Investigations for machinability of primary recycled thermoplastics with secondary recycled rapid tooling

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Abstract. This paper highlights the machinability of primary recycled thermoplastics as workpiece (WP) material with secondary recycled (reinforced) thermoplastic composites as rapid tooling (RT). Both WP and RT have been 3D printed on commercial fused deposition modelling. For investigating machinability of primary recycled thermoplastics, un-reinforced WP of low-density polyethylene (LDPE) and high-density polyethylene (HDPE) has been selected. The RT materials were secondary reinforced (recycled) LDPE with double particle size Al_2O_3 particles and HDPE with triple particle size Al_2O_3 . The machinability has been calculated in terms of weight loss of WP, while machining on a vertical milling set-up. This study also reports the surface hardness, porosity, surface roughness (Ra) and photomicrographic observations of WP and RT under controlled machining conditions. Further thermal analysis suggests that primary recycled thermoplastic can be successfully machined with secondary recycled RT, resulting in improved thermal stability and surface properties.

Keywords. Machinability; Al_2O_3 ; fused deposition modelling; LDPE; HDPE; surface properties.

1. Introduction

The pollution caused due to plastic disposal has been identified as one of the major threat to the environment [1–3]. To avoid this, plastic recycling and processing has increased extensively in modern times [2–5]. In the recent past, some studies have been reported for primary, secondary, tertiary and quaternary means of recycling in the field of plastic solid waste (PSW) management with metallic/non-metallic reinforcements via rapid prototyping (RP) route [5–9]. Recycling has proven to be one of the best possible ways to manage the polymer waste [10, 11]. Previous studies have shown that the recycling of PSW can be performed number of times for enhancing the reusability of waste polymers. Some studies outlined the enhancement in mechanical and metallurgical properties with use of metallic powder reinforcements in polymer wastes [5–7]. It has been reported that thermoplastics are versatile materials from their commercial use point of view and also have sustainability features [8]. Literature review outlined that the cost of replacing thermoplastics with alternative materials would be 4 times higher. For example the use of thermoplastics in commercial vehicles will help reduce 3000 l of fuel in total life span [9], improve failure rate for plastic pipes (≥ 100 years) [10] and requires $\leq 4\%$ of water to make poly-bags in comparison with paper-bags [11]. The

thermoplastics have high ability to be moulded into finished form without any post-processing requirements [12]. Typical shapes, holes and undercuts can be easily moulded with reduced tooling cost using RP-assisted rapid tooling (RT). From commercial application viewpoint, when a plastics component is specified and the number to be used is small, then machining the component is more economical. It should be noted that not all thermoplastics materials can be machined [13]. As a thumb rule, if a thermoplastic is more rigid then it becomes easier to be machined. Some commercial manufacturers have reported use of machinability index as a nominal ranking out of 20 (best value) while machining with conventional set-up/CNC [14]. It has been observed that due to poor thermal conductivity and low melting point of thermoplastics, heat generation must be kept to a minimum. The value of machinability index for thermoplastics is available only for virgin and commercial grades of thermoplastics, whereas for recycled (primary/secondary), no such index is available. Recent studies showed that RT can be developed using waste/recycled polymers and metallic reinforcements [15–20].

This work is an extension of work reported on reinforced thermoplastic composites (secondary recycled) as RT [21–23] and is focussed on machinability of thermoplastics workpiece (WP) material (primary recycled). It should be noted that the machinability index for thermoplastics is available only for commercial grade of virgin

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Figure 1. MFI tester used in study.

Table 1. Fixed input parameters for printing of WP and RT.

Static parameters for FDM	
Nozzle diameter (Φ 0.3 mm)	Infill density (80%)
Wire diameter (Φ 1.75 ± 0.05 mm)	Infill angle (60°)
Bed temperature ($55 \pm 2^\circ\text{C}$)	Infill speed (60 mm/s)
Printing temperature ($155 \pm 5^\circ\text{C}$ for LDPE and $170 \pm 5^\circ\text{C}$ for HDPE)

Figure 2. FDM set-up (Make: Divide by Zero, India).

thermoplastics. However, hitherto very little has been reported on machinability of primary and secondary recycled thermoplastics. In this study both WP and RT have been 3D printed with commercial open source fused

deposition modelling (FDM). The WP material has been selected as primary recycled low-density polyethylene (LDPE) and high-density polyethylene (HDPE), whereas RT materials were secondary, reinforced LDPE with double

Figure 3. 3D view of WP and RT prepared.

