Study on Abrasion Wear behaviour of Hybrid Composites using dimensional Analysis and Wear Models

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Abstract. The prediction of abrasive wear behavior of Glass-Basalt (GB) and Glass –Carbon (GC) hybrid composites in two body wear mode using dimensional analysis has been presented. The blend (PA66/PTFE) in 80/20 wt. % proportion was used as the base material. The individual effect of glass fibers and carbon fibers (10 wt. % each) were also studied and compared. Melt mix method using twin screw extrusion and injection molding process were used for developing hybrid composites. The mathematical model to predict the wear loss has been developed using dimensional analysis for the aforesaid hybrid composites and evaluated through justification using experimentally determined wear loss. Further, the wear behavior due to two body abrasion of hybrid composites is justified using abrasive wear models. It is noticed that developed mathematical model and wear models agrees with the abrasion wear behavior of composites studied. It is noticed that Ratner –Lancaster factor (σε) was used as one variable for the abrasion wear model. It is proved that specific wear rate is indirectly proportional to the wear resistance. Furthermore, the individual effect of short fibers is compared with GB and GC hybrid composites. It is proved that hybrid composites exhibited the better wear resistance.

Keywords: Dimensional analysis, Abrasion, two body, wear models, glass-Basalt, Hybrid composite

1. Introduction

The abrasion wear behavior of polymer composites must be superior in order to recommend them to the field of structural applications particularly to automobile sectors. There may be two body (2BAW) or three body (3BAW) abrasion effects when the polymer has put in to performance [1]. It is documented from the literature and research that 60% of the total failure of mechanical components was due to 2BAW effect [2]. This can be avoided through polymer modification which led the polymer to acquire resistance against these abrasions. They are modified through blending, adding fillers and fibers and also by copolymerization [3]. The advancement in the development of potential
fibers namely glass fibers, carbon fibers, basalt fibers and many more has thrown the light on the development of hybrid composites. Good modulus glass fiber and thermally stable basalt fibers have emerged as the effective combination for hybridization of fibers both for wear and strength [4]. Further, the development of thermoplastics blends such as PA66/PPS, PA66/POM, PA66/PEEK and such related associates has promised to be the best materials system to resist the wear of polymers. The dimensional analysis is one of the mathematical techniques used to establish the equation for a dependent variable using independent variables. It is a method of dimensions. It is used to formulate the mathematical model for a particular research problem using different process variables involved in the process. Srinath and Gnanamoorthy studied the 2BAW characteristics of Nylon clay Nano composites. They reported the impact of grit, load and velocity. They developed the mathematical abrasive wear model using the process parameters involved in the abrasion mechanisms by dimensional analysis. They evaluated the same model using experimentally determined wear values [5]. The effect of fillers and fiber reinforcement on 2BAW performance of polymers is reported by Bijwe et al. [6]. They showed the synergism between fillers and fibers on 2BAW characteristics of thermoplastic composites. They reported the effect of carbon filler, graphite, PTFE and MoS2 filler on SGF reinforced Polyetherimide (PEI), Polyimide (PI), Nylon 6 and PTFE composites. The results showed that in most of the cases, specific wear rate declined with rise in load. They showed that the reinforcement significantly reduced the ultimate elongation which is the crucial factor in controlling 2BAW of composites. Different wear models were developed to study the abrasive wear behavior of polymer composites. Ratner et al [7] has studied the 2BAW behavior of reinforced polymers. They showed from their model that wear rate is inversely proportional to the product of strain and stress at rupture ‘ζε’ factor. The wear volume of polymer composites varies directly as the product of load and distance which is proposed by Yamaguchi [8]. Horst Czichos [9] proposed the model on abrasive wear volume of polymers stating that the wear volume varied inversely as its rupture stress. Sahin studied the 2BAW characteristics of fiber reinforced PTFE composites through Taguchi technique [10]. He reported that SCF filled PTFE exhibited the better wear resistance and the load has proved to be the most significant factor. Harsha and Tewari [11] studied the abrasion wear characteristics of Polyaryletherketone composites. They showed that specific wear rate is directly proportional to wear volume loss. Further, they showed that the wear rate of composites is a function of [ζ]\(^{-1}\), [ζε]\(^{-1}\) and [Hζε]\(^{-1}\). In the research of polymer composites, the mathematical modeling is must using dimensional analysis for different types of composites. It always gives the effect of one variable on the other in the process.

