Effect of extrusion parameters on primary recycled ABS: mechanical, rheological, morphological and thermal properties

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Abstract

This paper reports the effect of twin screw extrusion (TSE) process parameters on primary (1°) recycled acrylonitrile butadiene styrene (ABS) for possible 3D applications. The ABS (virgin/recycled) is one of the most widely used thermoplastic materials for fused deposition modeling (FDM) based 3D printing of functional prototypes. But hitherto little has been reported on improving the mechanical/ rheological/morphological and thermal properties of (1°) recycled ABS while extrusion without any reinforcement (i.e. without secondary (2°) recycling). In this work the granules of 1° recycled ABS have been extruded after ascertaining suitable process parameters of TSE (namely: screw temperature, torque and dead weight). The results of study suggests that screw temperature 210 °C, 0.3Nm torque and dead weight of 13 kg are the best settings for TSE in the present case study. The TSE based extruded 1° recycled ABS has improved crash resistance properties (as modulus of toughness was significantly improved to 3.261 MPa (from 0.191 MPa for non TSE processed) and 0.081 for virgin ABS).

Introduction

The ABS thermoplastic is of significant importance in engineering applications due its good response towards mechanical properties. Being a co-polymer type thermoplastic, it is consumed at large scale in electrical and automobile industries. Its mechanical strength is excellent and hence a large number of industrial products are made of ABS [1]. Some researchers have explored injection molding process parameters for enhancing the mechanical strength of ABS. The material of mould used in the injection molding contributes in improving the flow ability and mechanical properties like elasticity and flexural modulus of ABS that also reduced the surface defects. It has been reported that the process parameter at which material is injected in molding process has non linear relationships with mechanical properties of ABS [2]. As ABS is widely used in industrial applications, lot of experimental data has been reported on this material (to increase its utility). Its tribological properties can be increased by reinforcement (2° recycling) of some specific polymers having good mechanical properties. Some studies explored that coating of graphene powder on polycarbonate ABS has reduced the wear of ABS and improved its tribological characteristics [3]. Reprocessing of ABS also affect its mechanical properties. After reprocessing it can be blended with virgin ABS to perform injection molding. Multiwall carbon nano tubes have been used by some researchers to increase mechanical properties of ABS. It has been observed that orientation of deposition angle can alter the fatigue nature of ABS polymer in FDM. It also has been investigated that mechanical properties are dependent on process parameters of FDM [4–7]. The scanning electron microscopy (SEM) and x-ray diffraction (XRD) are the favorable methods to investigate the changes occurred in recycled ABS after hybridization of nitrile rubber in it that made it more thermally stable. Also, melting viscosity of the hybrid material was reported to be increased [8]. The effect of printing parameters on properties of material has been investigated by some researchers. The path used for 3D printing also affects the mechanical characteristics of the polymer [9]. Statistical optimization performed on composites of ABS and glass revealed that mechanical properties of the material are affected by hygrothermal exposure of glass fibres in ABS due to which flexural
strength, ultimate tensile strength and impact strength decreases. Fibre orientation and fibre-to-resin ratio had been the important parameters that resist the degrading of mechanical properties of ABS/glass composite [10]. As 3D printing gained popularity in past 30 years, this approach had been used for printing ABS for geospatial imaging parts manufacturing that had better mechanical properties. The mechanical properties of ABS are also affected by influence of carbon nano tubes, carbon black etc [11–13]. Super tough and strong blends were made up of PA6 and ABS by using multi–phase compatibilizers. These blends showed tremendous increment in tensile strength and impact strength [14]. Use of ABS in automobile braking system revealed that this material failed quickly in rough terrain due to uneven and disturbing vibrations that caused failure in material [15].

