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Analysis of abrasive wear behavior of PTFE composite using Taguchi's technique

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Abstract: Polymeric composites are widely used for structural, aerospace, and automobile sectors due to their good combination of high specific strength and specific modulus. These two main characteristics make these materials attractive, compared to conventional materials like metal or alloy ones. Some of their typical benefits include easy processing, corrosion resistance, low friction, and damping of noise and vibrations. Wear behavior of Polytetrafluoroethylenes (PTFE) and its composites including glass-filled composites and carbon-filled composites are investigated using a pin-on-disc configuration. A plan of experiments in terms of Taguchi technique is carried out to acquire data in controlled way. An orthogonal array (L9) and the analysis of variance are employed to investigate the influence of process parameters on the wear of these composites. Volume loss increased with abrasive size, load, and distance. Furthermore, specific wear rate decreased with increasing grit size, load, sliding distance, whereas, slightly with compressive strength. Optimal process parameters, which minimize the volume loss, were the factor combinations of L1, G3, D1, and C3. Confirmation experiments were conducted to verify the optimal testing parameters. It was found that in terms of volume loss, there was a good agreement between the estimated and the

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Yusuf Şahin–is working as a senior lecturer of Manufacturing Engineering Department at the Faculty of Technology, Gazi University in Ankara/Turkey. His major fields are Metallurgy-Materials Science (Composite materials, Wear and friction, Powder metallurgy, Manufacturing processes, and Metal cutting processes). He received his PhD Degree (1995) from Aston University in Birmingham/UK (Department of Mechanical Engineering) in the field of continuous boron-reinforced MMCs based on fabrication, their mechanical, and wear behaviors.

He has already published about 30 research papers with different reputation Journals. Conference papers about 40 are published on metal matrix composite, wear, or metal cutting processes. Furthermore, he has also published several books such as "Metal cutting principles, Vol. 1, Vol. 2", "Manufacturing Processes," "Introduction to Composite Materials," and "AutoCAD Design."

PUBLIC INTEREST STATEMENT

Due to their good combination of high specific strength and specific modulus, polymer composites (PMCs) are widely used for structural, aerospace and automobile sectors such as gears, cams, wheels, brakes, clutches, bearings, etc. and also in other engineering applications like conveyor aids. Also, polymer composites are subjected to abrasive wear in many applications. Most of abrasive wear problems arise in chute liners in power plants, mining and earth moving equipments. Wear behavior of PTFE and its composites including Glass-filled composites and Carbon-filled composites are investigated against SiC abrasives. Taguchi technique is carried out to acquire data in controlled way because this method eliminates the need for repeated experiments and thus saves time, material and cost. An orthogonal array (L9) and analysis of variance are employed to investigate the influence of process parameters on the wear of composites. Optimal process parameters, which mimimise the volume loss, is determined using this technique.

experimental value of S/N ratio with an error of 1.604%. Moreover, abrasive size, load, and sliding distance exerted a great effect on the specific wear rate, at 51.14, 27.77, and 14.70%, respectively.

Subjects: Science; Materials Science; Composites; Technology

Keywords: PTFE; glass-filled composites; carbon-filled composite; load; wear; Taguchi technique

1. Introduction

Polymers and their composites are emerging as viable alternative products to metal or alloys in many advanced engineering applications. Because of the combination of high specific strength and specific modulus, the polymers and their composites find very useful applications in automotive components such as gears, cams, wheels, brakes, clutches, and bearings and also in other engineering applications like conveyor aids, chute liners, mining, agriculture, and other allied fields, where wear performance in no lubricated condition is a key parameter for the material selection (Friedrich, Lu, & Mager, 1995; Hutching, 1992; Khedkar, Negulescu, & Meletis, 2002). Polymer composites are subjected to abrasive wear in many applications (Schwartz & Bahadur, 2001). Abrasive wear is one type of wear where hard asperities on one surface move across a softer surface under load, penetrate and remove material from the softer surface, leaving grooves (Gates, 1998). Most of the abrasive wear problems arise in chute liners in power plants, mining, and earth moving equipments. Influence of various factors on the abrasive wear of composite is shown (Figure 1). The commonly used polymer matrices include polytetraflouroethylene (PTFE), polyetheretherketone (PEEK), vinyl ester, epoxy, etc. The extensively studied fibers are glass, carbon, boron, and kevlar. As PTFE exhibits poor wear resistance, the wear resistance of PTFE can be significantly improved by addition of suitable filler materials like short aramid, carbon, or glass fibers (Friedrich, Zhang, & Schlarb, 2005). Thus, particle-filled polymers are very promising materials for various application, such as sliding elements, which require low friction and wear, whereas for other applications, for example, in clutches or brakes, high friction combined with low wear is necessary (Kukureka, Hooke, Rao, Liao, & Chen, 1999). The friction coefficient and the wear resistance are not real material properties, but depend on the system in which these materials have to function (Byett & Allen, 1992; Harsh & Tewari, 2007; Hashmi, Dwivedi, & Chand, 2006). There have been considerable reports on the wear behavior of fiber reinforced epoxy composites (Mohan, Natarajan, & Kumar, 2011; Sampath, Seetharamu, Murali, & Kumar, 1999; Yousif & El-Tayeb, 2009) and the wear rate changes considerably with the fibers, their types, and weight fractions and parameters (Ray & Gnanamoorthy, 2007; Tong, Arnell, & Ren, 1998; Unal, Mimaroglu, Kadıoglu, & Ekiz, 2004). In addition, the friction and wear behavior of PTFE, glass fiber reinforced, and bronze and carbon-filled polymers are studied under different range of loads and speeds (Basavarajappa & Ellangovan, 2012; Sabeel Ahmed, Khalid, Mallinatha, & Amith Kumar, 2012; Tevrüz, 1999, 1998). Shipway and Ngao (2003) concluded that the abrasive wear behavior and rates of polymers depended critically on the polymer type. Furthermore, the wear was associated with indentation type morphology in the wear scar and low values of tensile strain to failure. Cirino, Friedrich, and Pipes (1988) reported that the wear rate decreased with increase in the fiber content for sliding and abrasive wear behavior of polyetheretherketone (PEEK) with different continuous fibers. The abrasive wear behavior of short carbon/glass fiber reinforced with PEEK/polyphenylene sulfide (PPS) polymers showed that the wear rate was sensitive to the orientation of the fiber axis with respect to the sliding direction (Harsha & Tewari, 2003; Lhymn, Tempelmeyer, & Davis, 1985; Mishra & Acharya, 2010). Similar works confirmed that the normal orientation indicated better wear resistance than anti-parallel and parallel directions (Chand & Dwivedi, 2007a; Dwivedi & Chand, 2009; Harsha & Tewari, 2002). The addition of ultra-high-molecular weight polyethylene (UHMWPE) reduced the wear rate. Friedrich (1993) investigated the abrasive wear behavior of epoxy reinforced with carbon, glass, and aramid fabrics and reported the wear performance of the fabrics in the order Aramid > glass > carbon. Bijwe, Logani, and Tewari (1989) tested polyamide 6,

