Materials Research Express

PAPER

Influence of glass/carbon fiber stacking sequence on mechanical and three-body abrasive wear resistance of hybrid composites

Dipak Kumar Jesthi1 and Ramesh Kumar Nayak2

1 Department of Mechanical Engineering, Ajay Binay Institute of Technology (ABIT), Cuttack, 753014, India
2 Department of Materials and Metallurgical Engineering, Maulana Azad National Institute of Technology, Bhopal–462003, India

E-mail: rameshkumarnayak@gmail.com

Keywords: hybrid composite, flexural, abrasion, wear, tribological

Abstract

Glass and carbon fiber reinforced polymer hybrid composites are the need of the hour to overcome the weakness of individual fibers. The mechanical and abrasive wear property of the hybrid composites needs to be evaluated to ascertain the feasibility in structural and tribological applications. In this article, hybrid composites of different stacking sequence such as [G3C2]5, [GCG2C]5 and [G2C3G]5 has been designed. The flexural strength and three body abrasive wear resistance of the hybrid composites were evaluated and compared among themselves. It is observed that the flexural strength and modulus of [GCG2C]5 type hybrid composite was improved by 46.1% and 49.5% respectively as compared to plain glass fiber reinforced polymer composites. The specific wear rate was evaluated by three-body abrasive wear at different operating parameters and optimized the same through response surface methodology. Box–Behnken design of the experiment was adopted to design the experiments. The model has predicted the minimum specific wear rate for [GCG2C]5 hybrid composite is 1.8476 × 10−3 mm3 Nm−1 at applied load of 33.15 N and sliding distance of 1100 m. The model predicted results were compared with experimental one and found a good agreement between them. The worn surface of the composites was analyzed by scanning electron microscope to understand the wear mechanism.

1. Introduction

Glass fiber reinforced polymer composites are widely accepted due to their better specific strength, modulus and durability. However, the carbon fiber reinforced polymer composites have better specific strength and more costly in comparison to glass fiber reinforced polymer composites. Hybridization of different fibers is necessary to overcome the weakness of individual fibers. The properties and cost of the hybrid composites can be optimized using different statistical tools [1, 2]. Scientists and researchers have reported that the addition of nano filler enhances the mechanical properties of glass fiber reinforced polymer composites [3–8]. The extent of improvement is sensitive to the shape, size, dispersion and the interaction of the filler with matrix and fiber [9]. However, the nano fillers are expensive and incorporation of nano filler into the polymer matrix is very complicated. Further, there is limitation on quantity of nano filler in nano-composites. Therefore, the alternative affordable method for the improvement of overall mechanical properties of glass fiber reinforced polymer composites is by hybridization of two or multiple fibers. It is reported that in continuous fiber reinforced polymer composites, the mechanical properties [10–12] are sensitive to the stacking sequence. Hybridization of glass and carbon fiber improves the mechanical strength and may be used in civil structures and wind turbines [13]. Dong et al [14] have reported that the flexural strength of hybrid carbon/glass fiber composites has improved and the volume fraction of glass and carbon fiber needs to be optimized [14, 15]. Jesthi and Nayak [16] have observed that the mechanical properties of hybrid carbon/glass composites is improved in dry and seawater aged condition.

Abrasive wear takes place when abrasive particles under applied load move over an object. In the process, the abrasive particles remove material from the surface of the object. This may result in gradual wear or uneven wear with grooves. The two body abrasion wear takes place when the abrasive particles are fixed and slide over a
The plain woven roving glass fibers and sliding motion is possible that lead to wear on the object surface [17]. Nowadays, the bi-directional fibers are used that facilitate convenient fabrication of composites. They have superior and equally distributed properties along both planar directions [18].

