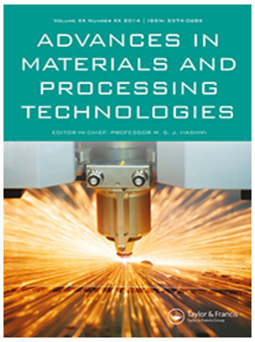

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Polymer- Ceramic composites: A state of art review and future applications

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Polymer- Ceramic composites: A state of art review and future applications

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ABSTRACT

The polymer-ceramic composites are best known for their superior fracture toughness, fatigue resistance; wear resistance, higher strength retention at higher temperature, higher strength to weight ratio, higher hardness, thermal response, chemical inertness and corrosion resistance as compared to other composites like: metal matrix composites, ceramic matrix composites and concrete matrix composites. Some studies have reported 3D printing of functional and non-functional prototypes of polymer-ceramic composites for various engineering applications. But hitherto little has been reported on use of 3D printing techniques for rapid tooling (by selecting polymer ceramic composites) in machining of thermo-plastic materials. This paper is a state of art review in progress made for various polymer-ceramic processing method, innovations in common ceramics (SiC, Al_2O_3, TiO_2, glass fibre, carbon and their allotropes etc.) reinforced polymeric composites from application prospective. Further in this paper, a case study has been presented for development of polymer-ceramic composites as rapid tooling for machining of thermoplastics.

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Keywords
Polymer-ceramic composites; SiC; Al_2O_3; TiO_2; glass fibre

1. Introduction

Ceramic-reinforced polymeric composite material is one of the recent advancement in the engineering fields which manufactured parts with superior mechanical, thermal, wear and morphological properties [1–4]. There are numerous methods developed in the recent past for fabrication of polymer-ceramic composites. Extrusion, injection moulding, thermoforming, cold pressing, hot pressing, foam moulding, calendaring, co-extrusion and heating are some of the processing techniques available for preparations of polymer-ceramic composites [5–8]. As per review made by Magalgiri (2005), the performance of polymer matrix composite is decided by their service temperature. As per this classification, the polymer matrix composite is divided into three major groups includes (i) polymer matrix composites with service temperature of 135–250°C which includes bismaleimides, cyanate esters, aromatic thermoplastics, thermoplastic

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polyimides, etc [9]. (ii) polymer matrix composites with service temperature of 250–350 °C which includes polyimides with high glass transition temperatures [10] and (iii) engineering plastic whose service temperature is above 350 °C like polyether ether ketone reinforced with ceramic and other metallic and non-metallic particles [11]. The preparation of polymer matrix composite through mentioned processing techniques may be used for the recycling of plastic solid waste. The plastic solid waste is classified into four basic categories namely: primary, secondary, tertiary and quaternary recycling. The primary recycling is processed by no addition of filler [12,13–15], secondary recycling is processed by addition of filler into matrix of the polymer [16–19], tertiary recycling is processed by dissolving plastic solid waste into some suitable chemicals [19] and quaternary recycling is processed by incineration of plastic solid waste [20].The preparation of plastic-ceramic ceramic is comes under the secondary recycling process where reinforcements (in form of ceramic, metals and non-metals) are incorporated to polymer matrix with improvement of material properties by mechanical mean (e.g. extrusion, co-extrusion, heating, thermoforming, injection moulding, hot and cold pressing etc.) [16–19].Polymer ceramic matrix composite is one of the engineering materials which enables a route for fabrication of parts for wind turbine blade, ship body, car body, truck panel, bathroom fixtures, helmet, sports good such as fishing rod, kitchen product, water cooler parts, plastic handle, engine cover and double curvature component by various processing methods including, pultrusion process, resin transfer moulding, injection moulding, diaphragm forming etc. Some studies have reported 3D printing of functional and non-functional prototypes for various applications. But hitherto little has been reported on use of 3D printing techniques for rapid tooling (by selecting polymer ceramic composites) in machining of thermoplastic materials. Further in this paper, a case study has been presented for development of rapid tooling of polymer-ceramic composites for machining of thermoplastics.