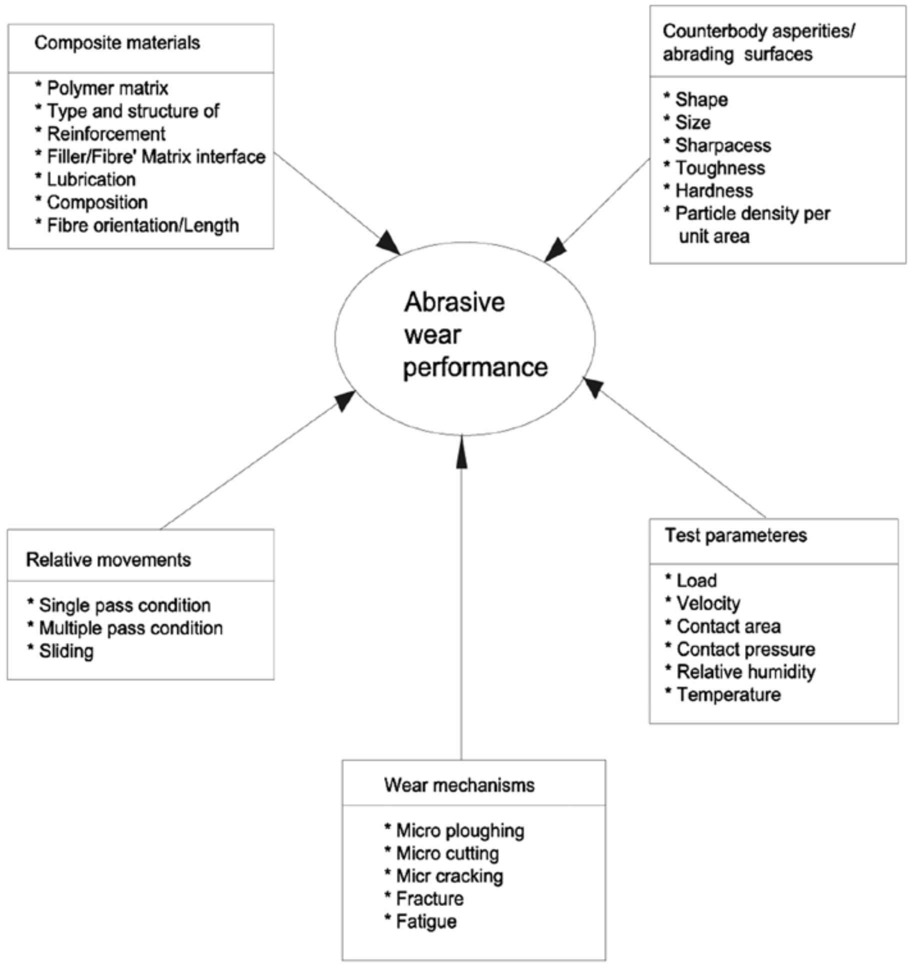


Figure 1. Influence of various parameters on the abrasive wear of composites (Harsha & Tewari, 2003).

polytetrafluoroethylene (PTFE) and their various composites in abrasive wear under dry and multipass conditions against SiC paper. The polymers without fillers had better abrasive wear resistance than their composites (Suresha, Chandramohan, Siddaramaiah, & Samapthkumaran, 2007). Suresha and Kumar (2009) studied the three-body abrasive wear behavior of particulate-filled PA66/PP composites at different conditions. It is indicated that addition of nanoclay/short carbon fiber in PA66/PP had significant influence on wear under varied abrading distance/loads. Further, it was found that nanoclay-filled PA66/PP composites exhibited lower wear rate compared to short carbon fiber-filled PA66/PP composites. Liu, Ren, Arnell, and Tong (1999) concluded that the applied load was the main parameter and the abrasive wear resistance improvement of filler reinforced UHMWPE polymer was attributed to the combination of hard particles, which prevent the formation of deep, wide, and continuous furrows. Ravi Kumar, Suresha, and Venkataramareddy (2009) revealed that the wear volume loss increased with increase in abrading distance/abrasive particle size for the two-body abrasive wear behavior of glass/carbon fabric reinforced vinyl ester composites. However, the specific wear rate decreased with increase in abrading distance and decrease in abrasive particle size. The results showed that the highest specific wear rate was for glass fabric reinforced vinyl ester composite with a value of 10.89×10^{-11} m^3/N m and the lowest wear rate was for carbon fabric reinforced vinyl ester composite with a value of 4.02×10^{-11} m^3/N m. Yousif, Nirmal, and Wong (2010) exhibited higher values in frictional coefficient when it was subjected against coarse sand of the treated betel nut fiber reinforced epoxy (T-BFRE) composite. Besides, higher weight loss was noticed at high sliding velocities.