Various researchers have carried out investigation on three body abrasive wear behavior of plain glass and carbon fiber reinforced polymer composites. It has been reported that the specific wear rate is affected by sliding distance and applied load [19–21]. However, specific wear rate is dependent on the material properties and operating conditions. The response surface methodology (RSM), a statistical tool is adopted for analyzing the effect of various independent operating parameters on specific wear rate. El-Tayeb et al [22] modeled wear properties using RSM to correlate input parameters such as sliding velocity, load and time. They tested two different composition of titanium alloys in dry and cryogenic condition and found the coefficient of friction depends on the type of titanium alloy [22]. Chang et al [23] studied the influence of talc and glass fiber reinforcements on friction and wear behavior of ultra high molecular weight polyethylene based composites. They reported that the wear volume loss is more sensitive to applied load followed by sliding distance. It is observed that the glass fiber has improved the wear resistance more as compared to talc particles. Extensive research has been undertaken on the wear properties of plain glass/carbon fiber reinforced polymer composites and the effect of micro and nano fillers. However, the variation in abrasive wear behavior of hybrid glass and carbon fiber reinforced polymer composites for different stacking sequences has not been explored and reported in open literature. Therefore, the current study investigates the influence of stacking sequence of glass and carbon fiber on tribological properties of \([G_3C_2]_S, [G_2C_3G]_S\) and \([GCG_2]_S\) hybrid composites. Further, worn surfaces are analyzed by scanning electron microscope (SEM).

2. Materials and Methods

2.1. Materials

The plain woven roving glass fiber (GF) of 360 gsm having warp and weft density of 6.3 and 5.5 threads/cm and twill woven carbon fiber (CF) of 200 gsm of warp and weft density of 5 threads/cm respectively were used as the reinforcement. The carbon and glass fiber were procured from Soller Composites and Owens Corning, India respectively. The epoxy polymer of Diglycidyl ether of Bisphenol A and hardener of Triethylene tetra amine was used as matrix material. The commercial name of the epoxy polymer is Lapox L-12 and hardener is K-6. The polymer and hardener were procured from Atul Industries, India. There are five types of composites were fabricated through hand lay-up method. The composites are \([G]_S, [G_3C_2]_S, [GCG_2]_S, [G_2C_3G]_S\) and \([G]_S\), where C denotes carbon and G denotes glass fiber. Figure 1 shows the stacking sequence of glass and carbon fiber for the current investigation. The ratio of glass to carbon fiber by weight is 72:28. The plain glass/carbon fiber and hybrid composites consist of ten fiber layers. The ratio by weight of total reinforcement fibers and epoxy polymer was 55:45. The composite laminates were cured in room temperature for 24 h in the first stage. The test samples were cut to dimensions according to ASTM specifications. The test specimens were post-cured in an oven at 140 °C for 6 h [24]. The hybrid composites are symmetrical about the central axis by design to ensure same mechanical and tribological properties on both sides of the composites. The central region of the hybrid composites \([G_3C_2]_S\) and \([GCG_2]_S\) is carbon fiber, whereas glass fiber is at the central region in \([G_2C_3G]_S\) hybrid composites.

![Figure 1. Stacking sequence of the hybrid composite laminates.](image-url)
2.2. Mechanical Properties (Flexural)

The flexural properties were evaluated according to the ASTM D7264 standard. The dimension of the sample was (70 mm × 13 mm × 3 mm). The span length was taken at 60 mm and span to depth ratio is 20:1. The flexural strength ($\sigma_F$), modulus ($E_F$) and strain to failure ($\varepsilon_F$) were determined according to the following expressions:

$$\sigma_F = \frac{3P_{\text{max}}L}{2wt^2}$$  \hspace{1cm} (1)

$$E_F = \frac{ml^3}{4wt^3}$$ \hspace{1cm} (2)

$$\varepsilon_F = \frac{6dl}{L^2}$$ \hspace{1cm} (3)

where $L$ denotes the span length, $w$ is the width and $t$ is the thickness of the test specimen. $P_{\text{max}}$ is the maximum load before failure, $m$ is the slope of the initial section of load versus displacement curve, $d$ is the highest bending before failure.