Commerically FDM is a process, where ABS is used extensively after its blending with thermoplastic polyurethane. The adhesive property of such blended materials increased the yield strength and 3D printing quality of ABS [16]. ABS has been friction stir welded with HDPE in which carbon nanotubes were used to improve the mechanical strength of the weld. The multi wall nanotubes of carbon when reinforced in ABS increased the tensile strength and elongation properties of ABS [17]. It also has been investigated that 1° recycled ABS is of great importance in industrial applications. Frictionally welded ABS sheets are useful in making components of automobile because of its acceptable mechanical properties [18]. ABS has been explored extensively for 3D printing applications. A study revealed that additives can alter the physical property of ABS in order to improve the mechanical properties of the material [19]. In order to reduce the plastic waste for clean and green environment, there is a need to manage this waste. Waste ABS can be used with subcritical and supercritical water treatment technologies to lower the burden of plastic waste on earth [20]. As ABS is of great value in production of engineering goods, there is a need to utilize the recycled versions of ABS to manage the plastic waste effectively.

The literature review reveals that numerous research studies have explored applications of ABS for joining, cost reduction/waste reduction, effective additive manufacturing processes and increment in mechanical and thermal characteristics. But hitherto little has been reported on improving the mechanical/rheological/morphological and thermal properties of (1°) recycled ABS without any reinforcement i.e. without secondary (2°) recycling. In this work the granules of 1° recycled ABS have been processed with TSE after ascertaining suitable process parameters (namely: screw temperature, torque and dead weight).

Methodology

Initially a pilot study was conducted to distinguish virgin and 1° recycled ABS thermoplastic by performing rheological, thermal stability (based upon differential scanning calorimetry (DSC) test) and mechanical characterization. It should be noted that virgin ABS of commercial grade (ABSplus-P430, Make: Stratasys, USA) was used for basic comparison. The melt flow index (MFI) observed for this material was 2.4 g/ 10 min as per ASTM- D 1238. The next step involved the selection of suitable working parameters of TSE to fabricate the wire specimens (to be further used for 3D printing on FDM). The granules of 1° recycled ABS were processed on screw extruder (Make: mini CTW Haake, Germany, twin screw extruder) machine. The working parameters of screw extruder were varied as per design of experiment (DOE) based upon Taguchi L9 orthogonal array (OA). The methodology adopted for investigation is shown in figure 1. After procurement of 1° recycled ABS (from local market) wire samples were prepared at different settings (table 2). These wire specimens were used for investigations of MFI, tensile properties, thermal properties, Shore D hardness test and porosity percentage.

Experimentation

Pilot study

In order to differentiate between 1° recycled ABS and virgin grade of ABS, thermal analysis based upon DSC has been used. By performing thermal testing of both grades of ABS on DSC setup, it has been ascertained that heat capacity and glass transition temperature (Tg) of 1° recycled ABS thermoplastic shows improvement in comparison to virgin ABS (figure 2).

The Tg of virgin ABS was observed to be 79.12 °C whereas Tg for 1° recycled ABS was 105.73 °C. The 1° recycled ABS showed significant rise in heat capacity as compared to virgin ABS (85.3 × 10⁻³ J g⁻¹ to 0.37 J g⁻¹). Hence it is ascertained that 1° recycled ABS has better thermal stability in comparison to virgin ABS.

Screw extrusion

For fabrication of wire shaped specimens commercial screw extruder (Thermo Fisher Scientific HAAKE miniCTW) having two co-rotating screws was used, in a manner such that the polymer got melted inside the preheated chamber and expelled out from the die cavity (figure 3). The operator can control the temperatures of screws, torque/ rotational speed and dead weight that helped in easy flow of raw material. Three input
parameters were selected with three levels based upon pilot study. Total 09 set of observations were made as per Taguchi L9 O.A with three repetitions to reduce the experimental error. Various parameters and their levels are shown in table 1. Based upon tables 1, 2 shows control log of experiment.

Wire shaped specimens of length 1.5 m and diameter 1.75 ± 0.005 mm were extruded as per table 2. These wires were used for the testing of various rheological, mechanical, thermal and morphological properties. Figure 4 shows the trend obtained for torque/rpm versus time during the extrusion process. The graph is plotted automatically on commercial TSE setup to help operator in maintaining uniform torque applied on screws during extrusion.

Figure 1. Methodology for present study.

Figure 2. Thermal characterization of virgin and 1° recycled ABS.
Figure 3. TSE for processing of 1° recycled ABS.

