility. The main advantages of twin-screw extruders (intermeshing co-rotating) are their exceptional mixing capability that endows extruded products with remarkable characteristics. In the twin-screw extrusion process, the raw materials may be solids (granules, powders and flours), slurries, liquids and possibly gases (John *et al.*, 2014, Wang *et al.*, 2016). Figure 1 shows the available processes and their variants for producing feedstock filament for FDM.

2.3 Melt flow index

The MFI represents the material flow behavior and quality of thermoplastic materials, (Ferg and Bolo, 2013). Many researchers have investigated and established the relationship of MFI with numerous mechanical, chemical and thermal properties such as yield stress, viscosity, molecular weight distribution and shear rate (Shenoy *et al.*, 1983; Dutta, 1984; Bremner *et al.*,1990; Nichetti and Manas-Zloczower, 1998; Teresa Rodríguez-Hernández *et al.*, 2007; Zulkifli Mohamad Ariff *et al.*, 2012). The ASTM D1238 is applicable for most of the thermoplastic materials. A 3.80-kg load is applied at 230°C through piston and material is collected every 10 min for determination of MFI (Figure 2).

The melt flow properties of any thermoplastic material can be improved and modeled for different field applications by adding certain proportions of fillers such as metallic and non-metallic powders, especially for friction welding application where any two dissimilar plastic-based materials can join by maintaining similar MFI, (Singh *et al.*,2016; Kumar *et al.*, 2017). Table III shows that the MFI changes considerably by varying the proportion of Al metal powder (Commercial, 50 micron grain size) in ABS and PA6 polymer matrix

It has been observed that in case of ABS polymer matrix, increasing the Al metal filler up to 20 per cent leads to increase in the MFI, but above this level there was significant decrease in MFI (Figure 3). It should be noted that molecular weight and density are the two different polymer properties which define the characteristics of polymers. The density is an inherent property of polymer matrix, which does not ascertain the determination of melt flow rate. Molecular weight is an interesting polymer property, which practically ensures the melt flow rate. Higher molecular weight ensures lower melt flow characteristics. Branched long carbon chain causes the increase in molecular weight, but linear or no branched carbon chain results in lower molecular weight (www.ptonline.com). In the present study, MFI of ABS matrix is increased by reinforcing with Al content (by weight) because of the effect of density. But further on, the melt flow decreased mainly because of increase in the molecular weight. This may be because of carbon chain branching/elongation caused by the effect Al powder reinforcement beyond 20 per cent (by weight) under the present environmental conditions. For PA6 polymer matrix, an increase was observed in MFI up to 30 per cent of Al filler but after that, the MFI decreased.

This MFI analysis was considered for the selection of the Al filler concentration for the joining/welding application. PA6 matrix with 50 per cent Al filler and ABS matrix with 15 per cent Al filler resulted in MFI of 11.97 g/10 min and 11.57g/10 min, respectively. Because at these proportions (PA6 with 50 per cent Al and ABS with 15 per cent Al), the MFI values were almost similar, these proportions of Al filler were judicially selected for preparation of feedstock filament for the

Figure 1 Methods for producing feedstock filament (John *et al.*, 2014, Wang *et al.*, 2016)