Figure 4. Vertical milling machine set-up.

particle size (DPS) Al_2O_3 particles and HDPE with triple particle size (TPS) Al_2O_3 . It should be noted that DPS refers to particle size of 100 and 120 μm (in equal weight proportion) and TPS refers to particle size of 100, 120 and 150 μm (in equal weight proportion) [21–23]. Thermo-plastic granules and reinforcements were blended by a twin screw extruder (TSE). The feedstock filament prepared was

made to run on FDM set-up to print 3D functional prototype, i.e. WP and RT. The 3D printed WP was further mounted on a fixture for possible machining with RT on vertical milling set-up (for machinability evaluation). The changes in surface hardness, porosity, Ra and morphology (based upon photomicrographs) of WP under machining conditions have been reported.

Table 2. Weight losses for WP and RT.

	WP					RT						
	Speed	Feed	Depth of cut	Composition	A: initial weight of WP (g)	B: final weight of WP (g)	A-B: weight difference (g)	Composition	A: initial weight of RT (g)	B: final weight of RT (g)	A-B: weight difference (g)	
Case 1	500	20	1	LDPE	2.750	2.196	0.554	HDPE	3	2.877	2.856	0.021
	500	30	2		2.780	2.058	0.722	reinforced		2.742	2.714	0.028
	500	40	3		2.458	1.425	1.033			2.846	2.800	0.046
	750	20	2		2.482	1.930	0.552			2.764	2.740	0.024
	750	30	3		2.894	2.148	0.746			2.487	2.453	0.034
	750	40	1		2.587	1.546	1.041			2.549	2.510	0.039
	1000	20	3		2.984	2.420	0.564			2.657	2.629	0.028
	1000	30	1		2.567	1.806	0.741			2.841	2.803	0.038
	1000	40	2		2.354	1.300	1.054			2.981	2.934	0.047
	500	20	1	HDPE	3.204	3.018	0.186	LDPE	4	2.235	1.773	0.462
Case 2	500	30	2		3.214	2.990	0.224	reinforced		2.249	1.757	0.492
	500	40	3		3.025	2.779	0.246			2.357	1.796	0.561
	750	20	2		3.425	3.243	0.182			2.192	1.733	0.459
	750	30	3		3.475	3.229	0.246			2.259	1.770	0.489
	750	40	1		3.224	2.945	0.279			2.367	1.793	0.574
	1000	20	3		3.146	2.954	0.192			2.320	1.893	0.427
	1000	30	1		3.164	2.956	0.280			2.204	1.722	0.482
	1000	40	2		3.012	2.698	0.314			2.014	1.442	0.572

Three repetitions are made and average values for weight difference are quoted

Composition/proportion 1: LDPE as 100% by weight

Composition/proportion 2: HDPE as 100% by weight

Composition/proportion 3: HDPE as 90% by weight, Al₂O₃ TPS

Composition/proportion 4: LDPE as 50% by weight, Al₂O₃ DPS

Table 3. SN ratios for weight loss of WP.

Composition	Speed	Feed	Depth of cut	SN ratios for weight loss of RT
Case 1				
1	500	20	1	-5.12980
	500	30	2	-2.82926
	500	40	3	0.28201
	750	20	2	-5.16122
	750	30	3	-2.54522
	750	40	1	0.34901
	1000	20	3	-4.97442
	1000	30	1	-2.60364
	1000	40	2	0.45681
Case 2				
2	500	20	1	-14.6097
	500	30	2	-12.9950
	500	40	3	-12.1813
	750	20	2	-14.7986
	750	30	3	-12.1813
	750	40	1	-11.0879
	1000	20	3	-14.3340
	1000	30	1	-11.0568
	1000	40	2	-10.0614

Note: Negative SN ratio shows that signal power is less than noise power. For calculation of SN ratio, larger the better type case was used as per the formula: $\eta = -10 \log \left[\frac{1}{n} \sum_{k=1}^n \frac{1}{y_k^2} \right]$, where η is SN ratio, n is the no. of experiment and y is the material property at experiment no. k . Since for calculation logarithmic scale is used, if the value of y is <1 , negative SN ratio values are observed.

