A fuzzy logic approach for investigating the tribological behavior of polymer composite

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Abstract: The application spectrum of natural fiber reinforced polymer composites has been increasing tremendously because of enhanced tribological behavior. The present study investigates the wear and coefficient of friction of castor oil fiber reinforced composites for developing as new tribo-material. Composites with 40 vol.% with short fiber length of 5mm were fabricated by hand lay-up method. The tribology tests were performed with pin on disc tribometer at normal loads (15N, 30N & 45N) and sliding distances (1000m, 2000m & 3000m). A fuzzy logic model has been developed to predict and analyze the wear and friction characteristics at unknown test cases. Each input variable was divided into three linguistic variables and each output variable was divided into five linguistic variables. A triangular membership function was used for defining all the variables. The capabilities of fuzzy logic model were tested by confirmatory experiments. The model predicted the wear results with an error of 3.12% and coefficient of friction by 2.19%.

1. Introduction
In recent years, polymer matrix composites [1] and metal matrix composites [2] are being extensively used in all engineering fields. Among the polymer matrix composites, natural fiber reinforced composites were preferred because of low cost, biodegradable nature, effective mechanical properties, low density, energy recovery, enhanced CO₂ sequestration, reduced respiratory irritation and good tribological behavior. A large number of natural fibers have been used to enhance the wear and friction characteristics of polymers. For instance, reinforcing epoxy polymer with oil palm fiber and kenaf fiber improved the tribological behavior significantly [3]. At low temperature, fine grooves, debonding and micro-cracks were observed. However, at large temperature, predominant wear mechanisms such as delamination and fractured fibers were observed. Similarly, addition of short Agave Americana fiber to epoxy resin improved the wear resistance by 60% [4]. The best wear resistance was obtained at 3mm fiber length. In another research, adding chemically treated hemp fibers to polypropylene matrix improved the mechanical strength and wear resistance significantly [5]. In order to improve the tribological performance of synthetic fiber reinforced composites, natural fiber such as sisal was incorporated. The hybrid ratio of 25/75 wt% for sisal/carbon and sisal/glass hybrid composites has shown the best friction performance [6]. Addition of chopped castor oil fibers to epoxy matrix improved the amount of wear by 70%, CoF by 40%, and interfacial temperature by 24%. Also, the optimum fiber length was found to be 5mm. At 5mm fiber length, the lowest wear was found to be
2.05mg and CoF 0.239 [7]. As it was impossible to perform experimentation at every condition, soff computing techniques such as Fuzzy Interface system (FIS), Artificial Neural Networks (ANN) has been employed to predict and analyze the output responses at unknown test cases. This study aims at developing a fuzzy logic model to analyze the wear and coefficient of friction of chopped castor oil fiber reinforced epoxy composites.

2. Material & Methods
Castor oil plant stalk was dispersed in water for 9 days at ordinary temperature in order to separate xylem, cortex and pith. The cortex fiber was found to exhibit higher strength and rigidity than xylem fiber. Hence, cortex fibers having fiber length 5mm and diameter 0.3mm were used for fabrication of specimens. The matrix material was Epoxy (LY556 grade) and it was combined with hardener (HY 951grade) to form a resin. The composites with 60 vol. % resin as matrix material and 40 vol.% chopped castor oil fiber as reinforcement were fabricated by hand lay-up technique. The tribological characteristics were measured by pin on disc equipment. The tribometer set up was represented in Figure. 1. The tribological tests were performed as per ASTM G99 standard. EN-31 steel disc having hardness of 69 HRC was used as the contour surface. The track diameters were maintained between 100-120 mm such that sliding distances between 1000-3000m were achieved respectively and the normal load is varied at three levels (15,30&45N). The initial surface roughness of contact surfaces was maintained with the help of emery papers having grit sizes 220 & 600. The initial and final weights of specimens were measured to determine the amount of wear.

3. Results & discussion
3.1 Experimental results
The tribology tests were performed as per design test conditions and the results were formulated in Table 1. Each experiment was conducted twice and average of two readings was taken for analysis. Each experiment has exhibited better accuracy and precision.

3.2 Fuzzy logic approach
A fuzzy logic system is an approach of mapping input data set nonlinearly to a scalar output [9]. Broadly, it comprises of five steps.