Recently, some attempt has been taken to study the wear anisotropy of natural fibers like cotton (Eleiche & Amin, 1986), bamboo (Chand & Dwivedi, 2007b; Chand, Dwivedi, & Acharya, 2007), sisal (Chand, Naik, & Neogi, 2000), jute (Tong, Ren, Li, & Chen, 1995). Raju, Suresha, and Swamy (2012) investigated the abrasive wear behavior of SiO_2 filled glass fabric reinforced epoxy (G–E) composites containing 5, 7.5, and 10 wt.%. The results showed that as the filler loading increased, the wear volume loss decreased and increased with increasing abrading distance (Patnaik, Satapathy, & Biswas, 2010). The wear behavior of polymer composites indicated that tribolfilms were formed on the counter face surface (Bahadur & Sunkara, 2005; Bahadur, Zhang, & Anderegg, 1997; Vande Voort & Bahadur, 1995).

Apart from experimental studies, several numbers of models, which attempt to relate the abrasive wear resistance of polymer composites, have been proposed. Three-body abrasive wear behavior of carbon fabric reinforced epoxy composite filled with graphite filler using Taguchi analysis was investigated by Sudarshan, Varadarajan, and Rajendra (2013). They reported that applied load showed the major impact on abrasive wear, followed by abrading distance and filler content. A similar result on the glass–epoxy polymer composites with SiC and Graphite particles as secondary fillers was obtained under dry conditions (Basavarajappa, Arun, & Davim, 2009). Later on, however, effect of filler material on three-body abrasive wear behavior of glass–epoxy composites was investigated by Basavarajappa, Joshi, Arun, Kumar, and Kuma (2010) using a L9 orthogonal array and analysis of variance (ANOVA). The result shows that the abrading distance has more effect on the wear compared to other parameters. The filler material (SiC) contributes a significant wear resistance of the G–E composites. Sahin (2005) developed weight loss model of aluminum alloy composites with 10 wt.% SiC particles using Taguchi method. They reported that the abrasive grain size was the major parameter, which affect the abrasive wear, followed by the reinforcement size. Chauhan, Kumara, Singh, and Kumar (2010) concluded that, the sliding wear of the of glass fiber reinforced vinyl ester composites filled with fly ash particulate composites was affected by the (pv) factor and filler content, whereas the effect of sliding distance was insignificant. The effect of the filler weight fraction, normal load, and sliding distance on the abrasive wear behavior of glass–epoxy composite showed that among the control parameters, sliding distance had the highest statistical influence on the abrasive wear of the composites, followed by normal load and filler content (Sudarshan, 2013). It was also found that the specific wear rate for all the vinylester composites decreases with the sliding distance and after certain duration attains approximately a steady state value (Chauhan & Thakur, 2013).

The above literature reviews have demonstrated that the dry wear of PA6G, UHMWPE and PEEK polymer, and its composite (Byett & Allen, 1992; Hashmi et al., 2006; Harsh & Tewari, 2007; Sampath et al., 1999); epoxy, fabric, vinyl ester, and polyester (Mohan et al., 2011; Ray & Gnanamoorthy, 2007; Yousif & El-Tayeb, 2009); bamboo, PEEK (Tong et al., 1998; Unal et al., 2004); bronze, PTFE, and epoxy (Basavarajappa & Ellangovan, 2012; Sabeel Ahmed et al., 2012; Tevrüz, 1999, 1998) based composites are studied in terms of experimental work. For abrasive wear of composites, microscale wear, short fiber (Cirino, 1988; Lhymn et al., 1985; Mishra & Acharya, 2010; Shipway & Ngao, 2003); influence of fiber orientation (Chand & Dwivedi, 2007a; Dwivedi & Chand, 2009; Harsha & Tewari, 2002); effects of fillers like carbon and glass fiber (Bijwe et al., 1989; Friedrich 1993; Suresha et al., 2007); Vinyl ester, UHMWPE, and Polyamide 6G (Liu et al., 1999; Suresha & Kumar, 2009; Ravi Kumar et al., 2009; Yousif et al., 2010); cotton fiber, anisotropic bamboo, and short glass fiber (Chand et al., 2007; Chand & Dwivedi, 2007b; Chand et al., 2000; Eleiche & Amin, 1986); bamboo, SiO_2, glass fabric, and particulate glass fillers (Chand et al., 2000; Raju et al., 2012; Tong et al., 1995); and tribofilm formation (Bahadur & Sunkara, 2005; Bahadur et al., 1997; Patnaik et al., 2010; Vande Voort & Bahadur, 1995) are studied experimentally. However, there are only a few studies on the application of Taguchi method for wear results of graphite, glass, SiC composites (Basavarajappa et al., 2009, 2010; Sudarshan et al., 2013); effect of fly ash content, glass epoxy and SiC (Chauhan et al., 2010; Sahin, 2005); and HMWPE and polyphenylene sulfide-based composites in terms of the statistical method (Liu et al., 2001; Sudarshan, 2013). Therefore, the aim of this work is to study the abrasive wear behavior of PTFE, and its composites (G15 and C25) under SiC abrasives. The Taguchi L9 (3^3) method and ANOVA are adopted to identify the effect of process parameters on the wear of tested materials.