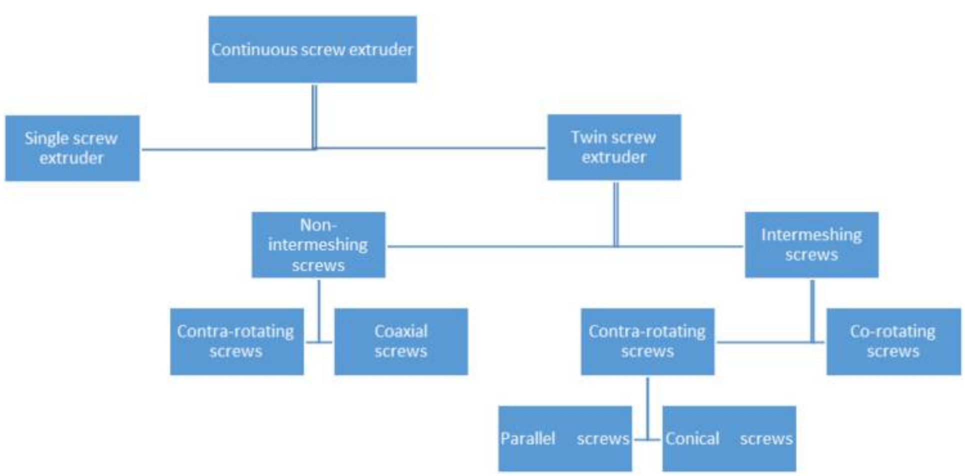


Figure 2 Melt flow indexer and internal configurations

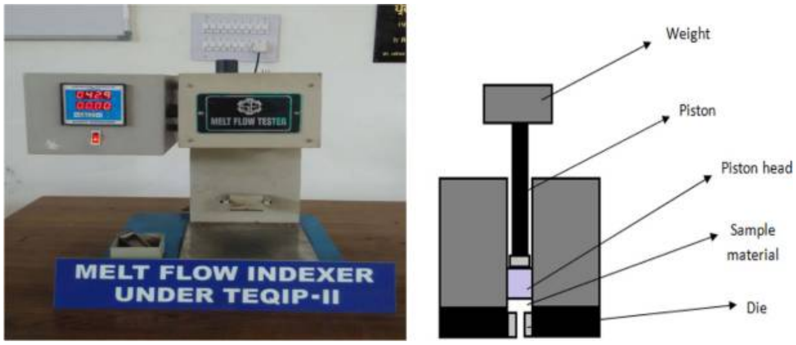
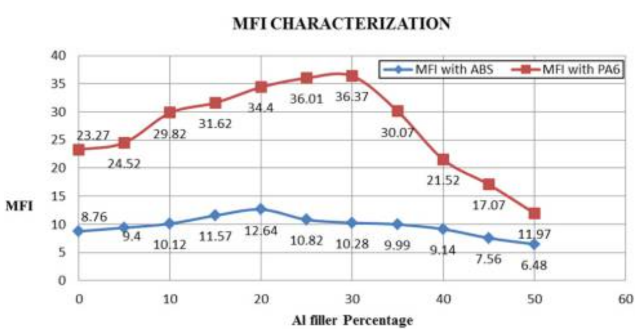


Table III MFI Variation of ABS and PA6 with proportions of Al metal powder filler

Trial no.	Pure ABS	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
1	9.05	8.11	10.54	11.44	12.47	10.38	10.26	9.37	9.33	7.23	7.09
2	8.39	10.39	10.57	11.8	12.49	11.12	10.59	10.63	8.87	7.43	6.81
3	8.86	9.71	9.27	11.48	12.98	10.98	10.01	9.98	9.23	8.04	5.56
Avg.	8.76	9.40	10.12	11.57	12.64	10.82	10.28	9.99	9.14	7.56	6.48
Trial no.	Pure PA6	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
1	23.58	25.17	29.82	33.05	35.23	38.87	36.85	31.82	20.23	15.02	10.76
2	23.27	23.01	30.56	30.93	34.54	33.64	35.39	29.86	21.11	19.27	12.33
3	22.98	25.4	29.09	30.89	33.45	35.53	36.88	28.54	23.23	16.94	12.84
Avg.	23.27	24.52	29.82	31.62	34.40	36.01	36.37	30.07	21.52	17.07	11.97

Figure 3 Variation of MFI over changing Al filler proportion



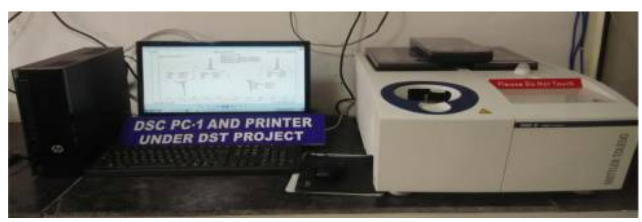
preparation of functional prototypes with FDM for friction welding applications.

2.4 Differential scanning calorimetry analysis

The DSC is advanced thermal analysis equipment that is used to evaluate the glass transition temperature, melting point and melting range and specific heat capacity of different thermoplastic materials with precise outputs (Figure 4).

The DSC evaluation was performed under controlled experimental environment conditions of continuous heating (endothermic changes, 10°C/min) and continuous cooling (exothermic changes, 10°C/min) in 30-250°C temperature range through two consecutive cycles at 50 ml/min of N_2 gas supply. Natural grain of commercial ABS was evaluated under above said conditions of DSC, because ABS comes under the amorphous thermoplastic category so a melting range in between

Figure 4 Laboratory DSC setup

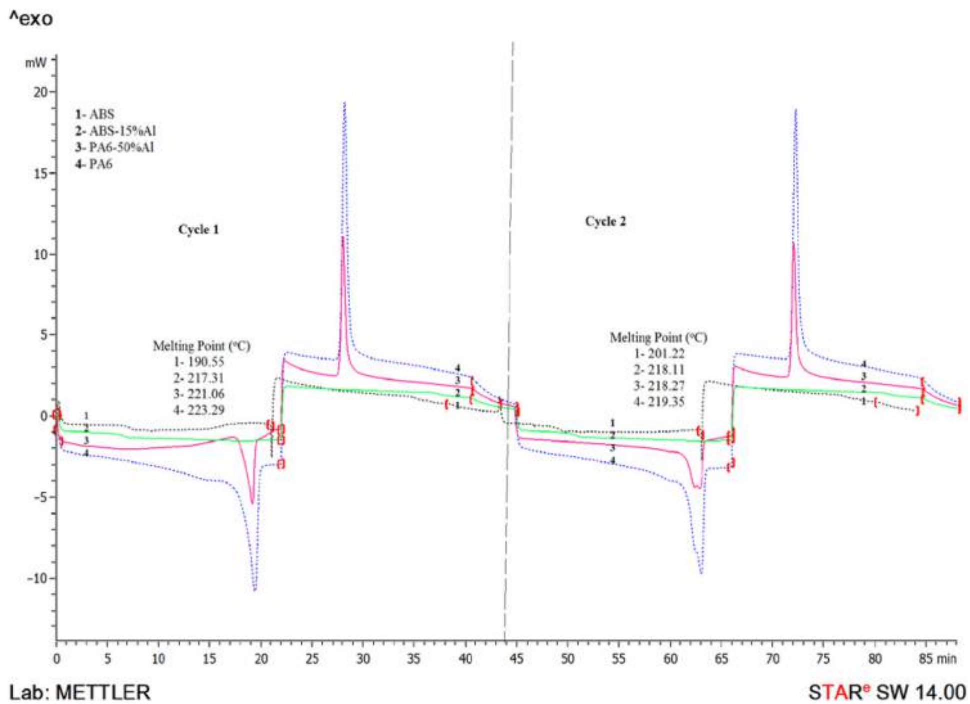


190.55 and 201.22°C was obtained as small melting curve emerged toward end point of continuous heating (Figure 5).