2. Methods and applications of polymer-ceramic composites

Figure 1 shows the common classification of processing techniques for preparation of ceramic-reinforced polymeric composites. As polymers are broadly divided into thermosetting and thermoplastic, their processing methods are also different for different applications. For preparation of thermosetting composites reinforced with ceramic particles, generally cold processing over hot processing techniques are preferred to retain the inherent properties of thermosetting. For processing of thermosetting-ceramic composites the commonly used processing techniques includes: injection moulding, pultrusion, pressure bag moulding, casting injection moulding, compressing moulding, resin transfer moulding and spraying [2,3]. Vulcanisation is a heating method for thermosetting polymer where heating/curing is performed at the higher temperature for cross linking of carbon chain in the thermosets. As per prospective of application of final product, injection moulding is used for preparations of objects such as milk bottle crates, electrical insulations and castings. The extrusion moulding is largely applicable for production of pipes, threads of fabric and electrical cable insulations. Applications of compression moulding includes, bulk moulding compounds (BMC) and sheet moulding Compounds

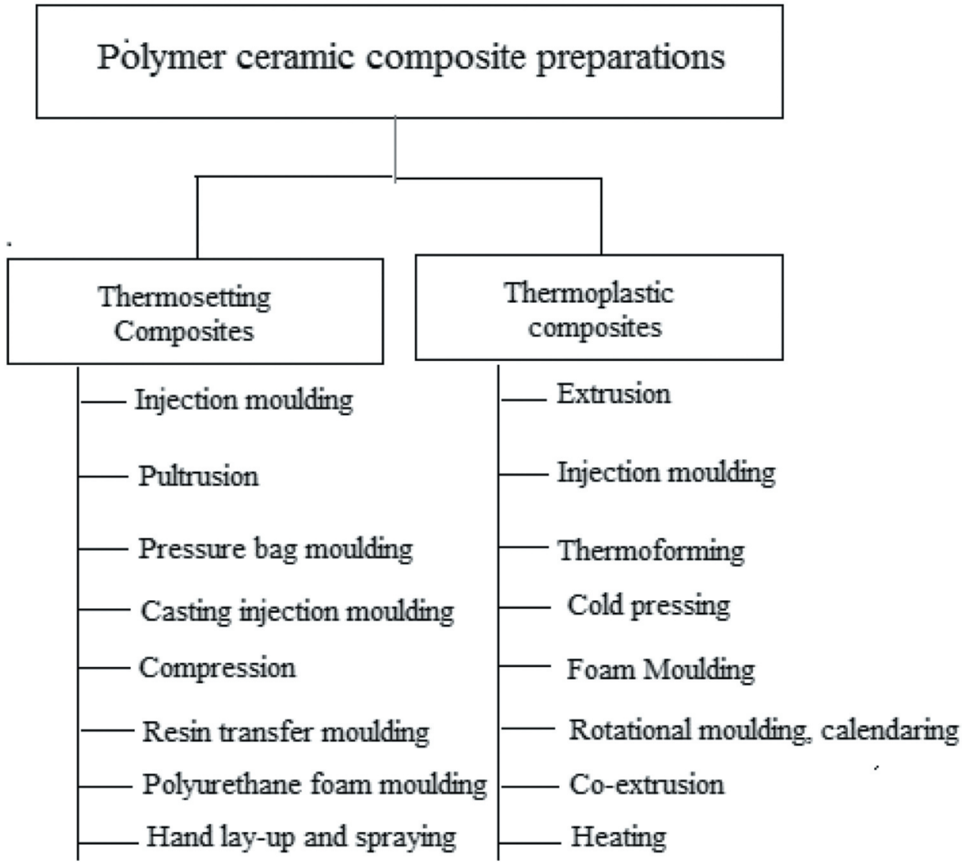

Figure 1. Processing techniques for polymer-ceramic composites.

(SMC). Spin casting is another method which is used for production of fishing lures and jigs, gaming miniatures, figurines, emblems as well as production and replacement parts [18–20].