Table 1. Selected parameters and their levels.

| Parameter levels | Screw temperature (°C) | Torque (Nm) | Dead weight (kg) |
|------------------|------------------------|-------------|-----------------|
| 1                | 190                    | 0.3         | 10              |
| 2                | 200                    | 0.4         | 11.5            |
| 3                | 210                    | 0.5         | 13              |

Table 2. Control log of experiment (as per table 1).

| S. No. | Screw temperature (°C) | Torque (Nm) | Dead weight (kg) |
|--------|------------------------|-------------|-----------------|
| 1      | 190                    | 0.3         | 10              |
| 2      | 190                    | 0.4         | 11.5            |
| 3      | 190                    | 0.5         | 13              |
| 4      | 200                    | 0.3         | 11.5            |
| 5      | 200                    | 0.4         | 13              |
| 6      | 200                    | 0.5         | 10              |
| 7      | 210                    | 0.3         | 13              |
| 8      | 210                    | 0.4         | 10              |
| 9      | 210                    | 0.5         | 11.5            |

Note: The experiment was performed 03 times to reduce the experimental error.

Figure 4. Variation of rpm versus time in TSE process.
MFI testing
The ASTM D1238 standard was followed to test the MFI of twin screw extruded 1° recycled ABS wire samples by applying standard load of 3.8 kg, keeping the die at standard temperature of 230 °C. The weight of the material that flow through the MFI tester die for 10 min gives the MFI of the material in g/10 min. Figure 5 shows the MFI tester used for the investigation.

Tensile testing
The UTM (Make: Shanta Engineering, Pune, India) has been used to perform tensile testing of wire specimens. All the samples obtained have been tested for tensile strength by following ASTM D638 type IV standard. The desired length of wired shape specimens have been cut from the wires extruded.

Thermal analysis
In order to investigate the thermal behavior of 1° recycled ABS after screw extrusion, DSC testing of samples has been performed. The commercial METTLER TOLEDO DSC setup as per ASTM D3418 has been used to analyze the thermal characteristics of ABS.

Shore D hardness test
After performing MFI test, tensile test and thermal analysis of the specimens, Shore D hardness at two different surfaces; first along the longitudinal surface of the wire and second along the cross section from where the specimen breaks during tensile test has been performed for all the specimens (as per ASTM D 2240). The Shore D hardness has been checked at three different locations for each sample and the average value of hardness has been recorded.

Surface morphology
The specimens have been observed with Tool maker’s microscope along the cross section and along the longitudinal surface in order to study the surface quality and porosity in the wire specimens. The images of samples have been obtained at × 30 magnifications. Also images of samples have been obtained at ×100 magnifications with metallurgical microscope. The porosity of extruded wires was calculated (based on the images obtained from metallurgical microscope) by using QSMIAS 4.0 image analysis software.

Result and discussion

Rheological (MFI) testing
Based upon table 2, the wired samples obtained were used for calculating their MFI. The results obtained for MFI test are listed in table 3. Based upon observations for MFI signal to noise (SN) ratio was calculated for maximum the better type case by using formula:

\[ \eta = -10 \left( \frac{1}{\sum_{k=1}^{n} \frac{1}{y^2}} \right) \]

where: \( \eta \) is SN ratio, \( n \) is the no. of experiment and \( y \) is the material properties at experiment no. k.

The MFI of non-screw extruded 1° recycled ABS was 2.112 ± 0.14. Hence it is ascertained that screw extrusion resulted into improvement in MFI. Based upon table 3, figure 6 shows the mean effect plot for SN ratios.
Based upon table 3, figure 6 the best setting of input parameters was observed at screw temperature 210 °C, 0.3 Nm torque and dead weight of 13 kg. These settings are available at S. No. 7, table 2 hence no confirmation is required. The tables 4 and 5 shows analysis of variance (ANOVA) and rank table for SN ratios based upon table 3.