Another experiment was conducted to check the DSC as thermal properties of natural commercial grade of PA6 polymers under previous controlled conditions of endothermic and exothermic changes. In the case of natural PA6 material, true melting curve emerged, and melting point was obtained as 223.29°C and 219.35°C respectively in the first and second heating cycle. PA6 started to solidify from 192.57°C. More specific heat capacity was obtained in the case of PA6 as compared to the ABS material. Another comparison can be made between the ABS and PA6 on the basis of their melting range where the PA6 was melted at high temperature as compared to ABS

The huge difference in thermal properties of natural ABS and natural PA6 restricted their compatibility for friction welding application because friction welding requires similar thermal and rheological properties to perform joining between dissimilar materials. Melt flow property ensured the compatibility of ABS and PA6 in terms of MFI (Table III), at

Figure 5 DSC of ABS, ABS-15%Al, PA6 and PA6-50%Al



ABS with 15 per cent Al filler and PA6 with 50 per cent Al filler. An attempt has been made to see the effect of fixed filler content in terms of their effect on thermal properties which ensured the compatibility of these two mentioned polymers. Thermal properties evaluated for ABS with 15 per cent Al resulted in an improvement in melting range in between 217.31 and 218.11°C and reduced the specific heat capacity at a significant level. After evaluation of thermal properties of ABS with 15 per cent Al, PA6-50 per cent Al matrix was subjected to thermal analysis under the same controlled conditions on which ABS-15 per cent Al was evaluated. Almost similar melting range to ABS-15 per cent Al is achieved. The peak melting point was between 217.31 and 221.06°C both for the ABS-15 per cent Al and PA6-50 per cent Al. The addition of Al fillers have played important role, as the specific heat capacity rate of the thermoplastics was reduced on addition of filler contents. So, based upon these rheological and thermal analyses of ABS and PA6 materials, a condition can be easily obtained for compatibility at certain Al filler level for friction welding applications. At the certain filler level, the melt flow properties of ABS and PA6 material were varied and were brought into similar range. This addition of filler at certain level has contributed toward their similarity in melting point as well as specific heat capacity. The thermal analysis of these selected proportions/compositions ensured that ABS-15 per cent Al and PA6-50 per cent Al is mechanically compatible for friction welding of these two different thermoplastics.

2.5 Dynamic mechanical analysis

The DMA is also known as dynamic mechanical spectroscopy (DMS) which is used to determine the viscoelastic characteristics of polymeric materials. The DMA characteristics of polymer can be expressed as the tan δ which is the ratio of loss modulus and storage modulus which is the function of temperature:

$$\text{Mathematically}\tan\delta = \frac{Loss\ modulus}{Storage\ modulus} \tag{1}$$

The storage modulus measures the stored energy in polymers or composite, representing the elastic portion, and the loss modulus measures the energy dissipated as heat, representing the viscous portion. For the present study, the specimens have been prepared with dimensions of 20 mm $\times$ 9.5 mm $\times$ 1.75 mm on FDM in normal solid mode having raster angle of 45°. The evaluation of DMA characteristics is performed as three-point bending mode at heating rate of 2°C/min with dynamic force of 10 N. The normal frequency of 1 Hz has been maintained. The specimens of ABS, ABS-15 per cent Al, PA6 and PA6-50 per cent Al have been tested to determine their "tan δ" values. Table IV shows the value of "tan δ" for different specimens.

Table IV Observed values of "tan δ" evaluated for specimens

Specimen	tan δ
ABS	0.23
ABS-15%Al	0.09
PA6	0.12
PA6-50%Al	0.08

As observed from the achieved values of "tan δ", initially the difference was significantly large between ABS and PA6. Reinforcement with Al metal powder at desired level for both the polymers has contributed toward the interesting change in "tan δ" value. The values were observed for ABS-15 per cent Al and PA6-50 per cent Al as 0.09 and 0.08, respectively, which are relatively close. The "tan δ" values suggested that the selected polymer with desired Al powder reinforcement have compatibility in terms of DMA.

2.6 Design of experiment (taguchi L9 orthogonal array)

For extrusion of any metals, alloys and thermoplastics, the extrusion temperature is the most important parameter from dimensional accuracy and material stability point of view. DSC results of Figure 5 shows that a peak melting point was obtained in between the range of 217.31 and 221.06°C for all the selected compositions. The levels of extrusion temperature for the present study have been selected on the basis of various considerations:

- The DSC results were obtained in the static environmental condition (controlled) whereas twin-screw extrusion was performed in the dynamic environmental condition (less controlled). Because of dynamic environmental conditions such as influences of external temperature, light and humidity, the extrusion temperature needs to be higher as compared to that obtained with DSC results.
- The DSC results were computed for small material quantity (e.g. 3-15 mg) whereas extrusion was performed under bulk material quantity (e.g. 10-50 gm.). Heat sinking occurs during extrusion process. This may be one of the reasons for selecting an extrusion temperature higher than DSC melting peak results.
- The reinforcement of Al powder leads to absorption of heat because of greater heat capacity behavior. Hence, the extrusion temperature is required to be a little higher based upon pilot experimentation.