2. Experimental

2.1. Materials

The tribological behavior of polymer-based composite materials sliding against SiC paper on hardened steel under dry conditions is studied using a unidirectional pin-on-disk tribometer. For glass-filled polymer composites, E-glass milled fibers with nominal diameter of 13 μm, nominal length of 0.8 mm, and aspect ratio minimum 10 were used while carbon which is amorphous petroleum-coke with a particle size less than 75 μm, and purity of 99% C were utilized for carbon-filled composites. In this study, three polymeric composite (PMC) materials are tested namely; PTFE, known with the trademarks Teflon, carbon-filled composite (C25) including 25 wt.% C and 75 wt.% PTFE; glass-filled composite (G15) including 15 wt.% glass and rest of it is PTFE. The characteristics of the polymer-based composites are shown in Table 1. Polymer Chemical Industry Ltd. (Polikim A.Ş., Gebze/Turkiye) in Turkey provides the materials in the form of rods. Molded rod's size is about Ø15–Ø425 mm in size, and 100–150–200 mm in length.

2.2. Experimental design

An orthogonal array and ANOVA are applied to investigate the influence of process parameters on the wear behavior of composites. The Taguchi design of experiment approach eliminates the need for repeated experiments and thus saves time, material, and cost. Taguchi approach identifies not only the significant control factors, but also their interactions influencing the wear rate predominantly. The most important stage in the design of experiment lies in the selection of the control factors. In the Taguchi method, the experimental results are analyzed: (1) to establish the best or optimum condition for a product/process, (2) estimate the contribution of individual factors, and (3) estimate the response under the optimum conditions. The limitation of this method is the need for timing with respect to product development. The technique can only be effective when applied early in the design of the product/process. Otherwise, it cannot be cost effective.

This experiment specifies four principle wear testing conditions including the applied load (L), grid size (G), sliding distances (D), and compressive strength (C) of the tested materials as the process parameters. Codes and levels of control parameters are shown in Table 2. This table shows that the experimental plan has three levels. A standard Taguchi experimental plan with notation L9 (3^3) is chosen, as shown in Table 3. Each combination of experiments is repeated twice to acquire a more accurate result in the process. In the Taguchi method, the experimental results are transformed into

Table 1. Some properties of polymer composites

Samples	Code	Color	Compression strength (MPa)	Fracture strain (%)	Density (g/cm³)
Polytetrafluoroethylene	PTFE	White	4.80	165	2.15
Glass-filled PTFE polymer composite	G15	White	6.3	235	2.20
Carbon-filled PTFE polymer composite	C25	Black	9.8	87	2.25

Table 2. Control factors and their levels

Symbol	Controlling parameters	Level 1	Level 2	Level 3
L	Applied load, N	5	10	20
G	Grit size, mesh or (μm)	400 (~16 μm)	800 (~8 μm)	1200 (~3 μm)
D	Sliding distance, m	45	90	150
S	Material's compression strength at 1% fracture, MPa	4.8	6.3	9.8

Table 3. L9 orthogonal design

Experimental number	Factor L	Factor G	Factor D	Factor C
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The S/N ratio for minimum wear rate coming under smaller the better characteristic, which can be calculated as logarithmic transformation of the loss function by the equation:

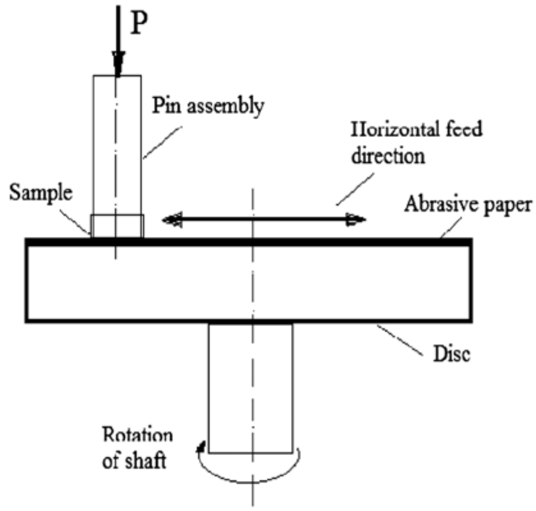
$$\eta = -10 \log 10 \frac{1}{n} \left(\sum_{i=0}^{n} yi^2 \right) \tag{1}$$

where "n" is the number of observations and "y" is the observed data. ANOVA is performed using S/N ratio. The objective of ANOVA is to evaluate the significance of testing parameters and their interactions on the wear performance of polymers. If some testing parameters do not have considerable impact on wear, they can be kept within a suitable range for the test and can be excluded in building future prediction and optimization models. The percentage contribution of variance can be calculated through ANOVA. In an ANOVA table, there is a p-value for each independent parameter in the model, which is used to test the significance of each parameter and interaction between parameters. Smaller the p value, greater is the significance of the factor/interaction corresponding to it. In conjunction with an ANOVA, main effect plots are used to examine differences among level means for one or more factors. When the effect of one factor on the level of other factor, interaction plots are used. A design factor with a large difference in the signal to noise ratio from one factor setting to another indicates that the factor or design parameter is a significant contributor to the performance characteristic. The final step in design of experiment approach is to predict and verify the arrived values for the optimal combination level of control factors.

2.3. Wear test

The experiments are carried out using polymer-based composites in a pin-on-steel disk configuration in accordance with the ASTM standard G99 (Figure 2). The counter surface material for the wear testing is a steel disk 160 mm in diameter by 12 mm in thick, which is heat-treated to give a surface hardness of 59–63 RC. This is ground to a surface finish of approximately 0.15 μm centerline average. The composite bars are machined into small cylindrical shapes with lathe machine for the pin-on-disk wear testing. The samples are loaded against the SiC abrasives fixed on the hardened steel disk with the help of a cantilever mechanism. The pin is then mounted in a steel holder in the wear machine so that it is held firmly perpendicular to that of the flat surface of the rotating counter disk. The specimen of 6.5 mm in diameter for composites tested under different loads against smooth hardened steels. The wear tests are carried out at a sliding speed of 0.8 m s^{-1}. The experiments are carried out at normal loads of 5, 10, and 20 N and the abrading distances chosen are 45, 90, and 120 m. The grit size is about 400, 800, and 1200 mesh during the test. The wear is measured by the loss in weight. The wear pin is cleaned in acetone prior to and after the wear tests, and then weighed on a microbalance with 0.1 mg sensitiveness. Each test is performed with new track of disk. The wear rate is calculated by measuring the mass loss, density and known sliding distance and load. The specific wear rate (Ks) is then expressed on volume loss basis (Chand & Dwivedi, 2007b):