Table 1 shows detailed literature for processes for fabrication of polymer-ceramic composites, applications and their resultant outputs [21–53]. As per the fundamentals, thermoplastics are those polymer which retains its inherent properties even if processed through number of heating cycles. Thermoplastic-ceramic composites are generally prepared by various heating processing which includes, extrusion by heating, hot injection moulding, thermoforming, foam moulding, calendaring, co-extrusion and by direct heat forming. The extrusion processes are applied for production of various civil engineering structural and non-structural parts, fabrication of multifunctional nanomaterials, anti-wear flexible components. 3D printing by fused deposition modelling (FDM) as one of the extrusion processes is used for production of tailor-made functional and non-functional prototypes. Injection moulding is one of the largely used composite preparation techniques for fabrication of automobiles and aviation parts. The chemical mixing is also used as polymer-ceramic composites preparations techniques for fabrication of microstrip antenna. The biomedical polymer like; polylacticacid (PLA)is reinforced for

Table 1. Polymer ceramic composites, their method of processing, physical strength and prospective applications.

Base polymer	Ceramic filler and amount	Method of processing	Physical strength	Application	Ref.
ABS	Graphene oxide:2% by weight	Extrusion	Young's modulus:2500MPa	Structural application	[21]
	barium titanate:74.2% by weight	3D printing (FDM)	Young's modulus:2970MPa	Tailored dielectric device	[22]
	Glass fibre: 10% by weight/carbon fibre: 30% by weight	Injection moulding	Compressive strength:3158 MPa	Low cost structures	[23]
	Bakelite:10% by weight/Al_2O_3+ SiC: upto 25%	3D printing (FDM)	Tensile strength: 25.12MPa	Structural applications	[24]
	Glass fibre: 30% by weight	Single screw compounder	Tensile strength: 50MPa	Structural applications	[25]
PLA	Glass fibre/20% by weight	Twin screw extruder	Tensile strength: 81.67MPa	Thermal resistance applications	[26]
	10 % $Al_2O_3$by weight	Electro spinning	Flexural modulus: 7.5GPa	Dental scaffolds	[27]
	10% $Al_2O_3$by weight	Electro spinning	Tensile strength: 0.5MPa	Dental scaffolds	[28]
	50% Sic and 10% C by weight	Extrusion	Density: 1.75 g/cm^3	Shape memory applications	[29]
	9% MWCNT	3D printing	Tensile strength: 78.4 ± 12.4MPa	Energy storage, biosensors and tissue engineering	[30]
Nylon 6	30%SiC by weight	Injection moulding	Tensile strength:68.69MPa Hardness: 77.6 Shore D	Gear manufacturing	[31]
	1% SiC-% coated rod-shaped Si_3N_4 by weight	Extrusion	Tensile strength: 602MPa	Fabrication of multifunctional nanomaterials	[32]
	30% SiCa by weight	Twin screw extruder	Young's modulus: 8.8 GPa	Anti-wear flexible composites applications	[33]
	25%SiC+30% Al_2O_3 by weight	Single screw extruder	Young's modulus: 1.67 GPa	Anti-wear flexible composites applications	[34]
Nylon 66	59% hexagonal boron nitride (hBN) by volume	Twin screw extruder	Thermal conductivity: 2.16 W/m K	Structural applications	[35]
Nylon 12	10% SiC by weight	Injection moulding	Young's modulus: 1456.6MPa	Structural applications	[36]
PET	40% glass fibre by weight	Single screw extruder	Flexural strength: upto 200MPa	Structural applications	[37]
	4% EntadaMannii fibres by weight	Moulding	Flexural strength: 6.09 MPa	Structural applications	[38]
LDPE	25% Al_2O_3 and 25% SiC by weight %	3D printing	Tensile strength: 679.38MPa	Thermodynamic sink	[39]
	6% Al_2O_3 by volume	Chemical mixing	Density: 1.52 g/cc	For fabrication of microstrip antenna	[40]
	2% Al_2O_3 by weight	Co-mixing by stearic acid	-	Dielectric components	[41]
	10% TiO_2 and 20% $Al_2O_3$by weight	Injection moulding	Tensile strength:12.65MPa	Bio-material	[42]
HDPE	15% SiC by weight	Compression moulding	Tensile strength: 24.70MPa	Wear resistance applications	[43]
	15% $Al_2O_3$and 15% SiC by weight	Twin screw extrusion	Tensile strength: 23.87MPa	Industrial applications	[44]
	9% glass fibre by weight	Twin screw extruder	Tensile strength: 26.50 MPa	Structural applications	[45]
	30% glass fibre by weight	Moulding	Tensile strength: 46.74 MPa	Structural applications	[46]
	31% graphene by weight	Injection moulding	Tensile strength: 26.0 MPa	Low cost industrial components	[47]
PMMA	60% Al2O3 by weight	Solution casting	Tensile strength: 16.93 MPa	Preparation of composite film	[48]
	30% CNT by volume	Twin screw co-rotating extruder	Tensile strength: 47.60 MPa	High impact part fabrication	[49]
PCL	Hydroxyapatite	3D printing	Flexural strength:8.0Mpa	Load bearing applications	[50]

(*Continued*)

Table 1. (Continued).

