Wear Behavior of Coconut Fiber Reinforced Polyamide Matrix Composites

P. Rajasekhar, G. Ganesan, C. Senthilkumar

Abstract: ***Nowadays, the polymer matrix fiber reinforced composites have greater attention of many important manufacturing sectors particularly construction, automotive and packaging industries due to its low density, good mechanical and better tribological properties. Recently, the coconut fiber reinforced composites have replaced the most widely used synthetic fiber (Glass, Kevlar) reinforced polymer composites in many applications. In the present study, the polymer matrix composites were prepared and developed through hand layup process with treated short coconut fiber. Composite specimens were prepared according to the ASTM Standard G-99 and the wear tests were conducted on the Pin-On-Disk wear testing machine. The experiments were carried out according to the central composite second order rotatable design. Optimization has been carried out using Response surface methodology (RSM). The morphology of worn surfaces was examined through scanning electron microscope (SEM) and various wear mechanisms were discussed.***

Keywords: ***Friction coefficient, Wear Rate, Polyamide, Coconut fiber, Pin On Disc.***

I. INTRODUCTION

There has recently been an expanding demand for new materials with high performance at affordable cost. Over the past decade, rising environmental concerns and international treaties along with the resultant changes in the content of governing policies have boosted interest on natural fibers in various fields [1, 2]. Natural fiber reinforcements in the form of short fiber or fabric have become better alternatives to synthetic fibers as reinforcements, due to their high flexural modulus and strength as well as impact strength and modulus. They are lighter in weight, less cost, lower in density and higher in specific strength as well as renewable, non corrosive and easier to manufacture. These and their biodegradability have helped in their widespread application including in the automotive, aerospace and transportation industries [3-6]. The biodegradability of natural fibers is well in line with the demands of a healthier environment, while their high performance and affordable cost satisfies the economic benefit of industries. Pineapple leaf, oil palm fiber, hemp, sisal, jute, kapok, rice husk, bamboo and wood are some natural fibers most commonly used as reinforcing materials in polymer composite industry [7]. Of all the plant fibers, natural fibers are most useful, commercially available and inexpensive that can be molded into different shapes [8].

Fabrics are mainly used with tribological mechanisms such as seals, cams, and bearings because their higher thermal as well as dynamic mechanical stability, higher strength and rigidity as well as suppleness [9]. These days, polyamide, polypropylene, polyethylene and poly vinyl chloride dominate as matrices for natural fibers. Polyamide is extensively used as advanced composite matrix because it is cheap, strong and easily processable, while polyamide based lining material is now in use owing to its superiority in resistance to wear [10].

Increasing applications of polymer matrix composites for various mechanical parts including gears, wheels, clutches, bush bearing and artificial prosthetic joints require adequate knowledge of their tribological properties, which are different from much better understood tribological properties of metals and ceramics. Natural plant fiber reinforced polymer composite components can be applied in many situations for tribological loading conditions. An important part of tribology deals with materials selection and surface processing in as much as they affect wear and tear. A good grasp of interacting surfaces is a must for their optimal functioning, long-term reliability of components and devices and for economic viability. Work is now in progress to improve the composite's coefficient of friction and sliding wear, since 90% failure in mechanical parts are as a result of tribological loading [11-15]. Moreover several studies have shown that wear properties of polymer composites filled with smaller particles are superior to those with larger ones. In recent years, great efforts devoted to the development of nano particles filled polymer composites have made it possible to investigate the effect on the tribological properties of the nano composites [16-19]. However, for the tribological process of polyamide matrix composites, optimal tribological parameters must be determine to achieve less wear rate and coefficient of friction. The principle of multiple performance optimizations is differing from those of single performance optimization. In multiple performance optimizations, there is more than one objective function, each of which may have a different optimal solution. Most of the time, these objectives are conflict with one another. Limited research has been done on coconut fiber. Further, to the author's best knowledge, no work has been reported regarding treated short coconut fabric reinforced polyamide matrix composite.

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Hence, given the marvelous advantages and opportunities related to coconut fabric reinforced polymers, there is a need to further examine the effect of coconut fibre reinforcement on the tribological characteristics of polyamide based composites. Therefore, the aim of the present study is focused on the tribological behavior of polyamide matrix composites, whose field of applications is in constant growth, is carried out. Consequently, an analyze on the influence of input parameters like normal force, sliding velocity and reinforcement, over technological variables such as WR and COF is performed using design of experiments (DOE) and regression analysis. The use of these techniques has enabled creation of second order polynomial models, which make it possible to explain the variability associated with each of the technical variables studied. In addition, these models can be used for optimization by which minimize WR and COF as objectives. It is to look into the effect of the Coconut fabric reinforcement on the sliding wear and friction characteristics of the resulting composites.