Since the melting range was obtained from DSC analysis for proposed composition of Al metal filler with polymer matrix, so the input variables were decided based upon outcomes of DSC results (for the twin screw extruder setup)for further preparations of composite feedstock filament for FDM. The pilot experimentation was conducted and input process parameter was decided based upon the uniformity of the filament extruded. Except temperature, applied load and screw speed were two other process parameters which have significant effect on the change in the properties of the obtained feedstock filaments. During twin-screw extrusion process, there is a role of applied load and screw speed. The screw speed and applied load contributes to the mixing; therefore, these parameters were judicially selected. The selected process parameters for investigations of mechanical properties of ABS-15 per cent Al were selected for temperatures of 220, 225 and 230°C, for applied loads of 10, 15 and 20 kg and for screw speeds of 20, 25 and 30 RPM, respectively. During pilot experimentation, it was observed that the feedstock filaments of PA6-50 per cent Al were obtained uniformly in between temperature range of 240 and 250°C and load conditions of 10-15 kg. So the levels of all the three parameters were selected in given range (Table V and Table VI).

2.7 Twin-screw extrusion process

After selection of input process parameter and their level based upon pilot experimentation according to Taguchi L9 orthogonal array, the experimentation has been performed on the twin-screw extruder setup. The entire filaments were extruded through nozzle with diameter of 1.5 mm (Figure 6).

3. Results and discussion

3.1 Process capability analysis

The diameters of the feed stock filament were measured using Mitutoyo's absolute digimatic micrometers (as per ISO3611-1978) having accuracy up to 0.001 mm. The dimensional analysis was performed to check the eligibility and uniformity of the prepared feedstock filaments toward obtaining the best set of process parameters. The lower and upper critical limit was considered as diameter of 1.50 mm and 1.75 mm, respectively, because conventional FDM setup required the filaments in between this range to fabricate the parts (Tao *et al.*, 2017). It was also observed with pilot experimentation that for printing of functional prototypes on FDM, the feed stock filament diameter below 1.50 mm and 1.75 mm either breaks down or get choked. ABS-15 per cent Al, in experimental condition 5, which is the combination of temperature 225°C, 15 kg load and at 30 RPM screw speed (Table V) is giving better results. Total

Table V Control log of experimentation as per taguchi L9 O.A for ABS-15%Al

Experiment no.	Temperature (°C)	Applied load(Kg)	Screw speed(RPM)
1	220	10	20
2	220	15	25
3	220	20	30
4	225	10	25
5	225	15	30
6	225	20	20
7	230	10	30
8	230	15	20
9	230	20	25

Table VI Control log of experimentation as per taguchi L9 O.A for PA6-50%Al

Experiment no.	Temperature (°C)	Applied load(Kg)	Screw speed(RPM)
1	240	10	15
2	240	15	20
3	240	20	25
4	245	10	20
5	245	15	25
6	245	20	15
7	250	10	25
8	250	15	15
9	250	20	20

Figure 6 Twin-screw extruder

five trial dimensions of each filament has been subjected to the process capability analysis and C_p and C_{pk} value was obtained as best at 6.267 and 4.211, respectively (Table VII).

Experimental condition 5 has been selected as the best process parameter toward attainment of better dimensional accuracy. Figure 7 shows histogram and normal probability plot for experimental condition 5 (as per Table VII).

Table VIII shows dimensional variations for PA6-50 per cent Al filament. The best dimensional accuracy was obtained in experiment no. 8 (Table VI) in terms of best Cp and Cpk values. Figure 8 shows histogram and normal probability plot for experimental condition 8 (as per Table VIII).

3.2 Mechanical properties

3.2.1 Mechanical properties evaluation for prepared feedstock filaments

Based upon Tables V and VI, mechanical properties (namely: peak load, peak strength and hardness) were calculated. Tables IX and X respectively show the mechanical properties and their signal to noise (SN) ratios for ABS-15 per cent Al and for PA6-50 per cent Al filaments. Tensile properties have been sub-categorized as peak strength, peak load, break strength break load, percentage elongation and Young's modulus. Peak strength is the maximum strength of the tensile test specimen before fracture. It was experienced for all specimens tested that fracture strength was lower than the peak strength. The load applied at the peak strength was termed as peak load.

3.2.2 Optimization of input process variables

Figure 9 shows the main effects plot for SN ratios for peak load in case of ABS-15 per cent Al based filament (for larger the better type case). Temperature at level 1, applied load at level 1 and RPM at level 3 contributed most toward better SN ratio of filament preparations process.

Table XI shows the analysis of variance for SN ratios for peak load for ABS-15 per cent Al filament. Based upon Table XI, Table XII shows ranking of input process parameters. These results are at 95 per cent confidence level.