From the above literature survey, many researchers have showed the relation existing between variables in the wear process. But developing a model for a particular composites using dimensional analysis and evaluating the same using experimented values is not reported. Keeping all these in mind, an attempt has been made to develop a model which incorporates maximum variables affecting the dependent variable (output variable). For this, hybrid composite such as GB and GC composites were used and the response of these composites was compared with the individual fibers to justify the results using wear models.

2. Materials and formulations

The material used for the study and some of their physical data is tabulated in table 1. All the data’s are related to room temperature. The formulations of hybrid composites are recorded in the table 2.
Table 1. Materials data used for the study

| Materials           | Mat. ID | Melting point (°C) | Density (g/cc) |
|---------------------|---------|--------------------|----------------|
| Polyamide66         | PA66    | 279                | 1.75           |
| Polytetrafluoroethylene | PTFE  | 325                | 2.81           |
| Glass fibers        | SGF     | ---                | 2450           |
| Carbon fibers       | SCF     | ---                | 750            |
| Basalt Fibers       | SBF     | ---                | 2450           |

Table 2. Materials formulations in weight fraction percentage

| Weight fraction Percentage | Mat.ID | PA 66 | PTFE | SGF | SBF | SCF |
|----------------------------|--------|-------|------|-----|-----|-----|
| Blend(PA66/PTFE)           | Blend  | 80    | 20   | --- | --- | --- |
| Blend/SGF                  | SGF    | 80    | 20   | 10  | --- | --- |
| Blend/SBF                  | SBF    | 80    | 20   | --- | 10  | --- |
| Blend/SCF                  | SCF    | 80    | 20   | ----| ----| 10  |
| Blend/SGF/SBF              | GB     | 80    | 20   | 10  | 10  | --- |
| Blend/SGF/SCF              | GC     | 80    | 20   | 10  | --- | 10  |

2.1. Processing and Testing of Composites

The polymer materials for processing were dried in an oven at suitable temperature at about 50 °C to free them from moisture and plastic effects. The twin screw extruder with five heating zones was used and the composites were processed using melt mix method followed by injection moulding [12]. The processing of composites has been carried out across the five heating zones in the extruder chamber where the temperature of 200, 230, 240, 250 and 255 °C respectively have maintained [13]. The two body abrasion wear behaviour of hybrid composite was carried out using ASTM G99 method. The abrasion effect was initiated using 180 grit SiC paper at a load of 10 N through 0.25, 0.5, 0.75 and 1 m/s abrading velocity. The interaction span of 100 m has been maintained to study the abrasives effect. The wear volume loss through weight loss has been determined using experimentally determined density [14]. The specific wear rate (Ks) of fibrous composites is determined using the following formula (1):

\[
K_s = \frac{\delta V}{L \times D} \text{ mm}^3/\text{N-m}
\]

(1)

The pin on disc setup of Ducom Bangalore was used as the experimental set up for 2 BAW test and the procedure followed is as per ASTM G99 [14]. The experimentation was carried out for a applied load of 10 N, 180 Grit, 100 m abrading distance under the abrading velocity of 0.25, 0.5, 0.75 and 1 m/s in multipass condition. The wear volume loss through multipass has been recorded and the specific wear rate for the applied condition was calculated.
### 3. Results and Discussion

The development of mathematical model using dimensional analysis has been designed and the same is justified using the experimentally responded values. The table 3 documents the parameters which could effectively control the abrasive wear behaviour.