**Table 3.** Observations for MFI of 1° recycled ABS.

| S. No. | MFI (g/min) | SN ratio (dB) |
|--------|-------------|---------------|
| 1      | 2.216 ± 0.14 | 6.9114        |
| 2      | 2.364 ± 0.10 | 7.4729        |
| 3      | 2.431 ± 0.17 | 7.7157        |
| 4      | 2.568 ± 0.16 | 8.1919        |
| 5      | 2.674 ± 0.18 | 8.5432        |
| 6      | 2.532 ± 0.14 | 8.0693        |
| 7      | 3.419 ± 0.20 | 10.6780       |
| 8      | 3.156 ± 0.19 | 9.9827        |
| 9      | 3.217 ± 0.13 | 10.1490       |

Note: MFI of virgin ABS was 2.4 g/10 min.

**Table 4.** ANOVA for SN ratios of MFI.

| Source          | DF | Seq SS  | Adj SS  | Adj MS  | F      | P      | % C  |
|-----------------|----|---------|---------|---------|--------|--------|------|
| Screw temperature| 2  | 13.2485 | 13.2485 | 6.62425 | 208.76 | 0.005  | 94.81|
| Torque          | 2  | 0.0083  | 0.0083  | 0.00416 | 0.13   | 0.884  | 0.06 |
| Dead weight     | 2  | 0.6532  | 0.6532  | 0.32662 | 10.29  | 0.089  | 4.67 |
| Residual Error  | 2  | 0.0635  | 0.0635  | 0.03173 | 0.45   |        |      |
| Total           | 8  |         |         |         |        |        |      |

Note: DF: Degree of freedom, Seq SS: Sequential sum of squares, Adj SS: Adjusted sum of squares, Adj MS: Adjusted mean of squares, F: Fisher's value, P: Probability, %C: Percentage contribution.

**Table 5.** Rank table for SN ratios for MFI result (Larger is better).

| Level | Screw temperature | Torque | Dead weight |
|-------|-------------------|--------|-------------|
| 1     | 7.367             | 8.594  | 8.321       |
| 2     | 8.268             | 8.666  | 8.605       |
| 3     | 10.270            | 8.645  | 8.979       |
| Delta | 2.903             | 0.073  | 0.638       |
| Rank  | 1                 | 3      | 2           |
Table 6. UTM results of TSE 1° ABS (prepared as per table 2).

| S. No. | PL (kg) | PE (mm) | BL (Kg) | BE (mm) | PS (kg/mm$^2$) | BS (kg/mm$^2$) | EP (%) | EB % | SB | SP | YM (MPa) | MoT (MPa) | SN ratio for PS |
|--------|---------|---------|---------|---------|---------------|---------------|--------|------|-----|----|----------|----------|-----------------|
| 1      | 67.1    | 1.99    | 60.39   | 2.09    | 27.91         | 25.12         | 5      | 5    | 0.052 | 0.049 | 561.005   | 0.656     | 28.915          |
| 2      | 69.1    | 3.23    | 62.19   | 8.93    | 28.74         | 25.87         | 8      | 22   | 0.223 | 0.080 | 355.913   | 2.887     | 29.169          |
| 3      | 85.3    | 2.85    | 76.77   | 4.75    | 35.48         | 31.93         | 7      | 12   | 0.118 | 0.071 | 497.964   | 1.895     | 30.999          |
| 4      | 113.2   | 2.09    | 101.88  | 5.89    | 47.09         | 42.38         | 5      | 15   | 0.147 | 0.052 | 901.244   | 3.120     | 33.458          |
| 5      | 119.1   | 2.66    | 107.19  | 4.94    | 49.54         | 44.59         | 7      | 12   | 0.123 | 0.066 | 744.962   | 2.753     | 33.899          |
| 6      | 82.8    | 2.09    | 74.52   | 4.75    | 34.44         | 31            | 5      | 12   | 0.118 | 0.052 | 659.138   | 1.840     | 30.741          |
| 7      | 126.5   | 3.23    | 113.85  | 5.51    | 52.62         | 47.36         | 8      | 14   | 0.137 | 0.080 | 651.640   | 3.261     | 34.423          |
| 8      | 98      | 2.28    | 88.2    | 5.7     | 40.76         | 36.69         | 6      | 14   | 0.142 | 0.057 | 715.087   | 2.614     | 32.204          |
| 9      | 109.8   | 2.28    | 98.82   | 5.32    | 45.67         | 41.11         | 6      | 13   | 0.133 | 0.057 | 801.228   | 2.733     | 33.192          |