Base polymer	Ceramic filler and amount	Method of processing	Physical strength	Application	Ref.
PVC	55% $Al_2O_3$by weight	Hot press	-	Accelerometers, acoustic emission sensors	[51]
PS	25% SiC by weight	Twin screw extruder	Tensile strength: 20 Mpa	3D printing	[52]
PC	1.5% MWCNT by weight	Twin screw extruder	Tensile strength: 54.2 ± 4.1 MPa	3D printing	[53]

ABS: acrylonitrile butadiene styrene, PLA: polylactic acid, PET: polyethylene terephthalate, LDPE: low-density polyethylene, HDPE: high-density polyethylene, PMMA: Poly(methyl methacrylate) (PMMA), PCL: polycaprolactone, PVC: polyvinyl chloride, PS: polystyrene, PC: polycarbonate ceramic particle by electro-spinning process to fabricate the dental scaffolds with improved hardness and wear resistive properties.

3. Case studies for hybrid route of polymer-ceramic composites preparations and their application

A case studies of polymer-ceramic composite materials has been discussed in this section for preparations of polymer-ceramic rapid tooling [54] In this case study, the secondary-recycled LDPE without any post reinforcement and HDPE with 10% Al_2O_3 reinforcement were printed on FDM setup followed by twin screw extrusion after establishing required melt flow index (MFI). Further, tooling of HDPE were acted under 500, 750 and 1000rpm, feed rate of 20, 30 and 40 mm/min with depth of cut 1, 2 and 3 mm following Taguchi L9 orthogonal array. The mechanical and thermal analysis has been performed on machined LDPE work piece andAl_2O_3reinforced HDPE tooling for investigations of role of input process variables on material removal rate. Figure 2 shows step by step procedure for machining of LDPE with Al_2O_3reinforced HDPE tooling materials.Figure 3 details the photographic view of methodology involved for present case study.

As per Taguchi L9 orthogonal array a design of experiment has been prepared and experimentation was conducted and output properties in form of material removal have been calculated. Table 2 shows the experimental condition for machining and experimentally determined values of material removal. As per output of this study, it has been observed that maximum material losses were obtained at no. 9 (1.054 g) and minimum losses at experiment no. experiment no. 4 (0.552 g).

It may be due to the fact that at higher rotational speed and higher transverse speed, tool acted upon work pieces may have applied maximum force so that material losses were minimum. On the other hand, at experiment no. 4, the lower transverse speed, intermediate rotational speed and intermediate depth of cut may have processes good condition to minimise the material losses.

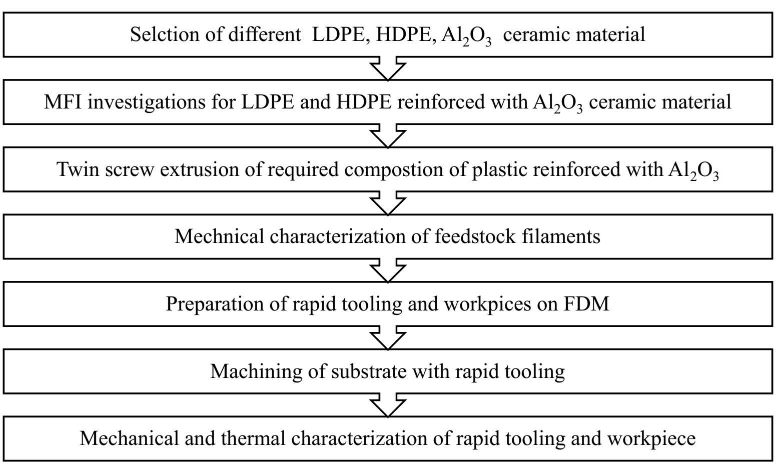

Figure 2. Route for rapid tooling and their application.