#### Table 3. Factors controlling 2BAW behaviour of Hybrid composites

| Controlling factors | Particulars          | GB     | GC     |
|---------------------|----------------------|--------|--------|
|                     | Ultimate tensile strength (σ) | 88.5   | 97.22  |
|                     | % elongation (ε)       | 14     | 12.5   |
|                     | Factor (σε)            | 12.39  | 12.15  |
|                     | Hardness (H)           | 75     | 63     |
|                     | 1/ (σε)               | 0.0807 | 0.0822 |
|                     | 1/H (σε)              | 1.76 x 10^{-3} | 1.32 x 10^{-3} |

#### 3.1 Abrasive Wear Modelling using the Concept of Dimensional Analysis

The Buckingham – Pi (π) theorem is used to establish the relation between variables involved in abrasive wear phenomenon. When the variables involved in the problem are more than four, Buckingham pi theorem method is used for the analysis. This theorem can be applied effectively for the tribological process. In this discussion, 2BAW behaviour of polymer composites was considered. The Wear volume loss (W) of polymer composites due to abrasion depends on abrading load in N (L), abrading velocity in m/s (V), abrading distance in m (D), Ratner- Lancaster factor in mm²/N (R) (1/σε) and density of composites (ρ) in kg/mm³.

Therefore, W is a function of L, D, V, R, ρ.

Wear volume is a dependent variable and L, D, V, R and ρ are independent variables. Therefore, W is a function of (L, D, V, R, ρ). From Buckingham- pi theorem method

Therefore, f (W, L, V, D, R, ρ) = 0

Number of fundamental dimensions (Length, Mass and Time) = m = 3

Number of variables in the problem = n = 6

#### Table 4. Dimensions of variables used in the problem

| Variable                | Symbol | Units   | Dimensions   |
|-------------------------|--------|---------|--------------|
| Volume                  | W      | mm³     | [L³]         |
| Distance                | D      | m       | [L]          |
| Velocity                | V      | m/s     | [LT⁻¹]       |
| Density                 | ρ      | Kg/mm³  | [ML⁻¹]       |
| Ratner–L Lancaster factor | R    | mm²/N   | [M⁻¹LT⁻²]    |
According to Buckingham Pi- theorem method,
Number of \( \pi \) terms = \( n - m \) = 3
Therefore, \( f(\pi_1, \pi_2, \pi_3) = 0 \)  \hspace{1cm} \text{(2)}

According to Buckingham pi theorem,
Number of repeating variables = \( m \) = 3
Repeating variables = Geometry variable, flow parameters and fluid property = \( D, V, \rho \)
Therefore, \( \pi_1 = D^a V^b \rho^c W \), \( \pi_2 = D^a V^b \rho^c L \), \( \pi_3 = D^a V^b \rho^c R \)

Writing the dimensions of each variable involved in the problem.
\( \pi_1 = [M^0L^0T^0] = D^a V^b \rho^c W = [L]^a [LT^{-1}]^b [ML^{-3}]^c [L^3] \),
Equating the powers of \( L, M \) and \( T \) on either side of the equation, the term \( \pi_1 \) is obtained.
\[ \therefore \pi_1 = \frac{W}{D^7} \text{, the arbitrary constants } a, b \text{ and } c \text{ are determined using principle of dimensional homogeneity. From the principle of Buckingham pi theorem method, following dimensionless } \pi \text{ terms are obtained.} \]
\[ \pi_1 = \frac{W}{D^7}, \pi_2 = \frac{L}{\rho V^2 D^2} \quad \text{and } \pi_3 = R \rho V^2 \]
\[ \frac{W}{D^7} = f\left(\frac{L}{\rho V^2 D^2}, R \rho V^2 \right) \hspace{1cm} \text{(3)} \]
Using the concept of dimensional analysis, the following formulations can be written depending on the dependent variable available in the dimensionless \( \pi \) term.
\[ \therefore \pi_1 = f(\pi_2, \pi_3), \pi_2 = f(\pi_1, \pi_3), \pi_3 = f(\pi_1, \pi_2) \]
Hence,
\[ \frac{W}{D^7} = K \left(\frac{L}{\rho V^2 D^2}\right)^a \left(\frac{R \rho V^2}{R \rho V^2}\right)^b \hspace{1cm} \text{(4)} \]
Therefore, \( W = K L^a D^{3.32} V^{2.01} R^{0.46} \hspace{1cm} \text{(5)} \)