The optimum value of peak load in this case can be predicted by using following equation:

Table VII Dimensional variation for ABS-15%Al

Exp. no.	Ø1	Ø2	Ø3	Ø4	Ø5	Ø Mean	Deflected samples	Value of C_p	Value of Cpk
1	1.66	1.70	1.69	1.76	1.72	1.71	1	1.17	0.41
2	1.71	1.71	1.70	1.69	1.68	1.69	0	6.27	2.61
3	1.69	1.75	1.68	1.69	1.73	1.70	0	1.04	0.35
4	1.64	1.62	1.68	1.66	1.67	1.67	0	1.71	1.31
5	1.66	1.66	1.66	1.68	1.67	1.67	0	6.27	4.21
6	1.67	1.68	1.64	1.67	1.74	1.68	0	1.25	0.70
7	1.73	1.68	1.67	1.67	1.68	1.69	0	2.69	1.37
8	1.64	1.63	1.67	1.69	1.62	1.65	0	1.34	1.07
9	1.64	1.61	1.66	1.64	1.65	1.64	0	1.71	1.50

Figure 7 Histogram and normal probability plot for experimental condition 5

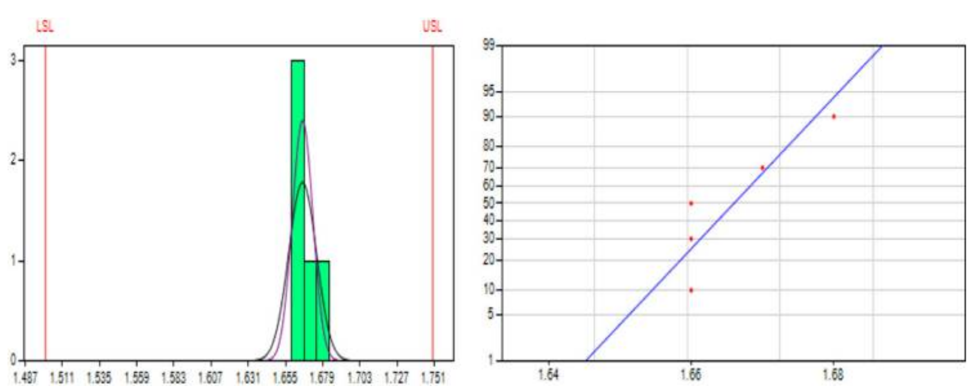


Table VIII Dimensional variation for PA-50%Al

Exp. no.	Ø1	Ø2	Ø3	Ø4	Ø5	Mean	Deflected samples	Value of C_p	Value of Cpk
1	2.07	1.91	1.93	1.99	1.78	1.94	5	0.42	−0.62
2	1.55	1.63	1.68	1.65	1.78	1.66	1	0.65	0.48
3	1.88	1.71	1.61	1.63	1.60	1.69	1	0.59	0.30
4	1.98	1.70	1.57	1.75	1.67	1.73	1	0.28	0.04
5	1.59	1.43	1.54	1.51	1.52	1.52	0	0.61	0.09
6	1.63	1.70	1.66	1.74	1.66	1.66	0	1.45	1.04
7	1.56	1.60	1.67	1.67	1.74	1.65	0	1.04	0.58
8	1.65	1.70	1.67	1.66	1.63	1.66	0	1.57	1.10
9	1.42	1.44	1.63	1.63	1.61	1.55	0	0.82	0.30

Figure 8 Histogram and normal probability plot for experimental condition 8

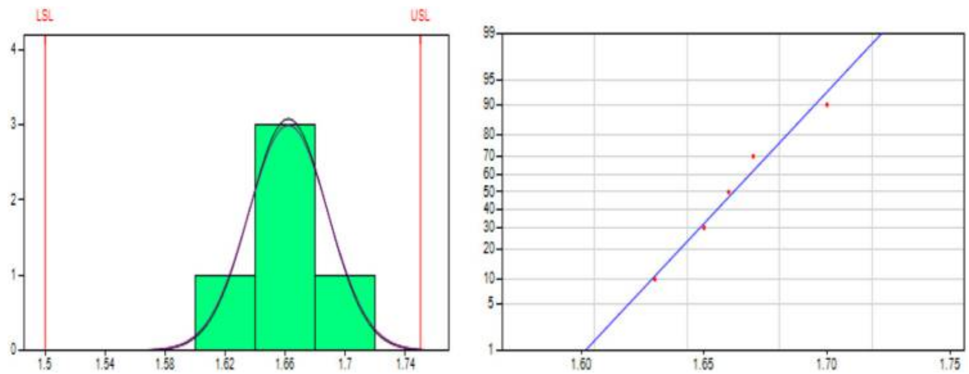


Table IX Mechanical properties and their SN ratios obtained for ABS-15%Al filaments

Experiment no.	Peak Load (N)	S/N ratio (dB)	Peak strength(kg/mm^2)	S/N ratio (dB)	Shore D hardness	S/N ratio (dB)
1	38.7	31.75	17.18	24.70	76.5	37.67
2	40.2	32.08	17.76	24.98	78.5	37.89
3	48.5	33.71	21.18	26.51	79.5	38.00
4	37.2	31.41	17.32	24.77	77.0	37.72
5	43.6	32.79	20.01	26.02	78.5	37.89
6	29.9	29.51	16.50	24.34	79.0	37.95
7	38.7	31.75	17.34	24.78	76.0	37.61
8	23.6	27.46	13.29	22.47	77.5	37.78
9	25.1	27.99	14.09	22.98	78.0	37.84

Note: *For virgin ABS the maximum value of peak load is 59.2N, peak strength is 23.4 kg/mm^2 and shore D hardness is 73

Table X Mechanical properties and their SN ratios obtained for PA6-50%Al filaments

Experiment no.	Peak load (N)	S/N ratio (dB)	Peak strength (kg/mm^2)	S/N ratio (dB)	Shore D hardness	S/N ratio (dB)
1	32.8	30.31	11.15	20.94	76.0	37.61
2	40.2	32.08	13.63	22.68	76.5	37.67
3	49.9	33.96	16.89	24.55	77.0	37.72
4	39.7	31.97	16.82	24.51	74.5	37.44
5	47.2	33.47	20.57	26.26	75.0	37.50
6	64.2	36.15	25.05	27.97	74.0	37.38
7	29.0	29.24	12.98	22.26	74.5	37.44
8	36.4	31.22	15.81	23.97	72.0	37.14
9	38.7	31.75	17.18	24.70	73.0	37.26