Step I: Deciding the descriptors of input and output variables
A crisp data was collected and transformed to fuzzy set with the help of linguistic variables. They were the input variables or output responses with values as words, instead of numerical values [10]. Three linguistic variables were chosen for each input variable and similarly, five linguistic variables were chosen for each output variable, as shown in Table 2.
Table 1. Tribological results of castor oil fiber reinforced epoxy composite [8]

| SNo | Normal Load (N) | Sliding Distance (m) | Amount of Wear (mg) | CoF |
|-----|----------------|----------------------|---------------------|-----|
|     | Test 1 | Test 2 | Mean | Test 1 | Test 2 | Mean |
| 1   | 15     | 1000   | 2.1  | 2.0  | 2.05  | 0.231 | 0.247 | 0.239 |
| 2   | 15     | 2000   | 2.7  | 2.5  | 2.60  | 0.243 | 0.258 | 0.250 |
| 3   | 15     | 3000   | 3.5  | 3.3  | 3.40  | 0.259 | 0.289 | 0.274 |
| 4   | 30     | 1000   | 2.9  | 2.7  | 2.80  | 0.299 | 0.311 | 0.305 |
| 5   | 30     | 2000   | 3.7  | 3.3  | 3.50  | 0.319 | 0.323 | 0.321 |
| 6   | 30     | 3000   | 4.2  | 4.0  | 4.10  | 0.337 | 0.345 | 0.341 |
| 7   | 45     | 1000   | 4.6  | 4.5  | 4.55  | 0.365 | 0.371 | 0.368 |
| 8   | 45     | 2000   | 5.3  | 4.8  | 5.05  | 0.388 | 0.402 | 0.395 |
| 9   | 45     | 3000   | 5.8  | 5.5  | 5.65  | 0.406 | 0.418 | 0.412 |

Table 2. Linguistic variables of input and output variables

| Input variables | Output variables |
|-----------------|------------------|
| Normal Load (NL) | Sliding Distance (SD) | Amount of Wear | CoF |
| SL : Small NL   | SSD : Small SD   | VS : Very small wear |
| ML : Medium NL  | MSD : Medium SD  | S : Small wear   |
| LL : Large NL   | LSD : Large SD   | M : Medium wear  |
|                 |                  | L : Large wear   |
|                 |                  | VL : Very Large wear |

Step II: Defining the membership functions of each variable
Membership functions play a vital role in mapping the non-fuzzy input values to fuzzy linguistic terms during fuzzification and defuzzification respectively. A linguistic term was quantified by a membership function [11]. Triangular membership function having gradual increase and decrease characteristics has been used in this study. Membership function of each input and output variable was represented in Table 3.

Table 3. Membership function of each variable

| Membership function of normal load | Membership function of sliding distance |
|-----------------------------------|----------------------------------------|
| $\mu_{SL}(x) = \frac{30-x}{15}$  | $15 \leq x \leq 30$                  |
| $\mu_{ML}(x) = \frac{x-15}{15}$  | $15 \leq x \leq 30$                  |
| $= \frac{45-x}{15}$              | $30 \leq x \leq 45$                  |
| $\mu_{SSD}(y) = \frac{2000-y}{1000}$ | $1000 \leq y \leq 2000$               |
| $\mu_{MSD}(y) = \frac{y-1000}{1000}$ | $1000 \leq y \leq 2000$               |
| $= \frac{3000-y}{1000}$           | $2000 \leq y \leq 3000$              |
\[ \mu_{LL}(x) = \frac{x - 30}{15}, \quad 30 \leq x \leq 45 \]

\[ \mu_{LSD}(y) = \frac{y - 2000}{1000}, \quad 2000 \leq y \leq 3000 \]

**Step III: Forming a rule base**

A rule base was formulated to regulate the output responses. A fuzzy rule consists of ‘IF–THEN’ rule with a condition and a conclusion [12]. The database and rule base was used to predict the wear and friction characteristics of chopped castor oil fiber composites. As there were two input variables with three linguistic variables, a total of nine rules were formulated for each output response, as depicted in Table 4.

| Membership function of amount of wear | Membership function of CoF |
|--------------------------------------|-----------------------------|
| \( \mu_{LL}(x) = \frac{x - 30}{15}, \quad 30 \leq x \leq 45 \) | \( \mu_{LSD}(y) = \frac{y - 2000}{1000}, \quad 2000 \leq y \leq 3000 \) |