II. EXPERIMENTAL METHOD

A. Preparation of The Material and the Specimen

The basic raw materials utilized to prepare the experimental composites are Polyamide (PA) resin as matrix material and it was supplied by the Javantheeswarar Enterprises Limited, Chennai. The polyamide has the density of $1.13X10^3$ kg/m^3 and this resin is the first to be recognized as engineering thermoplastics. Due to the technological developments, the production industries and product developers are suggesting for light weight, higher strength and safer material to meet the demands of structural designs, economic benefit and implementation of new ideas in the competitive world from the existing procedure.

Brown coconut fibers are extracted from matured coconuts and it was treated with 4 % sodium hydroxide mixed with distilled water in a glass beaker at room temperature for 1 hr with continuous stirring, this process was repeated for several times to remove the impurities and alkali content from fibers, further the fibers were washed thoroughly with plain distilled water. To improve the bonding strength between the resin and coconut fibers further it was process with silane coupling agent treatment at room temperature and the fibers were dried in an air circulation oven at 80°C for 24 hours.

Polyamide matrix composites with treated short coconut fiber were prepared by simple hand lay-up process in a mold at ambient temperature with the size 150 L X 80 W X 50 H mm. Polyvinyl acetate was applied to the surfaces of the mold and the polyamide resins were sprayed on the mold and the coconut fibers were infused in the polyamide resin. The infused layers were placed one over the other in the mold for 1 hr before removal at ambient temperature. Uniform thickness was achieved then the mold was cured at room temperature for 24 hr. After the solidification of polyamide matrix composites then it was machined as per ASTM-G standard 99 for tribological test. The tribological test was conducted through pin on disc wear testing machine by varying predominant process parameters such as normal force, sliding velocity and reinforcement with fixed time interval. The size of the pin (test specimen) and disc are 10 mm X 20 mm and 55 mm X 10 mm, with surface roughness of 0.1μm and a hardness of 60 HRC. Mass loss was measured by an electronic balance of 0.01 mg accuracy before and after the tests. COF was measured by a load cell sensor directly from the computer running friction-measuring software.

B. Response Surface Methodology

Response surface methodology (RSM) approach is the procedure for determining the relationship between various process parameters with the various tribological criteria and exploring the effect of these process parameters on the coupled responses [20]. i.e. the WR and COF. In order to study the effect of the tribological parameters on the above-mentioned two most criteria, a second order polynomial response can be fitted into the following equation,

$$Y_u = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x^2{}_i + \sum_{j>1}^{k} b_{ij} x_i x_j \quad (1)$$

Where Y_U is response and the $x_{i\ (1,2,\ldots,k)}$ are coded level of k quantitative variables. The coefficient b_0 is the constant term, the coefficients b_i are the linear terms, b_{ii} are the quadratic terms and b_{ij} are the interaction terms [20]. The pertinent process parameter selected for the present investigations are normal force, sliding velocity and reinforcement on the WR and COF during the tribological process. Table. 1 shows the process parameters and their levels. For the three variables the design required 20 experiments with 8 factorial points, 6 axial points to form face centered composite design with α = 1 and 6 centre points for replication to estimate the experimental error. The design was generated and analyzed using MINITAB.16 software.

Table. 1. Process Parameters and Their Levels

Parameter	-1.682	-1	0	+1	+1.682
Normal force (N)	2	3	4	5	6
Sliding Velocity (m/sec)	0.2	0.4	0.6	0.8	1.0
Reinforcements %Vf (Coconut fiber)	1.5	2.0	2.5	3.0	3.5

Table. 2. Experimental Matrix and Responses

Sl. No	Normal Force (N)	Sliding Velocity (m/sec)	Reinforcement	WR (mm^3/Nm)	COF (μ)
1	3	0.4	2	0.527	0.322
2	5	0.4	2	0.532	0.353
3	3	0.8	2	0.512	0.343
4	5	0.8	2	0.508	0.349
5	3	0.4	3	0.42	0.399
6	5	0.4	3	0.421	0.398
7	3	0.8	3	0.436	0.428
8	5	0.8	3	0.428	0.403
9	2	0.6	2.5	0.414	0.326
10	6	0.6	2.5	0.409	0.316
11	4	0.2	2.5	0.413	0.366
12	4	1	2.5	0.442	0.381
13	4	0.6	1.5	0.656	0.349
14	4	0.6	3.5	0.569	0.472
15	4	0.6	2.5	0.502	0.36
16	4	0.6	2.5	0.501	0.359
17	4	0.6	2.5	0.502	0.36
18	4	0.6	2.5	0.501	0.358
19	4	0.6	2.5	0.502	0.36
20	4	0.6	2.5	0.501	0.358