Where \( K \) is the wear constant. The value of \( a, b \) and \( K \) are evaluated from experimentation data obtained and are correlated. As the density of composites tested are nearly constant, it is merged with the value of \( K \). Therefore, the final mathematical model obtained for the wear volume loss is:
\[ W = K L^{0.8} D^{1.32} V^{0.76} R^{0.46} \hspace{1cm} \text{(6)} \]
Where the value of \( K = 4.18 \times 10^{-3} \) and 3.98 \( \times 10^{-3} \) for GB and GC hybrid composites respectively. The equation (6) is holds good for the abrasive wear behaviour of studied hybrid composites.

Figure 1 shows the wear volume predicted from both experimentation and wear model. The wear volume loss predicted from the equation obtained from Buckingham Pi theorem method agrees with the experimental data conducted on 180 grit abrasive paper at a load of 10 N. But the large deviation from the experimental data is noticed for higher velocity of 1 m/s. This is due to interfacial temperature during friction. This is not considered for the analysis. The temperature is one of the important factor which can control the wear behaviour of composites. Both GB and GC hybrid composites agreed with the model of Buckingham pi theorem. The wear volume loss for GB and GC hybrid composites for particular conditions obeys the law of dimensional analysis.
3.2 Specific Wear Rate as a Function of Mechanical Properties: Abrasive Wear Models

The abrasive wear resistance of polymer composites is greatly influenced by their mechanical properties. These mechanical properties are related to some experimental response of abrasive wear behaviour. The different abrasive wear models have been designed by many researchers. Some of them are given in Table 5. The purpose of reinforcing fibres and fillers into polymer is to enhance the strength by the expense of ductility of a material. As expected, the ductility at yield was decreases with the corresponding increase in strength. According to abrasive wear models (Table 5), the factors ‘H’, ‘ζε’ and ‘Hζε’ played the important role in defining the abrasive wear behaviour.

The ‘Ks’ as a function of some mechanical properties of GB hybrid composites is presented in figure 2(a - c). Figure 2(a) depicts the relation between wear rate and rupture stress. It is found that the influence of hybrid fibres improved the rupture stress and hence the high wear resistance. The wear volume of composites varied inversely as its rupture stress [156]. This is true for the studied composites. Similarly, reinforcing fibers improved the strength of composites with decrease in elongation. The factor ‘ζε’ is high for the composites studied. Hence, GB composites exhibited the good abrasive wear resistance [7, 15]. The wear volume of studied composites is directly proportional to the Yamaguchi factor (PD) which is the product of load and sliding distance [8]. The hybrid GB composites exhibited good ‘Hζε’ factor which enhanced the abrasion resistance of composites [15]. From all the figures 2 (a - c), it is observed that the specific wear rate is inversely proportional to ‘σ’, ‘ζε’ and ‘Hζε’ factors. But wear resistance is directly proportional to all these factors. Hence the composites possessing higher value of these factors exhibit the good abrasion wear resistance. The obtained results agree with the wear models designed for the abrasion behaviour. From the table 5 and the experimental values, it is concluded that the abrasion wear resistance was in the order of GB hybrid > Blend/SGF > Blend/SBF > Blend (PA66/PTFE).
Table 5. Abrasive wear models

| Wear models | Authors |
|-------------|---------|
| \[ W = \frac{\mu L}{H \sigma \varepsilon} \] Where \( W \) = Wear volume/ distance, \( H \) = Hardness, \( L \) = Load, and \( \sigma \varepsilon \) = Product of stress and strain at rupture and \( \mu \) = friction coefficient | Ratner et al [7] |
| \[ W = \beta NPD \] where \( W \) = Wear volume , \( D \) = Sliding distance \( P \) = Normal load, \( \beta \) = abrasive wear factor and \( N \) = Scratching efficiency factor | Yamaguchi[8] |
| \[ W = \frac{K \mu P}{H \sigma \varepsilon} \] Where \( \mu P \) = Ploughing coefficient, \( \varepsilon \) = % elongation to failure, and \( K \) = Constant , \( H \) = Hardness, \( W \) = Wear volume per unit distance and \( \sigma \) = tensile strength | Vaziri et al [15] |
| \[ W = \frac{F_N S^5}{\sigma_y} \left[ 1 + 4f^2 \right]^{1/5} \] where \( W \) = Wear volume, \( f \) = friction coefficient, \( S \) = Sliding distance, \( \sigma_y \) = Rupture stress of the polymer and \( F_N \) = Normal load | Horst Czichos [9] |