2. Experimentation

Based upon pilot experimentations, different proportions of LDPE and HDPE granules along with Al_2O_3 and SiC reinforcements were blended. The different blends were put into a melt flow tester to check melt flow indices (MFI). It was observed in pilot studies that recycled LDPE when mixed with DPS Al_2O_3 and recycled HDPE when mixed

Table 5. Percentage (%) contribution of input parameter on weight loss of WP.

Parameter	Contribution on weight loss of WP (%) (Case 1)	Contribution on weight loss of WP (%) (Case 2)
Speed	0.11	13.51
Feed	99.82	81.91
Depth of cut	0.03	2.69
Error	0.04	1.89

with TPS Al_2O_3 result in lower MFI values [24]. Figure 1 shows the MFI tester used in the study [21–23].

Further, recycled LDPE granules without any reinforcement and with reinforcement as DPS Al_2O_3 and recycled HDPE granules without any reinforcement and with reinforcement as TPS Al_2O_3 were used for preparing the filament wires on TSE [21, 22]. The wires prepared as filament were investigated for tensile properties on a universal tensile tester (UTT). It has been reported that in case of LDPE/HDPE, composition/proportion comes out to be the major factor contributing to peak load, break load and Young's modulus and load comes out to be the major factor contributing to peak elongation and break elongation. After analysing signal to noise (SN) ratios for multi-factor optimization, the combined effect of all the process parameters on mechanical properties was studied separately for both LDPE and HDPE [21–23].

For final confirmatory experiments the filament wires with composition/proportion were prepared for batch production using TSE as follows:

- primary recycled LDPE 100% by weight,
- secondary recycled LDPE 50% by weight, Al_2O_3 -120 μm 25% by weight, Al_2O_3 -100 μm 25% by weight (i.e. DPS),
- primary recycled HDPE 100% by weight,

Table 4. Variance analysis data SN plots.

Case 1							Case 2						
Source	DF	Seq SS	Adj SS	Adj MS	F	P	Source	DF	Seq SS	Adj SS	Adj MS	F	P
Speed	2	0.0519	0.0519	0.0259	3.68	0.213	Speed	2	3.1751	3.1751	1.5876	7.15	0.123
Feed	2	44.7473	44.7473	22.3737	3177.82	0.000	Feed	2	19.2460	19.2460	9.6230	43.36	0.023
Depth of cut	2	0.0146	0.0146	0.0073	1.04	0.491	Depth of cut	2	0.6323	0.6323	0.3162	1.42	0.412
Residual error	2	0.0141	0.0141	0.0070			Residual error	2	0.4439	0.4439	0.2219		
Total	8	44.8279					Total	8	23.4973				

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.

Figure 5. SN ratio plots for case 1 and case 2.**Table 6.** Response table for SN plots for both cases.

Case 1				Case 2			
Level	Speed	Feed	Depth of cut	Level	Speed	Feed	Depth of cut
1	-2.5590	-5.0885	-2.4615	1	-13.26	-14.58	-12.25
2	-2.4525	-2.6594	-2.5112	2	-12.69	-12.08	-12.62
3	-2.3737	0.3626	-2.4125	3	-11.82	-11.11	-12.90
Delta	0.1853	5.4511	0.0987	Delta	1.44	3.47	0.65
Rank	2	1	3	Rank	2	1	3

Table 7. Shore-D hardness and porosity values of WP.

					WP			
	Composition	Speed (RPM)	Feed (mm/min)	Depth of cut (mm)		Hardness (Zone A)	Hardness (Zone B)	Porosity before m/c (%)
Case 1	1	500	20	1	LDPE	39.5	43	7.41
	1	500	30	2		40	46	3.94
	1	500	40	3		42.5	41.5	7.48
	1	750	20	2		41.5	40	3.22
	1	750	30	3		40.5	46.5	4.29
	1	750	40	1		42	47.5	7.81
	1	1000	20	3		40	44.5	3.47
	1	1000	30	1		39.5	41	4.78
	1	1000	40	2		40	46	8.42
Case 2	2	500	20	1	HDPE	56.5	61.5	15.54
	2	500	30	2		58.5	64.5	12.49
	2	500	40	3		57	62	10.22
	2	750	20	2		56	67	9.64
	2	750	30	3		56.5	68	11.49
	2	750	40	1		57.5	64	12.09
	2	1000	20	3		56.5	65.5	9.43
	2	1000	30	1		58	61.5	10.69
	2	1000	40	2		59.5	63	14.57

Figure 6. Machined LDPE disc

Figure 7. HDPE-TPS Al_2O_3 reinforced. RT.