2.3. Abrasive wear test

The tribological properties of glass and carbon fiber reinforced polymer composites subjected to three body abrasion was evaluated according to ASTM G 65 standard. The three body abrasion test set up is TR-50 and supplied by DUCOM, Bangalore, India shown in figure 2. It consists of a rotating wheel covered by chlorobutyl rubber having diameter of 228.6 mm. The shore hardness of the rubber wheel is A-60. The test sample of size 12.7 mm × 25 mm × 76 mm was placed against the rubber wheel. The dry abrasive quartz sand of AFS 50/70 was passed between the test sample and rubber wheel at a uniform rate of 363 gm min$^{-1}$. The speed of the rubber wheel was fixed at 1.5 m s$^{-1}$. The test sample was held against a rotating wheel at a specific applied load. The applied load was controlled by means of a lever arm and dead weights. The test sample surface was abraded by the dry sand passing between the test sample and the rubber wheel. The sliding distance and applied load were varied according to the design of experiments and limitation of the equipment. The test samples were weighed in a precision weighing machine having least count of 0.001 mg. The material loss due to abrasion was converted into volume loss by using the density of the material. The specific wear rate (SWR) is the loss of volume of the test sample measured per unit sliding distance per unit applied normal load calculated using equation (4)

$$\text{SWR} = \frac{\Delta V}{L \times D}$$ \hspace{1cm} (4)

where $\Delta V$ is the loss of volume (mm$^3$), $L$ is the load (N) and $D$ is sliding distance (m).
2.4. Response Surface Methodology
The enhancement of mechanical and tribological properties along with reduction of cost and weight are important considerations for the application of hybrid composites. This necessitates judicious analysis of the operating parameters affecting wear. Thus, a statistical method is necessary to arrive at a reasonable conclusion regarding the significance of parameters and extent of their effect on wear and their possible interaction. Response surface methodology (RSM) is a statistical technique, which was adopted to design a complete set of experiments, analyze and to arrive at optimal conditions for desired response or output. The specific wear rate was evaluated for different applied loads and sliding distances of the hybrid composites. The design of experiment was formulated using Box-Behnken of response surface methodology. The statistical software (Minitab17) has been employed for performing the optimization analysis. The input parameters considered for this analysis is type of hybrid composite, applied load and sliding distance. The influence of input parameters on specific wear rate was evaluated by response surface methodology. The relationship of the independent input parameters towards response or output was mathematically modeled by RSM and optimized.

3. Results and Discussions

3.1. Flexural Strength
The flexural strength and modulus of plain and hybrid composites were evaluated and are shown in figures 3(a) and (b) respectively. The plain carbon and glass composite have the highest and lowest flexural strength respectively. The flexural stress of hybrid composite of \([G3C2]_S\) type is the lowest. The change in flexural strength for different stacking sequence of hybrid carbon/glass epoxy composites has been reported by Dong C [15]. It is observed that the flexural strength reduces with rise in number of glass fiber layers in the outer region of the hybrid composites. The flexural strength and modulus of \([GCG2C]_S\) hybrid composites increased by 46.1% and 49.5% respectively in comparison to plain GF reinforced polymer composite. The improvement of the flexural strength of \([GCG2C]_S\) hybrid composites is attributed to the alternate layers of glass fiber of higher strain help to bridge and prevent premature failure of the carbon fiber of lower strain. Therefore the flexural strength and modulus of hybrid composite has been improved. Similar finding has also been observed by Zhang et al [10].

3.2. Abrasive Wear
The three-body abrasion wear test was carried out for the hybrid composites \((G3C2)_S, (G2C2G)_S\) and \([GCG2C]_S\) and plain glass and carbon fiber reinforced polymer composites. The specific wear rate (SWR) was determined for different operating parameters such as sliding distance (420 m–1260 m) and applied load (12.75–38.26N). The variation of specific wear rate with respect to sliding distance and applied load of the hybrid and plain composites is reported in figures 4(a)–(c).