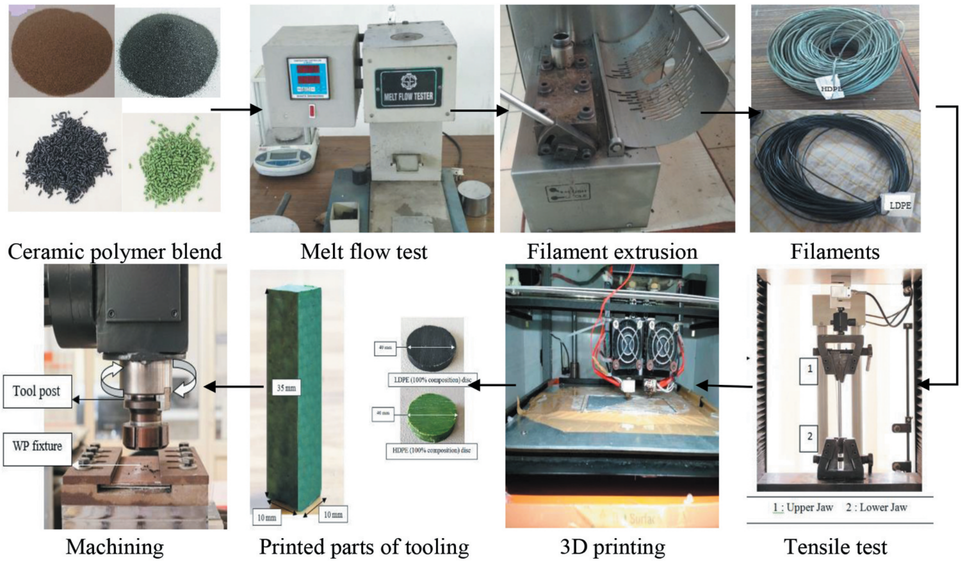

Figure 3. Processing method for development of rapid tooling [39,54–56].

Table 2. Design of experiment and results of material losses.

Experiment no.	Rotational speed	Transverse speed	Depth of cut	Material losses from WP	SN ratio of material losses
1	500 rpm	20 mm/min	1 mm	0.554 g	5.12 dB
2	500 rpm	30 mm/min	2 mm	0.722 g	2.82 dB
3	500 rpm	40 mm/min	3 mm	1.033 g	−0.28 dB
4	750 rpm	20 mm/min	2 mm	0.552 g	5.16 dB
5	750 rpm	30 mm/min	3 mm	0.746 g	2.54 dB
6	750 rpm	40 mm/min	1 mm	1.041 g	−0.34 dB
7	1000 rpm	20 mm/min	3 mm	0.564 g	4.97 dB
8	1000 rpm	30 mm/min	1 mm	0.741 g	2.60 dB
9	1000 rpm	40 mm/min	2 mm	1.054 g	−0.45 dB

The signal-to-noise (SN) ratio of the material losses has been calculated by the given relation as quantitative values desired minimum is better type's case.

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

Where η is SN ratio, n is the no. of experiment and y is the material properties at experiment no. k.

Figure 4(a) shows the rapid cutting tool (Al_2O_3 reinforced HDPE) prepared by FDM, The region 1 indicates the tool part where there is no contact between tool and work piece and region 2 is the surface tool is acted upon work piece. Figure 4(b) shows the machined surface of LDPE where region 2is machined surface and region 1 is non-machined surface.

Based upon Table 2, Table 3 shows the analysis of variance (ANOVA) for signal to noise (SN) ration for material losses from workpieces. It has been observed that