Note: PL: peak load, PE: peak elongation, BL: break load, BE: break elongation, PS: peak strength, BS: break strength, EP%: percentage elongation at peak, EB%: percentage elongation at break, SB: strain at break, SP: strain at peak, YM: Young’s modulus, MoT: Modulus of toughness.
Table 7. UTM results of virgin ABS wire and 1° recycled ABS wire extruded without screw extrusion.

| Material type                | PL (kg) | PE (mm) | BL (kg) | BE (mm) | PS (kg mm⁻²) | BS (kg mm⁻²) | EP (%) | EB % | SB | SP | YM (MPa) | MoT (MPa) |
|-----------------------------|---------|---------|---------|---------|--------------|--------------|--------|------|----|----|----------|----------|
| Virgin ABS wire             | 137.7   | 3.27    | 123.9   | 3.46    | 47.28        | 45.55        | 16     | 16   | 0.086 | 1.970 | 578.348  | 0.081    |
| 1° recycled ABS without TSE | 58      | 1.52    | 51.6    | 1.71    | 9.98         | 8.98         | 4      | 4    | 0.042 | 0.038 | 262.631  | 0.191    |
As observed from table 4 residual error of 0.45% shows high accuracy of the predicted model. Further the temperature at which crew extrusion was performed has significant role in improving the MFI of the samples as it has been ranked 1 in the rank table (table 5), whereas other two input parameters are insignificant as \( P > 0.05 \).

**Mechanical testing**

The tensile test of 9 sets of wire specimens has been performed on UTM to investigate the effect of screw extrusion process parameters on the mechanical properties 1° recycled ABS. Table 6 shows the results of tensile
test for $1^\circ$ recycled ABS wires after screw extrusion (performed as per table 2). Further table 7 shows UTM results for virgin ABS and $1^\circ$ recycled ABS wire (without screw extrusion).

As observed from tables 6 and 7, significant change was observed for MoT and other mechanical properties for $1^\circ$ recycled extruded ABS as compared to virgin ABS and non TSE sample. The improvement in mechanical properties of $1^\circ$ recycled thermoplastic material after TSE is certainly useful for enhancing the reusability/recyclability of the polymers. These results are in line with the observations made by other investigators [21–27].

The stress versus strain graph (figure 7) has been plotted to ascertain the effect of screw extrusion process parameters on $1^\circ$ recycled ABS. Based upon tables 6, 7 and figure 7 it can be ascertained that screw extrusion in general resulted into significant improvement in all mechanical properties. Further for statistical analysis of process parameters SN ratio for peak strength was calculated for larger the better type case and main effect plot for SN ratio was prepared (figure 8). Based upon figure 8 the best setting of input parameters was observed at screw temperature $210^\circ$C, $0.3$Nm torque and dead weight of 13 kg. These settings are available at S. No. 7,

| Level | Screw temperature | Torque | Dead weight |
|-------|-------------------|--------|-------------|
| 1     | 29.69             | 32.27  | 30.62       |
| 2     | 32.70             | 31.76  | 31.94       |
| 3     | 33.27             | 31.64  | 33.11       |
| Delta | 3.58              | 0.62   | 2.49        |
| Rank  | 1                 | 3      | 2           |

Table 9. Rank table for SN ratios for peak strength (Larger is better).

| Polymer | Shore D Hardness at surface | Shore D Hardness at cross section |
|---------|----------------------------|----------------------------------|
| $1^\circ$ recycled ABS | 42.5 | 36.5 |

Table 10. Shore D hardness data for $1^\circ$ recycled ABS without screw extrusion.