It is observed that at load of 12.75 N, and different sliding distances, the SWR of hybrid composite \([GCG2C]_S\) is the lowest as compared to other hybrid composites. Similarly, at applied load of 25.5N, the SWR of hybrid composite \([GCG2C]_S\) is lower than other hybrid composites. In figure 4(c) for applied load of 38.26N, it is observed that at sliding distance of 420 m, \([GCG2C]_S\) has the lowest SWR. However, at 840 m sliding distance both \((G3C2)_S\) and \([GCG2C]_S\) have nearly same SWR. At 1260 m sliding distance, \([GCG2C]_S\) has the lowest SWR. The results revealed that the lowest specific wear rate values changes for the different hybrid composites at
different operating parameters. Therefore, there is a need to design the experiments and optimize the operating parameters to minimize the SWR.

3.3. Modeling and optimization of SWR of $[\text{GCG}_2\text{C}]_3$ hybrid Composite

3.3.1. Design of experiment

The specific wear rate of the hybrid composite ($[\text{GCG}_2\text{C}]_3$) was evaluated at different operating parameters. In full factorial experimental design for three input factors having three values requires 27 number of experiments to be conducted as it takes into account all interactions possible among the parameters [25]. However, the Box–Behnken design requires only fifteen numbers of experiments to be performed to arrive at similar outcomes. In this investigation, the composite type (C), sliding distance (D) and applied load (L) are the input parameters for the response of specific wear rate (SWR). For each of the parameters, three levels were taken and are reported in table 1. The Box–Behnken design of the experiment (DOE) arrived at 15 numbers of experiments to be performed is shown in table 2. The experiments were generated randomly using DOE software (Minitab17).

3.3.2. Analysis of variance (ANOVA)

The analysis of variance (ANOVA) was performed to establish the relationships among input parameters to minimize the specific wear rate. The result of ANOVA analysis of specific wear rate is given in table 3. The parameter is significant when the probability value (P-value) is less than 0.05 [26]. For the hybrid composite, it is found that $R^2$ is 99.43%, which indicates that the predicted model is valid and agrees with the experimental data. The $R^2$(adj) 98.40% and $R^2$(pred) 91.18% are high, which shows the model has good predictability.

SM gives a mathematical model having the relationship between the independent input parameters and responses. The polynomial equation for specific wear rate (SWR) is given in equation (5).

$$\text{SWR} = 78.68 - 8.91C - 0.02503D - 2.477L + 2.157C^2 + 0.000005D^2 + 0.03658L^2 + 0.00120C \times D + 0.2011C \times L + 0.000109D \times L$$

Figure 4. The specific wear rate (SWR) of plain and hybrid composites condition for sliding distance of (420, 840, 1260 m) at applied load of (a) 12.75, (b) 25.5 and (c) 38.26 N.
The coefficients of the equation are arrived by regression analysis [27]. In the equation, it is seen that the lower value of the positive coefficients and higher values of negative coefficients lowers the specific wear rate (SWR). In terms of significant variables, it is observed that the applied load (L) followed by sliding distance (D) contribute towards minimization of specific wear rate (SWR). The normal probability plot of residuals for specific wear rate is reported in figure 5. The residuals approximate the straight line showing normal distribution of the experimental data. Thus, the experimental data are statistically acceptable and reliable [24].
3.3.3. **Effect of sliding distance and applied load on specific wear rate**