**Step IV: Rule evaluation**

The capability of developed fuzzy model can be determined through rule evaluation [13]. The fuzzy rules were evaluated for the condition: Normal load – 40N and Sliding distance – 2700m. Out of nine rules, four rules map to the condition, as represented in Table 5 and the corresponding fuzzified value

| Table 4. Fuzzy rules based on membership functions |
|-----------------------------------------------|
| Amount of Wear | CoF |
| SL | SSD | MSD | LSD | SL | SSD | MSD | LSD |
| ML | VS | S | M | ML | M | M | L |
| LL | L | L | VL | LL | L | VL | VL |

| Table 5. Fuzzified values for condition: Normal load – 40N and Sliding distance – 2700m |
|-----------------------------------------------|
| \( \mu_{VS}(U) = 2.65 - U, \quad 2.65 \leq U \leq 3.65 \) |
| \( \mu_{S}(U) = U - 1.65, \quad 1.65 \leq U \leq 2.65 \) |
| \( \mu_{M}(U) = U - 2.65, \quad 2.65 \leq U \leq 3.65 \) |
| \( \mu_{L}(U) = U - 3.65, \quad 3.65 \leq U \leq 4.65 \) |
| \( \mu_{VL}(U) = U - 4.65, \quad 4.65 \leq U \leq 5.65 \) |
| \( \mu_{VS}(V) = 0.25 - V, \quad 0.20 \leq V \leq 0.25 \) |
| \( \mu_{S}(V) = 0.30 - V, \quad 0.20 \leq V \leq 0.25 \) |
| \( \mu_{M}(V) = 0.35 - V, \quad 0.25 \leq V \leq 0.30 \) |
| \( \mu_{L}(V) = 0.40 - V, \quad 0.30 \leq V \leq 0.35 \) |
| \( \mu_{VL}(V) = 0.45 - V, \quad 0.35 \leq V \leq 0.40 \) |
was evaluated through rule map. Rule no. 2&4 found to exhibit higher strength than other two. Defuzzification was performed based on rule strength

**Table 5.** Rule evaluation for normal load 40N and Sliding distance 2700m

| Normal load – 40N | Sliding distance – 2700m |
|-------------------|--------------------------|
| $\mu_{ML}(x) = 1/3$ $\mu_{LL}(x) = 2/3$ | $\mu_{MSD}(y) = 3/10$ $\mu_{LSD}(y) = 7/10$ |

**Rule 1:** If the Normal load is Medium & sliding distance is Medium than the amount of wear and CoF is Medium

**Rule 2:** If the Normal load is Medium & sliding distance is Large than the amount of wear is medium and CoF is large

**Rule 3:** If the Normal load is Large & sliding distance is Medium than the amount of wear is large and CoF is very large

**Rule 4:** Normal load is Large & sliding distance is Large than the amount of wear and CoF is very large

Step V: Defuzzification

The fuzzified data has been converted to crisp data by defuzzification technique. It executes the reverse phenomenon of the fuzzification process [13]. It transforms the fuzzy values of output responses into corresponding practical values of wear and CoF. In the present work, ‘max-min’ defuzzification technique has been used and the results obtained were tabulated in Table 6.

**Table 6.** Defuzzification of predicted output response

| $Max\ Strength = Max(S_1, S_2, S_3, S_4)$ |
|------------------------------------------|
| $= Max(1/3, 7/10, 2/3, 7/10)$ |
| $= 7/10$ |

| Defuzzification of Rule 2 | Amount of Wear | CoF |
|--------------------------|----------------|-----|
| 3.65                     | 0.350          |
| Defuzzification of Rule 4 | 5.35           | 0.385 |
| Avg. Defuzzification value | 4.50           | 0.367 |

4. Validation of Fuzzy Model

In order to determine the capabilities of developed fuzzy logic model, confirmatory tests were conducted at rule evaluation condition. The experimental results and fuzzy model results were
depicted in Table 7. The results were in good accordance with each other. The fuzzy logic model predicted the wear results with an error of 3.12% and coefficient of friction by 2.19%. As the average error of fuzzy logic model was around 5%, the fuzzy interface system can be reliable technique for estimating the wear behavior at unknown test cases.

| Table 7. Validity check of Fuzzy logic model |
|---------------------------------------------|
| Output Variable | Experimental Value | Fuzzy Model Value | Error % | Avg. error % |
| Amount of Wear   | 4.80              | 4.65              | 3.12    | 2.65         |
| CoF              | 0.378             | 0.367             | 2.19    |              |

5. Conclusion

The fuzzy logic approach has been implemented in estimating the tribological behavior of chopped castor oil fiber composites successfully and the following conclusions were drawn:

- The amount of wear and CoF increased with increase in normal load and sliding distance.
- The normal load has high impact on tribological characteristics than sliding distance.
- The triangular membership functions can be used to analyze the wear response of polymer composites.
- The fuzzy logic model estimated the amount of wear with 3.12% and CoF by 2.19% with an average error of 2.65%.
- The fuzzy interface system can be a reliable technique in estimating the wear behavior of natural fiber reinforced polymer composites.

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