Similar responses were exhibited by GC hybrid composites. The wear rate of composites is directly proportional to factors \( [\sigma]^{-1} \), \( [\sigma \varepsilon]^{-1} \) and \( [H \sigma \varepsilon]^{-1} \). The variation of ‘Ks’ of GC hybrid composites as function of aforesaid factors are shown in figure 3(a, b and c). The 2BAW behaviour of GC composites is a function of mechanical properties. The abrasive wear models of composites established the relation between mechanical properties and wear rate of composites. It is well documented through the literature that the wear rate of composites varies inversely as ‘\( \sigma \varepsilon \)’ factor which is a controlling factor for 2BAW behavior. The wear rate of GC hybrid composites followed the same trend as per the abrasive models [154]. It is well proved through the abrasive models that the ‘Ks’ of composites is proportional to \( [1/\sigma \varepsilon] \) and \( [1/H \sigma \varepsilon] \) [7,15,16]. It was also proved that abrasive wear resistance of composites is directly proportional to ‘\( \sigma \varepsilon \)’ factor. The studied GC hybrid composites exhibited highest ‘\( \sigma \varepsilon \)’ factor (Table 5) and hence high abrasive wear resistance. All composites studied followed the abrasive wear models. The non-fiber filled composites exhibited the least abrasive wear resistance because of least Ratner - Lancaster factor (\( \sigma \varepsilon \)). The GC hybrid composites exhibited the better abrasive wear resistance than SGF filled and SGF filled composites. Further, it is observed that the material removal rate of thermoplastic will not improve by reinforcing short fibers if the wear process is highly abrasive [17]. Therefore, it is clear that the short fibers can improve the abrasive wear resistance of thermoplastic composites. In supporting to this, Bijwe et al. [18] reported the abrasive wear behaviour of PEI/PTFE and PEI/SGF composites. The wear volume loss of composites was in the order of PEI/PTFE > PEI/SGF. But the effect of higher weight percentage reinforcement of fibers into polymer increases the abrasivity of surface and hence high wear rate [18]. In the present study, 10 wt. % glass, 10 wt. % basalt and 10 wt.% carbon fibers each enhanced the abrasive wear behaviour of PA66/PTFE blend composites. But 30 wt. % SGF in PSU
enhanced the abrasive wear resistance of PSU/SGF composites [19]. This is in good agreement with work of many researchers [18 - 20]

**Fig.2.** Relation between Specific wear rate and some of mechanical properties of GB hybrid composites: a) $[\sigma]^{-1}$, b) $[\sigma\varepsilon]^{-1}$ and c) $[H\varepsilon]^{-1}$
Figure 3. The specific wear rate (Ks) as a function of some mechanical properties under 2-BAW behavior of GC hybrid composites: a) $\sigma \varepsilon$ v/s Ks, b) $[\sigma \varepsilon]^{-1}$ v/s Ks and c) $[H \varepsilon]^{-1}$ v/s Ks.

4. Conclusion

The following conclusion are made in the investigation of abrasive wear behaviour of GB and GC hybrid composites.

1. The concept of dimensional analysis has been applied effectively for GB and GC hybrid composites.
2. The predicted wear volume through designed model agrees with the experimental response for the condition studied.
3. The process temperature has not been used as the variable in the analysis which may varied the values to little extent.
4. The hybrid composites (GB and GC) have been responded in terms of tribological wear rate which suits the abrasive wear models.
5. It is proved from the investigation that the effect of hybrid fiber reinforcement could effectively enhance the abrasion wear resistance.
6. Higher percentage of fibre reinforcement transfers the polymer surface to become highly abrasive which is detrimental to abrasive wear resistance.
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