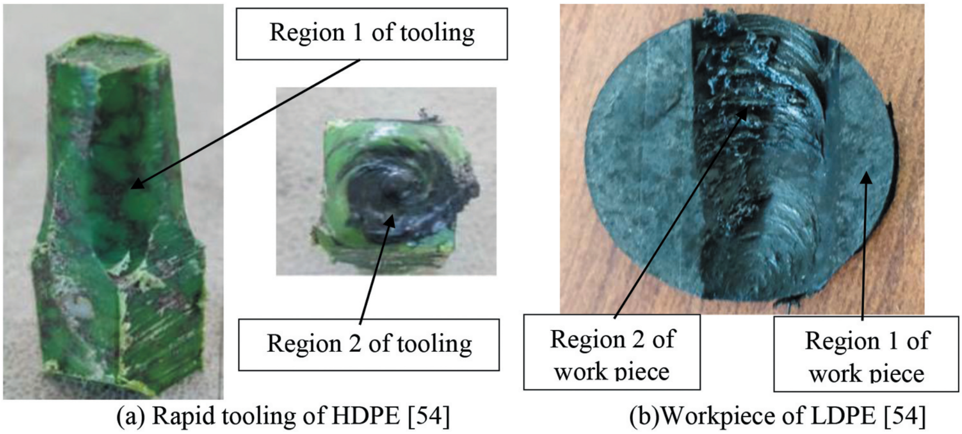

Figure 4. (a) Rapid tooling of HDPE [54] (b)Workpiece of LDPE [54].

Table 3. ANOVA for SN ratio of material losses.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotational speed (rpm)	2	0.05	0.05	0.0259	3.68	0.213
Transverse speed (mm/min)	2	44.74	44.74	22.373	3177.82	0.001
Depth of cut (mm)	2	0.01	0.01	0.007	1.04	0.491
Residual Error	2	0.01	0.01	0.007		
Total	8	44.82				

DF- degree of freedom. Seg SS- sum of square, Adj SS- Adjusted sum of square, Adj MS- adjusted mean of square, F- Fisher's value, P-probability

Table 4. Response Table for SN ratio of material losses.

Level	Rotational speed (rpm)	Transverse speed (mm/min)	Depth of cut (mm)
1	2.55	5.08	2.46
2	2.45	2.65	2.51
3	2.37	−0.36	2.41
Delta	0.18	5.45	0.09
Rank	2	1	3

transverse speed is the most significant parameter as P value obtained less than 0.05. Table 4 shows ranking table based upon Table 4.

For the output of material losses it has been calculated that transverse speed is most critical parameters followed by rotational speed and depth of cut.

Figure 5 shows main effects plot for SN ratios of material losses. It has been noted that for minimum material losses, combination of 500rpm, 20 mm/min transverse speed and 2 mm depth of cut has been obtained as optimum set of process parameters.

To find the optimum value of material loss at predicted set of process parameters, a relation has been used as;

η_{opt} = m+(m_{A1}–m) +(m_{B1}–m) +(m_{C2}–m)

'm' is mean of SN ratio (as per Table 7 2), $m_{A1}$is the SN ratio of rotational at level 1, $m_{B1}$is the SN ratio of transverse speed at level 1, and$m_{C2}$is the SN ratio for depth of cut at level 2 (see Table 4).

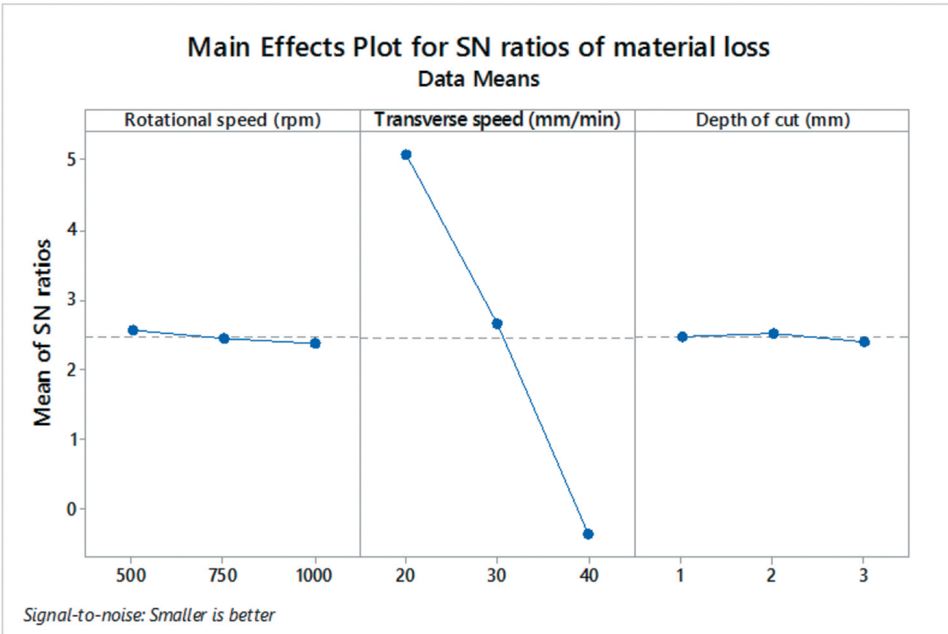

Figure 5. Main effects plot for SN ratios of material losses.