The three dimensional (3D) surface plot for the specific wear rate (SWR) according to equation (5) is constructed in figure 6. The 3D surface plots for SWR against C, D and L are plotted in figures 6(a)–(c) respectively. The figure 6(a) shows the 3D surface plot of SWR against C and L, it is observed that at lower applied loads (L), the specific wear rate (SWR) is higher and decreases with increase in load. Moderate SWR is observed for the hybrid composite of [GCG₂C₃] type. This is because initially the abrasive particles come into contact with softer epoxy polymer matrix which is at the top layer of the composites and wear out easily. Thus the SWR is higher at lower load and sliding distance. At higher load, less abrasive particles are able to penetrate into the contact area of test specimen and rubber wheel leading to decrease in SWR. Suresha et al [19] have reported that wear rate decreases at high load and abrading distance. Figure 6(b) shows the surface plot of SWR against D and L. It is seen that the SWR reduces as the sliding distance (D) increases and applied load (L) increases. However, at higher values of L, the SWR is minimized and increases thereafter. Therefore, for hybrid [GCG₂C₃]₁₉, the minimum SWR is achieved at higher values of D and L. The SWR reduces with increase in sliding distance due to exposure of bidirectional fiber which offer better wear resistance and accumulation of wear debris remains within the abrasive particles which protects the wear surface [19, 28]. The SWR increases at higher loads as the rotating rubber wheel imparts energy to the abrasive particles resulting in increase of wear [29, 30]. Figure 6(c) shows the surface plot of SWR against D and C. It is observed that SWR decreases with increase in sliding distance (D) increases. The SWR is higher for plain glass composite and lower for plain carbon composite. This is because the specific modulus of carbon fiber is higher in comparison to glass fiber. Moreover, the carbon fiber is self lubricating which further improves wear resistance over glass fiber [19]. The SWR of hybrid composite [GCG₂C₃] is moderate in between the plain glass and carbon composites.

3.3.4. **Main effect plot**

The main effect plot for SWR of composites is shown in figure 7. The mean of SWR is indicated in the y-axis. The factors which control the SWR are given in x-axis along with their levels. It is observed that as the composite type shifts from plain carbon composite towards hybrid composite, the SWR increases moderately. On the other hand, from hybrid composite to plain glass composite, the SWR increases rapidly. This may be due to better adhesion bond between carbon fiber and epoxy as compared to glass fiber. The SWR is higher at lower sliding distances as initially softer polymer is in contact with the abrading particles. The SWR reduces with increase in sliding distance. At lower loads, the SWR is high and decreases sharply with increase in load up to 25.5N. However, the SWR decreases moderately with further increase in applied load.

3.3.5. **Predictions of specific wear rate**

Response surface methodology is employed to optimize the output using different input parameters. In this investigation, the response i.e. specific wear rate (SWR) which need to be minimized. The RSM model predicts the optimal operating parameters, their levels and corresponding response (SWR) for the hybrid [GCG₂C₃]₁₉ composite. The figure 8 depicts the desirability plot for specific wear rate of the hybrid [GCG₂C₃]₁₉ composite. The predicted minimum SWR is 18.8476 × 10⁻³ mm³ N⁻¹ m⁻¹ of the hybrid [GCG₂C₃]₁₉ composite for sliding distance of 1100m and applied load 33.15 N with a desirability of 0.98186.

The confirmation of experimental runs to validate the predicted model experimentally is shown in figure 9. The specific wear rate obtained from the confirmation test is close to that of predicted value by the model is shown in table 4.

![Figure 5. Normal Probability Plot of residuals for SWR.](image)
3.4. Failure modes in worn surface (Scanning Electron Microscopy)

The abrasive worn surface of plain glass fiber reinforced composite samples is shown in figure 10(a). The matrix is worn by the abrasive sand particles through cutting and ploughing mechanism. During the abrasion process, the fibers are broken resulting in removal of glass fiber from the matrix. The smooth glass fibers indicate less adhesiveness of the matrix with the fiber.