| S. No. | Shore D hardness at surface | Shore D hardness at cross section |
|--------|----------------------------|----------------------------------|
| 1      | 38.5                       | 41.5                             |
| 2      | 40                         | 43.5                             |
| 3      | 42.5                       | 45                               |
| 4      | 46                         | 49.5                             |
| 5      | 48.5                       | 52                               |
| 6      | 44.5                       | 48.5                             |
| 7      | 52.5                       | 54                               |
| 8      | 49.6                       | 51.5                             |
| 9      | 51.5                       | 53.5                             |

Table 11. Shore D hardness data for $1^\circ$ recycled ABS with screw extrusion.

| S. No. | Normalized heat capacity | Onset temperature ($^\circ$C) | Peak temperature/Glass transition temperature ($T_g$) ($^\circ$C) | End set temperature ($^\circ$C) |
|--------|--------------------------|-----------------------------|---------------------------------------------------------------|-----------------------------|
| 1      | $-0.10$                  | 103.04                      | 107.14                                                        | 109.96                      |
| 2      | $-0.14$                  | 102.34                      | 107.26                                                        | 110.69                      |
| 3      | $-0.13$                  | 103.32                      | 107.97                                                        | 111.30                      |
| 4      | $-0.19$                  | 103.49                      | 108.31                                                        | 112.10                      |
| 5      | $-0.18$                  | 103.54                      | 105.72                                                        | 107.08                      |
| 6      | $-0.24$                  | 102.52                      | 107.05                                                        | 109.01                      |
| 7      | $-0.48$                  | 101.78                      | 107.48                                                        | 111.37                      |
| 8      | $-0.24$                  | 101.84                      | 106.48                                                        | 111.17                      |
| 9      | $-0.24$                  | 103.36                      | 107.19                                                        | 111.10                      |

Table 12. DSC results of $1^\circ$ recycled ABS.

Note: The normalized heat capacity for non screw extruded sample was $-0.09$ $\text{g}^{-1}$.
Table 2 hence no confirmation is required. Further based upon Table 6 (SN ratio for peak strength), tables 8 and 9 respectively shows ANOVA for SN ratios of peak strength and rank table for larger the better type case.

It has been observed that a residual error of 2.90% (Table 8) shows high accuracy of the predicted model. The temperature at which twin screws rotate has significant role in improving the peak strength of the samples as it has been ranked 1 in the rank table (Table 9). The dead weight has been ranked 2.

Figure 9. Curves obtained for DSC test of 1° recycled ABS.

Figure 10. Images of wire surface along longitudinal axis (at × 30).
Prediction for peak strength

For prediction of peak strength following equation has been used:

\[ \eta_{\text{opt}} = P + (PA_3 - P) + (PB_1 - P) + (PC_3 - P) \]

where, \( \eta_{\text{opt}} \) is the optimum value of SN ratio for peak strength, \( P \) is the SN mean for peak strength = 31.83 (table 6), \( PA_3 \) is the maximum value of screw temperature = 33.27 (table 9), \( PB_1 \) is maximum value of torque = 32.27 (table 9) and \( PC_3 \) is maximum value for the dead weight = 33.11 (table 9).

So,

\[ \eta_{\text{opt}} = 31.83 + (33.27 - 31.83) + (32.27 - 31.83) + (33.11 - 31.83)\]

\[ \eta_{\text{opt}} = 34.99 \text{ dB} \]

For larger is better case:

\[ V_{\text{opt}}^2 = \left( \frac{1}{10} \right)^{-\eta_{\text{opt}}/10} = \left( \frac{1}{10} \right)^{-34.99/10} \]

\[ \eta_{\text{opt}} = 56.16 \text{ kg mm}^{-2} \]

Therefore, predicted value of peak strength = 56.16 kg mm\(^{-2}\).

The observed for peak strength is 52.62 kg mm\(^{-2}\) (table 6, S.No.7) which is close to the predicted value and results are valid at 95% confidence level.

Shore D hardness

Shore D hardness of 1\(^{°}\) recycled ABS wires obtained via screw extrusion has been compared with Shore D hardness values of non screw extruded 1\(^{°}\) recycled ABS. Shore D hardness of primary recycled ABS (non screw
extruded) at two surfaces i.e. along longitudinal surface and along the cross section are listed in table 10 whereas results for Shore D hardness of screw extruded 1° ABS (as per table 2) has been listed in table 11.