Considering material losses as smaller is better case,
$y_{opt}^2 = (1/10)^{\eta opt/10}$
Calculation:
Overall mean of SN ratios (m) for peak load was calculated as;
m = 2.12 dB (see Table 2)
From Table 4, ratio, $m_{A1} = 2.55$, $m_{B1} = 5.08$, $m_{C1} = 2.51$
Now,
$\eta_{opt} = 2.12+(2.55–2.12) +(5.08–2.12) +(2.51–2.12\ dB)$
$\eta_{opt} = 5.9$
Now,
$y_{opt}^2 = (1/10)^{\eta opt/10}$
$y_{opt}^2 = (1/10)^{5.9/10}$
$y_{opt} = 0.257$ g
The optimum value of material losses at predicted setting = 0.257 g

The confirmatory experiment has been performed and the actual value at predicted setting obtained is 0.250 g.

Figure 6 shows the contour plot for material losses as SN ratio interaction of (a) rotational speed vs. transverse speed, (b) transverse speed vs. depth of cut and (c) depth of cut vs. rotational speed. As per interactions made for SN ratio, it has been observed that maximum value of SN ratio to minimise the material losses can be obtained at 750rpm rotational speed, 20 mm/min transverse speed and 2 mm depth of cut.

Figure 7 shows the DSC plots of region 1 and region 2 (Figure 4) of rapid tooling and work piece materials. DSC performed for comparing both non-machined zone region 1

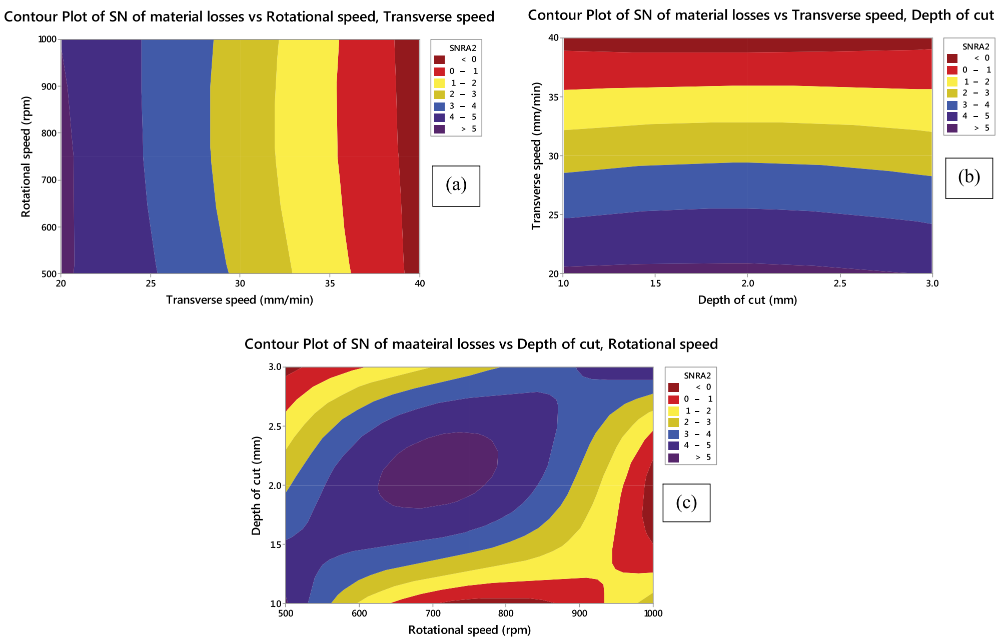

Figure 6. Contour plot for material losses as SN ratio interaction of (a) rotational speed vs. transverse speed, (b) transverse speed vs. depth of cut and (c) depth of cut vs. rotational speed.

and machined zone region 2 (for better tool life) by using DSC setup. As observed from Figure 7, enthalpy values for machined zone and work piece region 2 came out to be higher than that of non-machined zone region 1, giving a clear idea that machined portion becomes more thermally stable than that of non-machined zone. The results are in line with observations made by other investigators [56–60].