The figure 10(b) shows the abraded surface of plain carbon reinforced composite. It is observed that there is less breakage of fiber compared to plain glass fiber reinforced composite. The carbon fibers are well adhered to the matrix indicating good adhesive bond resulting in increase of wear resistance. Thus, the wear of plain carbon reinforced composite is lower than plain glass fiber reinforced composite. The worn surface of the hybrid composite [GCG2C]S, is shown in figure 10(c). It is observed that some fibers are broken while others are adhered.
to the matrix. The breakage of fiber occurs which may be due to dissimilar adhesiveness between fibers and matrix. The matrix fragments are observed on surface of the fibers, which indicates better adhesion of matrix with carbon fiber than glass fiber reinforced composite. Thus, the wear of the hybrid composite $[\text{GCG}_2\text{C}]_S$ is moderate.

4. Conclusions

In this investigation, the influence of stacking sequence of glass and carbon fiber in hybrid composites on flexural strength and specific wear rate were evaluated. The following conclusions are drawn.
The flexural strength and modulus of the hybrid \([\text{GCG2C}_S]\) composite was improved by 46.1% and 49.5% respectively in comparison to plain glass fiber reinforced polymer composites.

Among the hybrid composites, the specific wear rate of hybrid composite \([\text{GCG2C}_S]\) is the lowest i.e. \(18.8476 \times 10^{-3} \text{mm}^3 \text{Nm}^{-1}\) for a sliding distance of 1100m and applied load of 33N.

The tribological properties of the hybrid composites are better as compared to plain glass fiber reinforced polymer composite and shows wear performance is sensitive to the stacking sequence.

The improved mechanical and tribological properties of hybrid composites can create opportunity to be used in structural components such as wind turbine blades and automobile components (gears, clutches and conveyors).

**Acknowledgments**

The authors are heartily thankful to Maulana Azad National Institute of Technology, Bhopal, Ajay Binay Institute of Technology (ABIT), Cuttack and KIIT, Deemed to be University, Bhubaneswar for providing infrastructural support for carrying out the present research work. The technical support from Mr A K Dhal is highly appreciated.

**ORCID iDs**

Ramesh Kumar Nayak  
[https://orcid.org/0000-0002-5515-8986](https://orcid.org/0000-0002-5515-8986)

**References**

[1] Mishnaevsky L Jr and Dai G 2014 Hybrid carbon/glass fiber composites: micromechanical analysis of structure–damage resistance relationships  *Comput. Mater. Sci.* 81 630–40