- (iv) secondary recycled HDPE 90% by weight, Al_2O_3 -150 μm 3.33% by weight, Al_2O_3 -120 μm 3.33% by weight, Al_2O_3 -100 μm 3.33% by weight (i.e. TPS).

After preparation of the filaments, they were fed to the FDM set-up to fabricate the WP (circular discs) and RT. For analysis purpose, 18 WP of Φ 40 mm and thickness 10 mm were printed (09 WP of LDPE without reinforcement and 09 WP of HDPE without reinforcement) with three repetitions to reduce the experimental error. Similarly, 18 RT of $10 \times 10 \times 35 \text{ mm}^3$ were printed from wires prepared (as 09 RT (secondary reinforced) of LDPE-DPS Al_2O_3 and 09 RT (secondary reinforced) of HDPE-TPS Al_2O_3 on FDM set-up with three repetitions. The static

and input parameters considered for FDM are shown in table 1. Figure 2 shows the FDM set-up used and figure 3 shows WP and RT printed on FDM.

The 3D printed WPs (see figure 3) were machined with 3D printed RT (figure 4). Three input parameters, (i) speed (RPM) (ii) feed (mm/min) and (iii) depth of cut (mm), were judiciously selected with three levels of each (based upon availability in the set-up) as per Taguchi L9 orthogonal array (OA). It should be noted that for 03 parameters with 03 levels, a total of $3 \times 3 \times 3 = 27$ experiments (based upon full factorial approach) with 03 repetitions resulting into $27 \times 3 = 81$ experiments (separately for LDPE and HDPE) need to be conducted. They have been reduced to $9 \times 3 = 27$ sets of experiments by applying Taguchi L9 OA (for both LDPE and HDPE). Secondly the Taguchi approach is helpful to understand the factor effect on output properties statistically. Table 2 shows different levels of input parameters along with weight losses for WP and RT printed.

3. Results and discussion

Case 1: Primary recycled LDPE (100% composition) WP and secondary recycled RT of HDPE-TPS Al_2O_3

In case 1, 09 samples of primary recycled LDPE (100% by weight) WP and 09 RT of secondary recycled HDPE-TPS Al_2O_3 were selected. The WP was fixed on the base plate of milling machine and RT was mounted on tool post 90° to WP. To compute the weight loss during the machining, initial and final weights of WP and RT were compared.

Case 2: Primary recycled HDPE (100% composition) WP and secondary recycled RT of LDPE-DPS Al_2O_3

In case 2, 09 WPs of primary recycled HDPE (100% by weight) and 09 RT of secondary recycled LDPE-DPS Al_2O_3 were selected.

Case 3 with primary recycled 100% LDPE (WP) and secondary recycled LDPE-DPS Al_2O_3 (RT) and Case 4 primary recycled 100% HDPE (WP) and secondary recycled HDPE-TPS Al_2O_3 (RT) were not considered as it was observed that WP and RT got joined with each other. This may be because of the fact that with similar base material, friction/friction-stir welding occurs, resulting in joining of the WP and RT in place of machining [25–28].

Based upon table 2, various SN ratios of weight loss of WP (as obtained by using L9 OA) separately for compositions 1 and 2 are summarized in table 3. Further, tables 4 and 5 show the variance analysis for SN ratios and percentage contributions of each input parameter on weight loss of WP, respectively, for both the cases.

It is noteworthy that contribution of speed and depth of cut can be neglected as P value of these parameters is more than 0.05.

Figure 8. (a) Photomicrograph of LDPE workpieces (WP) after machining (zone B) as per table 7 case 1, (b) rendered images of photomicrographs and (c) surface roughness profile.

As observed from table 5, feed came out to be the major factor contributing to weight loss of WP in both the cases. SN plots and SN response tables for the both the cases are shown as in figure 5 and table 6, respectively.

As observed from figure 5 and table 6, for case 1, speed (1000 rpm), feed (40 mm/min) and depth of cut (3 mm) are the best settings and for case 2, speed (1000 rpm), feed (40 mm/min) and depth of cut (1 mm) are the best settings.