4. Conclusions

This paper details the review of various polymer-ceramic processing method, innovations in common ceramics (SiC, Al_2O_3, Mullite, TiO_2, glass fibre, carbon and their allotropes etc.). Following conclusions have been made from the present study.

The reinforcement of ceramic particles into polymeric matrix (both thermoplastic and thermosetting) lead to improved fracture toughness, fatigue resistance, wear resistance, higher strength retention at higher temperature, higher strength to weight ratio, higher hardness, thermal response, chemical inertness and corrosion resistance.

The polymer ceramic composite is an eligible candidate for various applications including, fabrication of parts for wind turbine blade, ship body, car body, truck panel, bathroom fixtures, helmet, sports good such as fishing rod, kitchen product, water cooler parts, plastic handle, engine cover and double curvature component. As per case study for preparation of rapid tooling for machining applications, it has been ascertained that reinforcement of Al_2O_3 in the polymeric matrix lead to the thermally stable polymer ceramic composites.

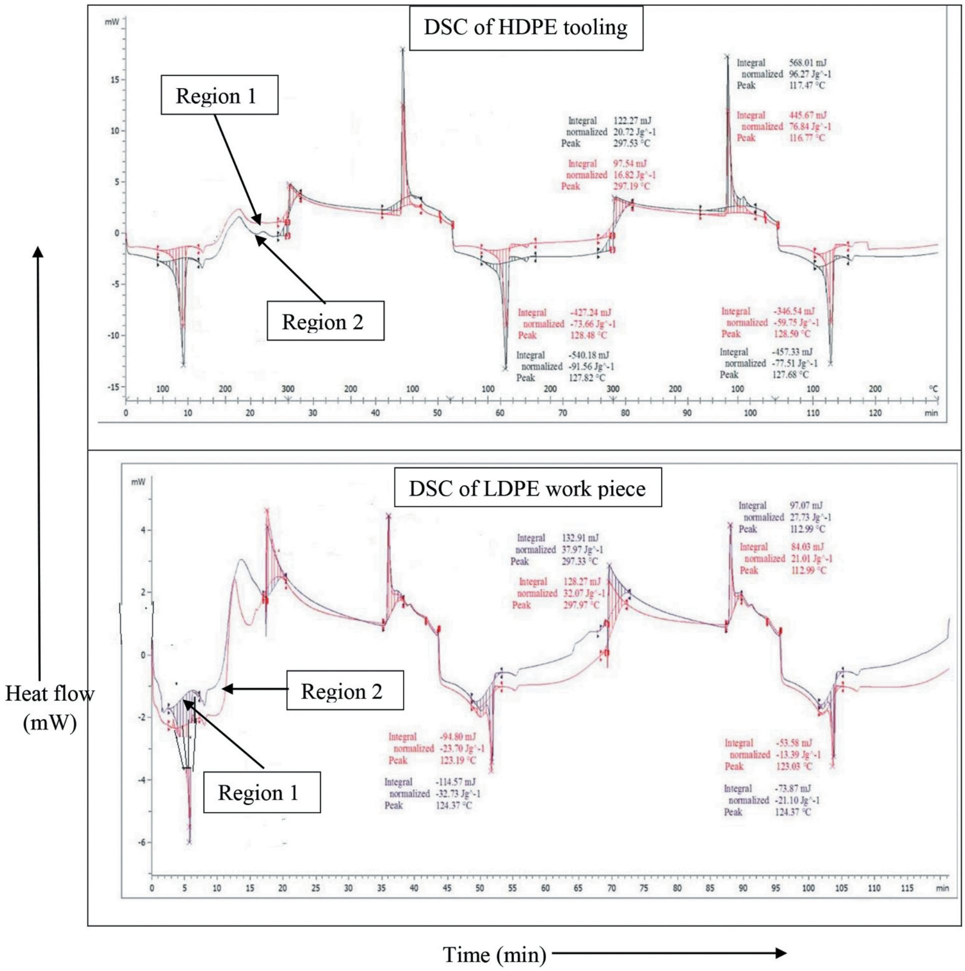

Figure 7. DSC analysis of rapid tooling and work pieces [54].

Disclosure statement

No potential conflict of interest was reported by the authors.

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