Figure 2. Schematic view of a pin-on-disk type of configuration.



$$Ks = \frac{\Delta M}{\rho L F n}\left(\frac{\mathrm{mm}^3}{\mathrm{N\,m}}\right) \tag{2}$$

where M is the mass loss in test duration (gm); ρ is the density of composite (gm/cm^3); F_n is the applied normal load (N); and D is the sliding distance (m). Two replicates are carried out for each material and results are averaged from the two test runs. Table 1 shows some properties of polymer composites.

3. Results and discussion

3.1. Analysis of wear results

The experimental lay out and results of the abrasive wear of polymer composites are shown in Table 4, Figures 3 and 4. The tests relevant to this table are carried out at a fixed speed, but indicated parameters. It is evident from the figure that the weight loss increases with increasing load and sliding distance, but decreases with increasing the grit size and compressive strength of the samples

Table 4. Experimental results of the abrasive wear test of polymer composites and their S/N ratios against SiC emery papers

	Control parameters				Weight loss, WL		Volume loss, VoL		Specific wear rate, SWR	
Run order	Load, L (N)	Grid, G (mesh)	Distance, D (m)	Compressive strength, *P* (MPa)	Mean weight loss (gm)	Density (g/cm^3)	Mean volume loss (mm^3)	S/N ratio (dB)	Mean specific wear rate (mm^3/N m)	S/N ratio (dB)
1	5	400	45	4.8	0.1100	2.15	0.05120	25.8146	0.0002140	73.3917
2	5	800	90	6.3	0.0480	2.20	0.02180	33.2309	0.0000484	86.3031
3	5	1200	150	9.8	0.0401	2.25	0.01780	34.9916	0.0000237	92.5050
4	10	400	90	9.8	0.1430	2.25	0.06350	23.9445	0.0000696	83.1478
5	10	800	150	4.8	0.1010	2.15	0.04690	26.5765	0.0000312	90.1169
6	10	1200	45	6.3	0.0250	2.20	0.01100	39.1721	0.0000244	92.2522
7	20	400	150	6.3	0.1910	2.20	0.08680	21.2296	0.0000289	90.7820
8	20	800	45	9.8	0.0610	2.25	0.02750	31.2133	0.0000296	90.5683
9	20	1200	90	4.8	0.0680	2.15	0.03162	30.0008	0.0000186	94.6097

Figure 3. Main effects plot for average the weight loss of polymer composites.

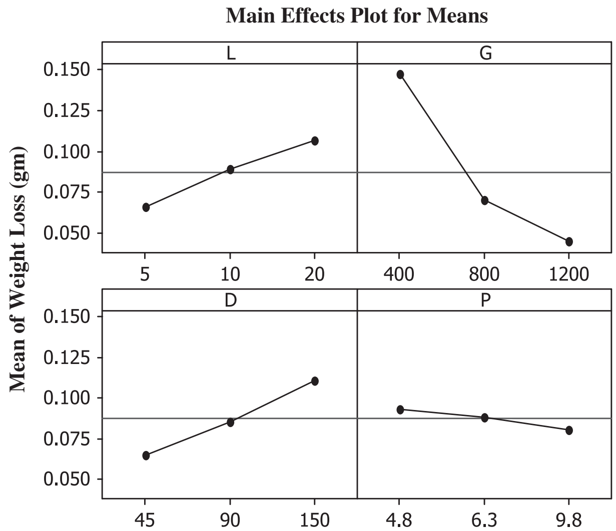
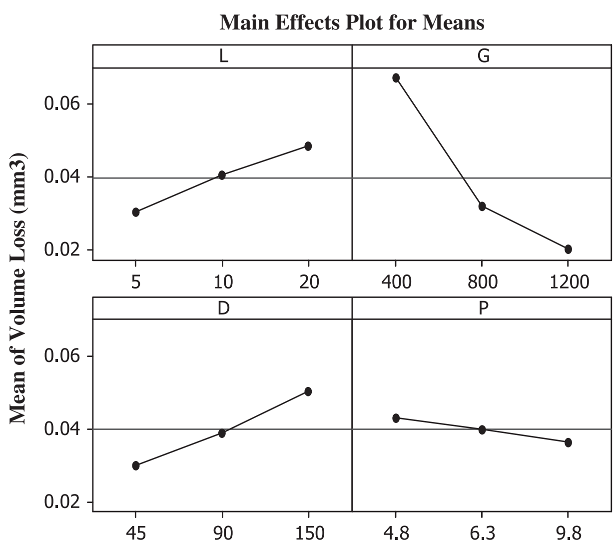


Figure 4. Main effects plot for average the volume loss of polymer composites.