[2] Jesthi D K and Nayak R K 2019 Improvement of mechanical properties of hybrid composites through interply rearrangement of glass and carbon woven fabrics for marine application  *Compos Part B Eng.* 168 467–75
[3] Al-Turaih HA 2010 Effect of nano TiO₂ particle size on mechanical properties of cured epoxy resin Prog. Org. Coat. 69 241–6
[4] Asi O 2010 An experimental study on the bearing strength behavior of Al₂O₃ particle filled glass fiber reinforced epoxy composites pinned joints Compos. Struct. 92 354–63
[5] Chang L N and Chow W S 2010 Accelerated weathering on glass fiber/Epox/Oraganomontmorillonite nanocomposites J. Compos. Mater. 44 1421–34
[6] Nayak S, Sadarang J, Panigrahi I and Kumar Nayak R 2018 Development of carbon/glass fibre reinforcement polymer hybrid composite through modeling and simulation Mater. Today Proc. 5 17838–44
[7] Nayak R K and Ray B C 2018 Influence of seawater absorption on retention of mechanical properties of nano-TiO₂ embedded glass fiber reinforced epoxy polymer matrix composites Arch. Civ. Mech. Eng. 18 1597–607
[8] Nayak R K and Ray B C 2018 Retention of mechanical and thermal properties of hydrothermal aged glass fiber-reinforced polymer nanocomposites Polym-Plast Technol. Eng. 57 1676–86
[9] Menbari S, Ashori A, Rahmani H and Bahrami R 2016 Viscoelastic response and interlaminar delamination resistance of epoxy/glass fiber/functionallized graphene oxide multi-scale composites Polym. Test. 54 186–95
[10] Zhang J, Chaisombat K, He S and Wang C H 2012 Hybrid composite laminates reinforced with glass/carbon woven fabrics for lightweight load bearing structures Mater Des. 1980–2013 36 75–80
[11] Bunsell A R and Harris B 1974 Hybrid carbon and glass fibre composites Composites 5 157–64
[12] Song J H 2015 Pairing effect and tensile properties of laminated high-performance hybrid composites prepared using carbon/glass and carbon/aramid fibers Compos Part B Eng 79 61–6
[13] Czél G and Wisnom M 2013 Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg Compos Part A Appl. Sci. Manuf. 52 23–30
[14] Dong C and Davies I J 2012 Optimal design for the flexural behaviour of glass and carbon fibre reinforced polymer hybrid composites Mater. Des. 37 450–7
[15] Dong C 2016 Uncertainties in flexural strength of carbon/glass fibre reinforced hybrid epoxy composites Compos Part B Eng. 98 176–81
[16] Jesthi D K and Nayak R K 2019 Evaluation of mechanical properties and morphology of seawater aged carbon and glass fiber reinforced polymer hybrid composites Compos Part B Eng 174 106980
[17] Gates JD 1998 Two-body and three-body abrasion: a critical discussion Wear 214 139–46
[18] Vishwanath B, Verma A P and Rao C K 1993 Effect of reinforcement on friction and wear of fabric reinforced polymer composites Wear 167 93–9
[19] Suresha B, Chandramohan G, Samapthkumaran P and Seetharamu S 2007 Three-body abrasive wear behaviour of carbon and glass fiber reinforced epoxy composites Mater. Sci. Eng. A 443 285–91
[20] Siddhartha S A K 2015 Mechanical and dry sliding wear characterization of short glass fiber reinforced polyester-based homogeneous and their functionally graded composite materials Proc Inst. Mech. Eng. Part J, Mater. Des. Appl. 229 274–98
[21] Yousif B F 2013 Design of newly fabricated tribological machine for wear and frictional experiments under dry/wet condition Mater. Des. 48 2–13
[22] El-Tayeb N S M, Yap T C and Brevern P V 2010 Wear characteristics of titanium alloy Ti54 for cryogenic sliding applications Tribol. Int. 43 2345–54
[23] Chang B P, Akil H M, Nasir R B and Khan A 2015 Optimization on wear performance of UHMWPE composites using response surface methodology Tribol. Int. 88 252–62
[24] Nayak R K, Mahato K K, Routara B C and Ray B C 2016 Evaluation of mechanical properties of Al₂O₃ and TiO₂ nano filled enhanced glass fiber reinforced polymer composites J. Appl. Polym. Sci. 133
[25] Montgomery D C 2008 Design and Analysis of Experiments. (New York: Wiley)
[26] Daneshpajeh S, Ashenai Ghasemi F, Ghasemi I and Ayaz M 2016 Predicting of mechanical properties of PP/LLDPE/TiO₂ nano-composites by response surface methodology Compos Part B Eng 84 109–20
[27] Akan N H and Taljsten B 2004 Testing of hybrid FRP composite beams in bending Compos Part B Eng. 35 227–33
[28] Gupta K 2012 Mechanical and abrasive wear characterization of bidirectional and chopped E-glass fiber reinforced composite materials Mater. Des. 35 467–79
[29] Basavarajappa S, Joshi A G, Arun K V, Kumar A P and Kumar M P 2009 Three-body abrasive wear behaviour of polymer matrix composites filled with SiC particles Polym-Plast Technol. Eng. 49 8–12
[30] Mohan N, Natarajan S and Kumaresh Babu S P 2011 Abrasive wear behaviour of hard powders filled glass fabric–epoxy hybrid composites Mater. Des. 32 1704–9