Figure 8. continued

The shore-D hardness and porosity of WPs were checked for both cases (see table 7). It is to be noted that zone A represents un-machined surface of WP and RT, whereas zone B represents machined surface of WP and RT. The porosity for machined zone was observed to be less compared with un-machined zone. This may be due to the fact that while machining with RT, material re-flow occurs over the surface of WP, resulting in controlled/reduced porosity.

For illustrative purpose, figures 6 and 7 show the machined LDPE disc and HDPE-TPS Al_2O_3 -reinforced

tooling used as tooling while machining. Zone B (machined portion) of WP for both the cases was examined through an optical microscope by support of software tool known as “Metallurgical image analysis software (MIAS)”. Figures 8 and 9 show optical photomicrographs along with the porosity values and Ra profile for all WP prepared (with cut-off length of 0.08 mm).

It can be easily interpreted from table 7 that shore-D hardness of zone A (un-machined portion) is less than that of zone B (machined portion) for the WP (which may be

Figure 9. (a) Photomicrograph of HDPE workpieces (WP) after machining (zone B) as per table 7 case 2, (b) rendered images of photomicrographs and (c) surface roughness profile.

due to work hardening phenomenon as a result of machining) in both the cases, whereas porosity of un-machined part (zone A) is more than that of porosity of machined portion (zone B) in both the cases. The maximum hardness of machined portion of WP in case 1 came out to

be 47.5 under 750 rpm, feed as 40 mm/min and depth of cut as 1 mm and maximum hardness of machined portion of tooling in case 2 came out to be 68 under 750 rpm, feed as 30 mm/min and depth of cut as 3 mm. The minimum percentage porosity of machined portion of tooling in case

Figure 9. continued

1 came out to be 3.12% under 500 rpm, feed as 20 mm/min and depth of cut as 1 mm and minimum percentage porosity of machined portion of tooling in case 2 came out to be 8.47% under 500 rpm, feed as 20 mm/min and depth of cut as 1 mm. Based upon figures 8 and 9 it is ascertained that LDPE is better WP material from porosity and Ra viewpoint. This may be due to the fact that better reflow of material occurred in LDPE (being a soft material in comparison with HDPE) as WP. Further, thermal analysis of machined WP with the maximum material removal (as per table 2 under case 1 and case 2) was performed for

comparing zone A and zone B using DSC at controlled heating/cooling rate as $\pm 10^\circ\text{C}/\text{min}$ (figure 10). During DSC analysis, sample is heated using a controlled temperature gradient with a defined heating rate; thereby, heat flow difference is measured by comparing the sample to a reference [29–33]. Figure 10 shows that heat capacity for zone B in both cases comes out to be higher than that of zone A, giving a clear indication that machined zone is thermally more stable, which may be due to better reflow of material (in machined zone), resulting into reduced porosity.

Figure 10. Comparative DSC plots of un-machined (a) and machined (b) zones for primary recycled LDPE case 1 and primary recycled HDPE case 2.

4. Conclusions

- The results of the study highlight that in case of primary recycled LDPE WP, 1000 rpm, 40 mm/min feed and 3 mm depth of cut are the best settings for better machinability of WP (machined by secondary recycled RT).
- In case of primary recycled HDPE WP: 1000 rpm, 40 mm/min feed and 1 mm depth of cut are the best settings for better machinability of WP (machined by secondary recycled RT).
- The maximum hardness of machined portion of primary recycled LDPE WP (case 1) came out to be 47.5 under 750 rpm, feed as 40 mm/min and depth of cut as 1 mm, and maximum hardness of machined portion of primary recycled HDPE WP (case 2) came out to be 68 under 750 rpm, feed as 30 mm/min and depth of cut as 3 mm.
- The minimum percentage porosity of machined portion of primary recycled LDPE WP (case 1) came out to be 3.12% under 500 rpm, feed as 20 mm/min and depth of cut as 1 mm, and minimum percentage porosity of machined portion of primary recycled HDPE WP (case 2) came out to be 8.47% under 500 rpm, feed as 20 mm/min and depth of cut as 1 mm. Overall, primary recycled LDPE may be graded as a better option from machinability viewpoint.
- Since the heat capacity values for zone B for both primary recycled LDPE and HDPE WP are observed to be more than those for zone A, it may be concluded that machined portion becomes thermally more stable than un-machined.

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