(Figure 3). Linear increases with load, distance, and decreases with compression strength and grit size are also evident here, although a slight change occurs with decreasing the grit size. With a rise in testing load, the wear loss of the polymer matrix increases slightly higher than that of the composites. This phenomenon reflects that different wear mechanisms might be involved. Furthermore, the carbon-filled composites give the slightly lower wears than that of other sample due to its intrinsic properties, but no significant variation is observed between them. In other words, the fillers used in the present study reduce the wear rate, which indicates that the role of tribofilm was important. It is well known that the wear resistance of polymer composites depends on the ability of the composite to form a thin, uniform, and adherent transfer film on the counter face (Bahadur & Sunkara, 2005; Bahadur et al., 1997; Schwartz & Bahadur, 2001; Vande Voort & Bahadur, 1995). This transfer film on the counter face prevents the direct contact between the polymer pin and the metal counter face, which avoids abrasive action and therefore these results in reduced wear. The transfer film is also observed for PTFE matrix, but its adhesion to counter face was not good and so it was detached easily (Bahadur & Sunkara, 2005; Basavarajappa et al., 2009; Chand et al., 2000). On the other hand, it is observed that the weight loss is maximal for the run 1 due to using the bigger grit size of 400 (~16 μm), the first level of sliding distance (45 m), the lowest load (5 N), and compressive strength (4.8 MPa), which is followed by run 9. The main effects plot gives the optimal combination of testing parameters for minimum volume loss. The slope of the main effect plot for each parameter determines this. Figure 4 shows the mean volume loss as a function of grit size, applied load, sliding distance, and compressive strength of the samples, respectively. The volume loss decreases with increasing grit sizes and compressive strength, but increases with increasing load, and sliding distance for all materials. These are clearly related to the Archard's equation (Harsha & Tewari, 2002).

Archard's equation is generally used to describe the sliding wear of metal caused by adhesion, but it has proven very useful in abrasive wear as well. The equation states that

$$V = k\frac{L \times D}{H} \tag{3}$$

where V is the volume loss of the material; L is the applied load; D is the sliding distance; k is a constant called wear coefficient, and H is the hardness of the materials. This equation clearly indicates wear volume is directly proportional to both the load and sliding distance and it is inversely proportional to hardness. The average size of contact area increases and the volume loss is independent of the apparent area of the contact. In this current case, the wear resistance of the materials is also related to their compression strength apart from load and distance, but the relation between the volume loss and compression is found to be weaker than that of hardness effect (see Figure 3(d)). It is observed that with increasing the load and sliding distance, the penetration of hard asperities of the counter surface to the softer pin surface increases and the deformation and fracture of asperities of the softer surface increases (Harsha & Tewari, 2002; Ravi Kumar et al., 2009; Sudarshan, 2013; Suresha & Kumar, 2009). Again, the grit size is dominant factor on wear resistance of materials among the other parameters (Chand & Dwivedi, 2007; Chand et al., 2000; Sahin, 2005; Suresha & Kumar, 2009; Unal, Sen, & Mimaroglu, 2005) because the plot having higher inclination will have higher influence. It is followed by the sliding distance. The size of the abrasive particle and applied load tends to increase abrasive wear volume of the composites (Chand et al., 2000), whereas wear rate tends to decrease with increasing sliding velocity at constant applied load. Secondly, higher weight fraction of glass fibers in the composite improves the abrasive wear resistance because high energy is required to facilitate failure in glass fibers, which is the case for the current study in terms of volume loss. However, carbon fabric reinforced vinyl ester composite revealed better wear resistance than that of glass fabric reinforced vinyl ester composite (Suresha & Kumar, 2009).

Parallel lines in any interaction plot indicate no interaction. Non-parallel lines are indicative of the presence of interaction while intersecting lines are indicative of the presence of strong interaction. Figure 5(a–c) shows the interactions plot of PTFE matrix and its composites. Figure 5(a–c) shows grit size vs. load, sliding distance vs. load and sliding distance vs. grit size, respectively. It is evident that some interactions appear for distance vs. load. There is decreasing trend with 5 and 10 N load, but the volume loss increases with sliding distance. In a similarly, it increases with 400 and 800 grit sizes of paper, but no interaction is observed while it is decreased with 1,200 grit, some interaction occurs. Figure 5(d–f) indicates compression strength vs. load, compression strength vs. grit size, and compression strength vs. distance, respectively. With increasing load, especially 20 N associates with 6.3 MPa compression strength, but 10 N load reaches to 9.8 MPa compression strength, indicating a strong interaction effect. Here, 800 and 1200 grit sizes of SiC shows parallel lines, it means that no interaction happens. However, 400 grit size indicates interaction effect, which is especially true when the compression strength is 6.3 MPa. A similar effect is also exhibited by increasing the sliding distance of 150 m (Figure 5(f)). The more interactions are observed for the combination of lower grit size under the higher load associated with the higher sliding distance. This might be because of relating to the initial stage of the wear process although the lower sliding distance results in the lower volume loss of the samples. The normal probability plot for tested samples is shown in Figure 6 with the cumulative distributions of the residuals. The error distributions seem to be normal. However, the error distribution may be slightly skewed, with the right trial not being longer than that of the left one, but there are few extreme points in the right side of the trail because of the nature of the tested samples. In generally, the residual is around ±0.5.

Figure 5. Interactions plot of PTFE matrix and its composites.