Note: *For virgin PA6 the maximum value of peak load is 203 N, peak strength is 9.49 kg/mm^2 and shore D hardness is 71.5

Figure 9 Main effects plot for SN ratio of peak load (ABS-15%Al)

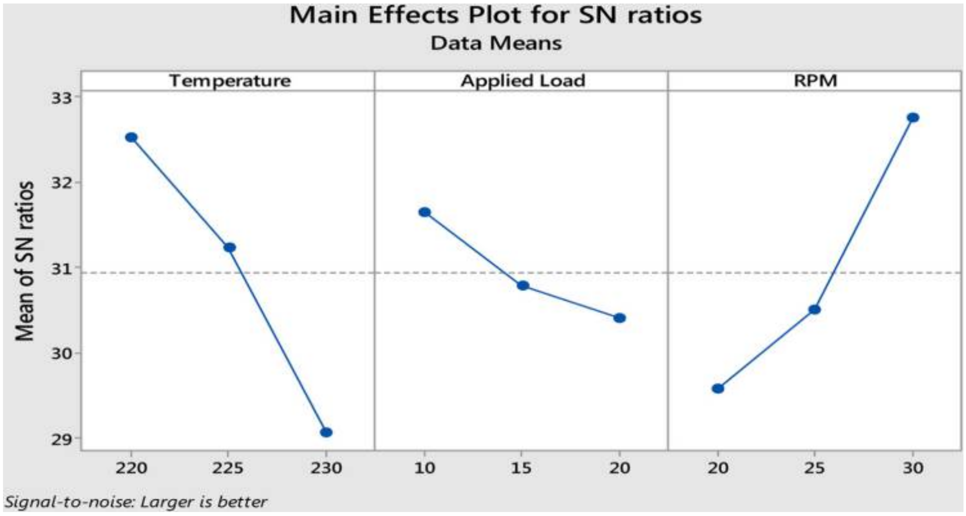


Table XI Analysis of variance for SN ratios of peak load

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	Significance
Temperature	2	18.24	18.24	9.120	130.69	0.008	Yes
Applied load	2	2.39	2.39	1.199	17.19	0.055	No
RPM	2	16.04	16.04	8.019	114.91	0.009	Yes
Residual error	2	0.14	0.14	0.069			Yes
Total	8	36.81					

Table XII Response table for ranking of input parameters for peak load (ABS-15%Al)

Level	Temperature	Applied load	RPM
1	32.52	31.64	29.58
2	31.24	30.78	30.50
3	29.07	30.41	32.75
Delta	3.45	1.23	3.18
Rank	1	3	2

$$\eta_{opt} = m + (m_{A1} - m) + (m_{B1} - m) + (m_{C3} - m) \tag{2}$$

Where "m" is the overall mean of SN ratio, m_{A1} is the mean of SN ratio for temperature at level 1, m_{B1} is the mean of SN ratio for applied load at level 1 and m_{C3} is the mean of SN data for RPM at level 3.

Now for lesser is better by type case:

$$y_{opt}{}^{2} = (1/10)^{\eta opt/10} \tag{3}$$

for properties, Larger is better type case:

$$y_{opt}{}^{2} = (10)^{\eta opt/10} \tag{4}$$

Calculation:

Overall mean of SN ratio (m) was taken from Minitab software (See Table VII):

$$m = 30.94 dB$$

Table XIII Calculated/predicted mechanical properties and experimentally determined values

		Output parameters		
Composition/proportion	Attribute	Peak load(N)	Peak strength(kgf/mm^2)	Hardness(Shore D)
ABS-15%Al	η_{opt}(dB)	35.03	36.68	37.99
	Predicted value(y_{opt})	56.42	21.57	79.34
	Actual value at optimized setup	55.36	21.37	79.5
PA6-50%Al	η_{opt}(dB)	35.91	27.95	37.81
	Predicted value(y_{opt})	62.44	24.97	77.71
	Actual value at optimized setup	38.78	25.01	78.0

Table XIV Combined SN ratios for ABS-15%Al and PA6-50%Al

Experiment no.	Combined SN ratios (ABS-15%Al)	Combined SN ratios (PA6-50%Al)
1	29.53	28.66
2	29.62	29.18
3	30.00	29.68
4	29.52	29.51
5	29.85	29.92
6	29.29	30.36
7	29.55	28.55
8	28.74	29.34
9	28.89	29.51

Now from response table of signal to noise ratio, $m_{A1} = 32.52$, $m_{B1} = 31.64$, $m_{C3} = 32.75$, (From Table IX).