On comparison of tables 10 and 11, it has been ascertained that screw extrusion resulted into improvement of Shore D hardness at surface and cross section for 1° recycled ABS. As observed from table 11, sample at S. No. 7 resulted into better Shore D hardness at surface and cross-section.

Thermal stability analysis
The results obtained for thermal stability by performing DSC test of screw extruded 1° recycled ABS are shown in table 12. A total time of 88 min has been consumed for thermal analysis of each sample (in which 22 min each has been consumed for two heating and cooling cycles respectively). It should be noted that for present thermal investigations the matter was processed up to maximum 250 °C, so no decomposition behaviour was observed.

Figure 9 shows DSC graphs for thermal behaviour (as per table 2). As ABS material is combination of two polymers acrylonitrile and styrene which are bonded to each other by binding action of butadiene, some impurities have been observed in curves during first cooling cycle. Whereas in second cooling cycle two sharp dips has been observed for DSC test of ABS. The first one is integrated for thermal analysis by using Star E software. This trend in calorimetric test reveals that screw extrusion improves the heat capacity of 1° recycled ABS. The best result was observed for sample at S. No. 7 (with 433.3% improvement) as it has more thermal stability because of its ability for better heat capacity. The Tg of each tested specimen lies in the range of 105–108 °C.

Morphological results
The images of surface of wire samples were captured with tool maker microscope along longitudinal axis and along the cross section from where the wire broke during UTM test (as per table 2). These images have been shown in figures 10 and 11 respectively.

Figure 12. Surface images of wires along the cross section (at ×100).
As observed from figure 11 some porosity was observed in wire samples, but no quantitative value for porosity was noted. For better analysis image of wire samples at cross-section were captured at ×100 (as per ASTM D276 standard) with metallurgical microscope (figure 12). Further based upon figures 12, 13 shows porosity results of the images obtained with the help of QSMIAS 4.0 software package. Figure 10 shows porosity for non screw extruded 1° recycled ABS.

As observed from figures 13 and 14, the porosity has been significantly reduced (84.59%) after processing through screw extrusion. Further minimum porosity was observed for sample at S.No.7 as per table 2 (figure 11). It should be noted that best MFI (table 3), mechanical properties (table 6), Shore D hardness (table 11) as well as
thermal stability (table 12) was also observed for this sample. Finally the optical photomicrographs captured at × 100 for sample at S.No. 7 figures 13 and 14 were processed to get 3D rendered image and surface roughness (Ra) profile at cut off length of 0.04 mm (figure 15) using image processing software.

As observed from figure 15, screw extruded sample resulted into uniform grain distribution with better Ra value as compared to non screw extruded samples.

Conclusions

Following are the conclusions from this study:

- The 1° recycled ABS when processed with TSE, shows significant improvement from virgin ABS in rheological, mechanical, thermal and morphological properties. Since the TSE significantly improves the MFI of 1° recycled ABS, hence after processing through screw extrusion the same thermoplastic material can be used for molding of thin sections.

- The result of study suggests that mechanical properties (like: peak/break elongation, peak/break strength, strain at peak/break, Young’s modulus, modulus of toughness of 1° recycled ABS is dependent on screw temperature and applied dead weight applied in TSE. Hence functional parts with customized properties can be prepared for possible 3D/4D printing applications. The specific improvement in modulus of toughness after TSE for 1° recycled ABS makes it more useful for crash applications (like for bumpers of automobiles).

- Based upon process parametric optimization of TSE for mechanical properties, screw temperature 210 °C, 0.3 Nm torque and dead weight of 13 kg are the best settings in the present case study at 95% confidence level. The screw temperature has been identified as most significant parameter with contribution of 67.02%. As regards to MFI screw temperature 210 °C, 0.5 Nm torque and dead weight of 13 kg are the best settings. Also in this case most significant parameter was noticed as screw temperature with contribution of 94.81%. Further the Shore D hardness of 1° recycled ABS, porosity percentage (based upon optical photomicrographs) and thermal stability data also supported the experimental observations.
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