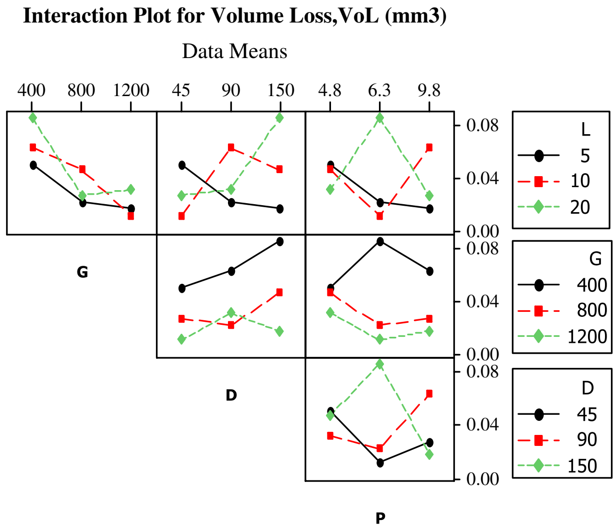
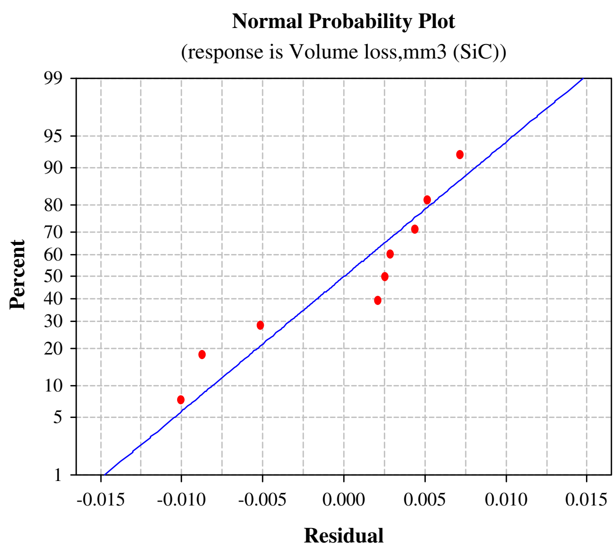


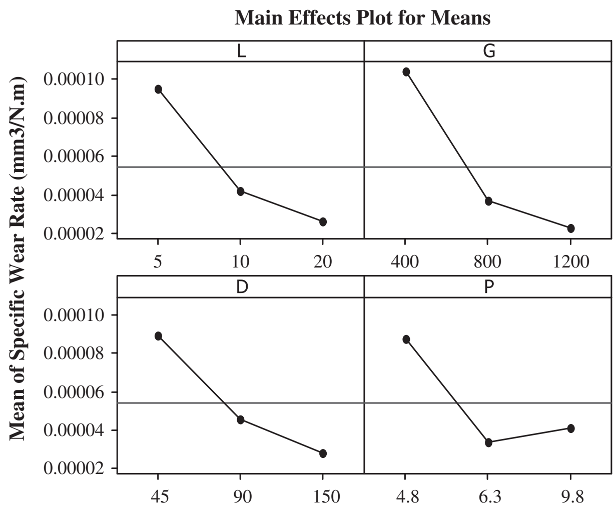
Figure 6. Normal probability plot of composites.



3.2. Wear rates

Figure 7 shows the specific volumetric wear rate as a function of abrasive size, applied load, sliding distance, and compressive strength of the samples. The specific wear rate decreases with increasing grit size, loads, sliding distance for all the materials, but partly decreases with compressive strength. Among the parameters, again, the grit size is dominant factor on wear resistance of materials (Chand & Dwivedi, 2007b; Sahin, 2005; Unal et al., 2005), which is followed by the load. The values are in the range of 2.27×10^{-4} mm^3/N m–7.05×10^{-5} mm^3/N m. The specific wear rate is very high initially for load, distance, grit size, and material's type. The wear rate decreases sharply when tested against from 400 to 800 grit due to increase in the penetration ability on the sample, and thereafter it decreases. This is followed by the load, sliding distance and compression strength, respectively. In addition, a more decreasing trend is observed with increasing the load from 10 to 20 N, sliding distance from 90 to 150 m. The wear rate again decreases with increasing the running distance (Chauhan et al., 2010; Suresha et al., 2007; Unal et al., 2004; Yousif & El-Tayeb, 2009). However, it increases slightly with changing the filler type from glass to carbon filed composite. In other words, with an increase in applied load from 5 to 10 N, there is a reduction in the wear rate because the apparent contact area is greatly increased at higher applied loads. Since there is an increase in

Figure 7. Main effects plot for the mean specific wear rate of polymer composites.



contact area, it allows a large number of particles to encounter the interface and share the stress (Anand & Kumaresh, 2012). This, in turn, leads to a steady state or reduction in the wear rate. The specific wear rate strongly depends on the applied load and abrading distance for all the tested materials. The load has stronger effect on the wear behavior of PTFE composites than the sliding velocity (Liu et al., 2001; Tevrüz, 1998; Unal et al., 2004), but the best wear resistance is achieved for PTFE + 18 % C + 7 % Gr composites due to using 7 % G filler in that matrix (Unal et al., 2005). However, the carbon fiber reinforced polyaryletherketone (PAEK) matrix composite had worse abrasion resistance as compared to glass fiber reinforced PAEK composites (Harsha & Tewari, 2002). Moreover, the wear rate decreases with the increase in grit grade number for the polymers like APK, POM, UHMWPE, PA66, and PPS + 30% GFR polymer composites. Moreover, the content of filler and bonding between the particles and the polymer matrix seems to be important for the wear reduction. For example, when there is a strong bond between the fillers and the matrix, separation of material from the pin surface becomes more difficult and hence contributes to high wear resistance. The weak bonding between the fillers of particles and the polymer matrix presumably leads to a considerable reduction in wear resistance because of the C particles, which are easily separated from the polymer, and/or three-body abrasion by their in contact zone (Schwartz & Bahadur, 2001). This is so because, as the filler proportion increases, the number of filler particles in the transfer film also increases, and it causes the disruption of transfer film due to the increased number of hard particles.

Experimental observations are transformed into signal to noise ratio (S/N = “μ”).

$$\mu = -10 \log_{10} \left(\sum_{i=0}^{n} y_i^2 \right) \tag{4}$$

The S/N ratio is computed using Equation 4 for each of 9 runs. The minimal and maximal S/N ratios are found to be about 73.391 and 94.609 dB, respectively. They correspond to run 1 and run 9, respectively. The optimum mean response value is found to be L3 G3 D3 C2. These results reveal that carbon-filled PTFE composites show slightly lower wear rate than glass-filled composites, but no significant variations appears. The penetration ability of SiC abrasives decreases with increasing the sliding distance of samples.