Now taking equation (2), putting the values:

$$\eta_{opt} = 30.94 + (32.52 - 30.94) + (31.64 - 30.94) + (32.75 - 30.94)$$

$$\eta_{opt} = 35.03$$

Now, from equation (4) $y_{opt}{}^{2} = (10)^{\eta opt/10}$

$$y_{opt}{}^{2} = (10)^{35..03/10}$$

$$y_{opt} = 56.42\text{N}$$

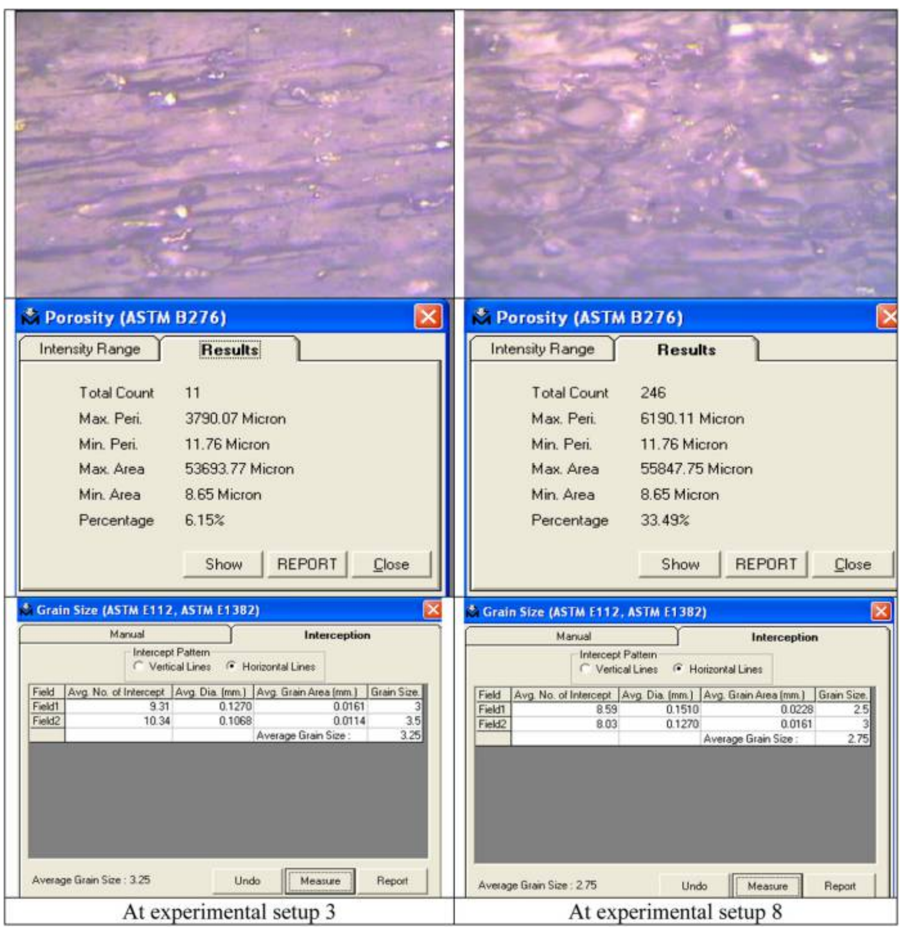
The predicted optimum value for peak load (ABS-15 per cent Al) = 56.42 N.

So, by applying above mentioned equation, predicted value can be determined toward optimization of process parameters, for remaining output parameters (mechanical properties). Based upon Tables IX and X, the predicted and experimentally determined values of output parameters (mechanical properties) at best settings are shown in Table XIII. It should be noted that experiment no. 3 as per Table IX and experiment No.6 as per Table X are optimized settings based upon SN ratio.

3.3 Combined optimization for process parameters

The SN ratios (obtained in Table IX and Table X) were combined to select the best and worst set of input process parameters, which contributed to the change in the mechanical properties from combined optimization point of view (Table XIV). As shown in Table XIV, it can be observed for ABS-15 per cent Al that the SN ratio was achieved maximum for experiment no. 3 as 30.00 and minimum for experiment no. 8 as 28.74. So based upon the

Figure 10 Micro structural evaluation of ABS-15%Al feedstock filaments at 400X magnification



observed values, the setting at experiment no. 3 and experiment no. 8 have been considered as the best and worst set of input process parameters respectively. Similarly in the case of PA6-50 per cent Al, the input parameter combination at experiment no. 6 (SN ratio 30.36) was considered best and at experiment no. 7 (28.55) was worst.

3.4 Morphology of feedstock filaments

The mechanical strength of feedstock filament is inversely proportional to the porosity value observed at the filament surface. The grain structure has been characterized in terms of percentage porosity and related to mechanical strength. For ABS-15 per cent Al, the best mechanical strength was obtained for experiment no. 3 which has the percentage porosity of 6.15 per cent which is lesser than the porosity obtained at experiment no. 8 (Table IX). Figure 10 shows the microstructure, their porosity percentage and grain size at those experimental conditions (i.e. at experiment no. 3 at and experiment no. 8 as per Table V).

Micro structural evaluations were conducted for PA6-50 per cent Al sample, at experiment no. 6 and 7, (as per Table VI) the mechanical properties were obtained as best and worst, respectively. The photomicrographs reveal that the filament samples which possess better mechanical strength has lesser porosity whereas filaments with lowest mechanical strength have greater surface porosity (Figure 11).

4. Compatibility of selected thermoplastic composites in terms of friction welding

After evaluation of all mechanical, metallurgical and thermal properties in terms of compatibility analysis of ABS-15 per cent Al and PA6-50 per cent Al, the parts with selected composition of polymers were fabricated using the commercial FDM setup. The three-dimensional (3D) printed parts of ABS-15 per cent Al and PA6-50 per cent Al were frictionally welded under the rotational speed condition of 775 RPM, 0.014 mm/rev feed rate and 5 s of feeding time at constant

Figure 11 Microstructural evaluation of PA6-50%Al feedstock filaments at 400X magnification

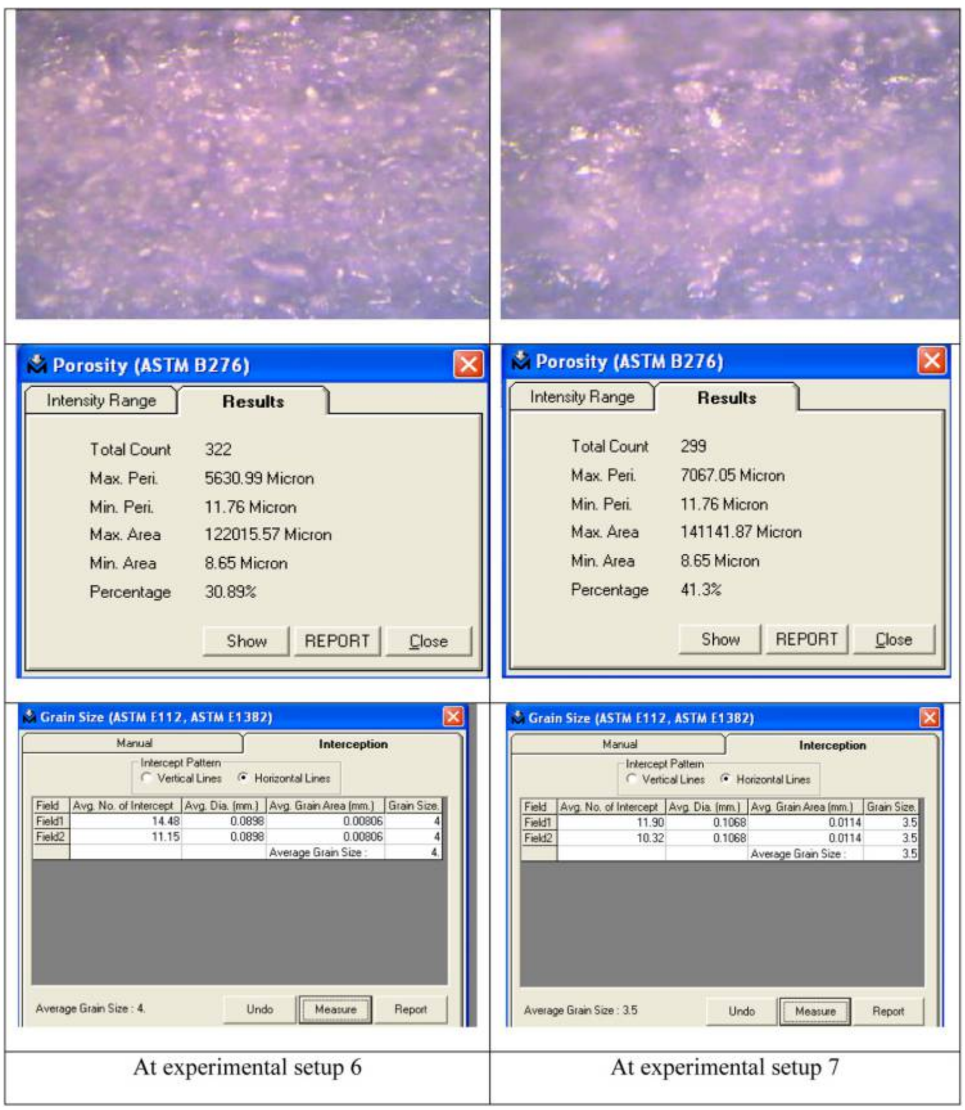


Figure 12 Friction welding process (a) welded piece after lateral cutting (b)

stirring for 10 s (Figure 12). The parts of ABS and PA6 were successfully welded and it was considered that after reinforcement at certain level, the joining compatibility of mentioned thermoplastic improved.

The welded piece was further mechanically tested by universal tensile tester (ASTM D638 – 14) to check the durability of joint. The welded piece has exhibited good tensile properties as shown in Table XV.

5. Conclusions

Following conclusions can be made from the present study:

- The results of the study suggest that virgin ABS and PA6 thermoplastic are not compatible because of their significant differences in glass transition temperature, melting point, MFI and specific heat capacity. So these thermoplastics are not compatible in virgin form for friction welding purpose. The reinforcement of Al metal powder at certain level for both the thermoplastics (through twin-screw extruder) refined their melt flow, mechanical and thermal properties and hence resulted into compatibility for friction welding applications.
- From combined optimization point of view, it has been observed for ABS-15 per cent Al (Table XIV) that the SN ratio was maximum for experiment no. 3 as 30.00 and minimum for experiment no. 8 as 28.74 (as per Table V). So based upon the observed values, the settings at experiment no. 3 and experiment no. 8 (as per Table V) have been considered as the best and worst set of input process parameters respectively. Similarly in the case of PA6-50 per cent Al, the input parameter combination at experiment no. 6 (SN ratio 30.36) was considered best and at experiment no. 7 (28.55) was worst (as per Table VI).
- Further, it has been observed that high mechanical strength was achieved by minimizing porosity in feedstock filament. The 3D printed parts of selected thermoplastic composite were gainfully friction welded and it was observed that compatibility issue of dissimilar thermoplastic has been addressed.

Table XV Mechanical properties of welded specimen

Property	Value
Peak load	388.30 MPa
Peak strength	16.18 kg/mm^2
Percentage elongation	11.05%
Young's modulus	43.73 Mpa

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