3.3. Analysis of variance

The ANOVA results for the abrasive sliding wear behavior of PMC materials are listed in Table 5. This analysis is undertaken for a level of significance of 10%, that is, for a level of confidence of 90%. It is clear from Table 5that factors L, G, and D have statistical and physical significance on the specific wear rate. As noted in the last column of ANOVA table, *P* of each factor on total variations shows the

Table 5. ANOVA for S/N ratio of the specific wear rate

Source	DF	SS	MS	Test-*F*	*F* (10%)	*P* (%)	*p*-value
L	2	94.55	47.275	4.22	9.0	27.77	0.066
G	2	174.102	87.051	7.78	9.0	51.14	0.003
D	2	49.384	24.692	2.21	9.0	14.50	0.044
P	(2)	(22.359)	(Pooled)	–	–	–	0.392
Error	2	22.359	11.1795			6.59	
Total	8	340.395				100	

Notes: SS is the Sum of squares, MS is the Mean of squares, DF is the Degrees of freedom, *P* is the Contribution percentage, and *p*-value is the Individual control factor.

degree of influence on the wear results. It can be observed that the factor L (p = 27.77%), the factor G (p = 51.14%), and the factor D (p = 14.50%) have the effects on the abrasive wear rates, but the factor C is not significant effect on it. The error associated to the ANOVA table for the mean S/N ratio is approximately 6.59%, which is highly above the volumetric wear rate analysis. The correlation of R^2 (adj.) is found to be about 0.87. On the other hand, the last column of the table indicates p-value for the individual control factors. It is known that smaller the p-value, greater the significance of the factor/interaction corresponding to it. The ANOVA table for S/N ratio (Table 5) indicate that the grit size (p = 0.003), sliding distance (p = 0.044), and load (p = 0.066) in this order, are significant control factors effecting the wear rate while the compression strength (p = 0.392) is insignificant effect on the wear rate of the tested samples. It means that the grit size is the most significant factor, which is followed by the sliding distance and load. The present study indicates that the wear behavior of PTFE matrix and its composites under abrasive sliding conditions using the Taguchi approach reveals that the wear property not only depends on the tribological system, abrasive grit, load, and sliding distance, but also among material's properties, a slightly compression strength.

3.4. Confirmation test

The final step is to verify the improvement of the quality characteristic using the optimal levels of design parameters (L1G3D1P3). The S/N ratio is calculated as the following formula.

$$\hat{\eta} = \eta_m + \sum_{i=0}^{n} \left(\eta_i - \eta_m\right) \tag{5}$$

where η_m is the total mean S/N ratio, η_i is the mean S/N ratio of the result at the optimum level and n is the number of the main design parameters. Based on the S/N ratio analysis, the optimal testing parameters for the volume loss of tested materials were the factor L at 1 level, factor G at 3 levels, the factor D at 1 level and finally, the factor P at 3 levels. According to this prediction, the theoretical value of S/N Ratio is calculated about 39.459 dB. It corresponded to about 0.0106 mm^3, which is the lower value within the obtained experimental results (Table 6). This table indicates that a comparison of the predicted volume loss with the actual volume loss using the optimal testing parameters. It can be seen that the difference between verification and calculation is in the reasonable limit (1.604 dB). However, optimal volume loss is calculated based on ANOVA results, using the significant factors (L1G3D1). In this case, the S/N ratio is about 38.99 dB and its corresponding value is about 0.01123 mm^3. In case of the specific wear ratio analysis, the optimal level of design parameters is found to be L3G3D3P2. The S/N ratio can be calculated from Equation 5 formula. The theoretical predicted value is about 101.146 dB. It corresponds to about 8.45×10^{-6} mm^3, which is the lower value within the experimental results (Table 6).

4. Conclusions

The following conclusions were drawn in terms of the experimental and analytical results for wear of polymer-based composites.

Table 6. Results of the confirmation experiment for the volume loss and wear rate of composites

Response	Prediction	Experiment	Difference
	L1G3D1P3	L1G3D1P3	$\eta_{i,\,ver} - \eta_{i,\,cal}$
Volume loss (mm^3)	0.0106	0.0128	0.0022
S/N ratio (dB)	39.459	37.855	1.604
Volume loss (mm^3)	0.01123	0.0128	0.00157
S/N ratio based on ANOVA (dB)	38.99	38.344	0.642
Specific wear rate	L3G3D3P2	L3G3P3D2	–
Wear rate (mm^3/N m)	8.45×10^{-6}	12.1×10^{-5}	3.65×10^{-6}
S/N ratio (dB)	101.146	98.34	2.81

(1) The experimental results showed that the weight loss and volume loss of the samples highly influenced by abrasive size, sliding distance, and load, but slightly with the compression strength of tested sample.

(2) The average specific wear rate decreased with increasing the grit size, load, and sliding distance, but partly decreased with the compressive strength for tested samples when tested against SiC abrasives.

(3) Inclusion of carbon-filled composites contributed slightly in reducing wear and these composites exhibited a slightly better wear resistant property than that of glass fiber reinforced and PTFE matrix.

(4) ANOVA indicated that abrasive size, applied load, and sliding distance exerted a great effect on the specific wear rate at 51.14, 27.77, and 14.50%, respectively. However, compression strength had a neglecting effect (6.50%) towards the quality characteristics.

(5) Optimal process parameters, which minimize the volume loss was the factors of combinations of L1, G3, D1, and C3. That was, the experiment carried out at 5 N load against a 1,200 grits for 25% carbon-filled composite running for 45 m sliding distance would lead to a minimum volume loss.

(6) Confirmation experiments were also conducted to verify the optimal testing parameters. The predicted volume loss and specific wear rate of the samples were found to lie close to that of the experimentally observed value of S/N ratio with an error of 1.604 and 2.81%, respectively.

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