C. Development of Empirical Models based on RSM

The mathematical relationship, obtained for analyzing the influences of the various dominant tribological parameters on the WR is given by,

$$WR=0.833284+0.201841A+0.460966B-0.634273C-0.023886A^2-0.497159B^2+0.105455C^2-0.011250AB-0.002000AC+0.077500BC \quad \text{-------} \ (2)$$

The mathematical relationship, obtained for analyzing the influences of the various dominant tribological parameters on the COF is given by,

$$COF = 0.228477-0.127460A-0.035540B-0.158193C-0.008784A^2+0.108523B^2+0.054364C^2-0.030625AB-0.015750AC+0.021250BC \quad \text{------} \ (3)$$

Where A indicates Normal Force (NF), B indicates Sliding Velocity (SV) and C indicate Reinforcements (RF) in percentage volume fractions.

III. RESULTS AND DISCUSSION

Wear has been recognized to mean the phenomenon of material removal from a surface due to interaction with a mating surface. “Wear is not a material property. It is a system response”. Wear changes drastically even with a relatively small change in a tribo system, which is composed of dynamic parameters, environmental parameters and material parameters.

A. Influencing of Input Parameter on Wear Rate

The surface plot for normal force and reinforcement on wear rate is shown in the Fig.5.1. From the figure it is clearly seen that, the wear rate increases with increase in normal force up to certain level.

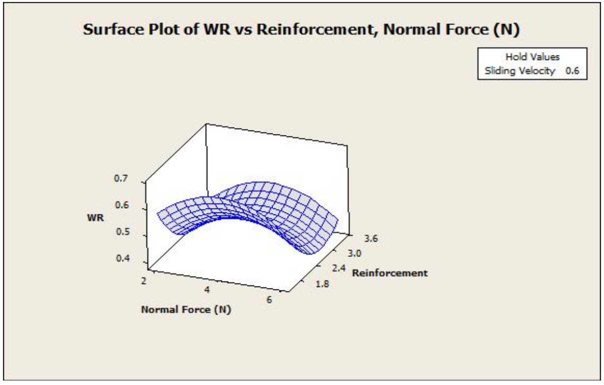

Fig.5.1 Influences of Normal Force and Reinforcement on WR

It is due to the matrix transfers and distributes the normal force on to the fibers, which in turn decreases the wear resistance of the composite and also the bonding between the coconut fiber and matrix is insufficient to resist normal force resulting matrix damage, formation of wear debris, micro-crack and wear scars are observed from the worn out surface of the micrograph is displayed in

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the Fig. 5.2, its evidence from the literature [21].

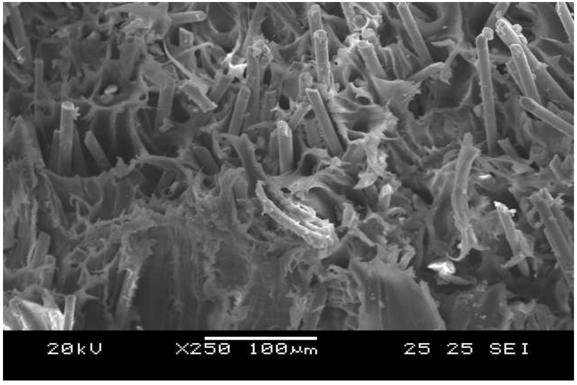

Fig. 5.2 SEM Image of Wear Debris, Micro-Cracks and Wear Scars

Further increase in normal force the wear rate decreases, this is because of the fiber pullout takes place from the matrix and some fibers are fractured which act as a lubricant, which results in less tangential frictional force between the mating surfaces of sample and disc leads to less wear rate [22]. The surface of composite gets damage is caused by combination of fracture at the ends of the fibers and severe damage of the matrix leading to fracture and debonding of the fibers and subsequent matrix removal is clearly visible from the micro graph as shown in Fig. 5.3.

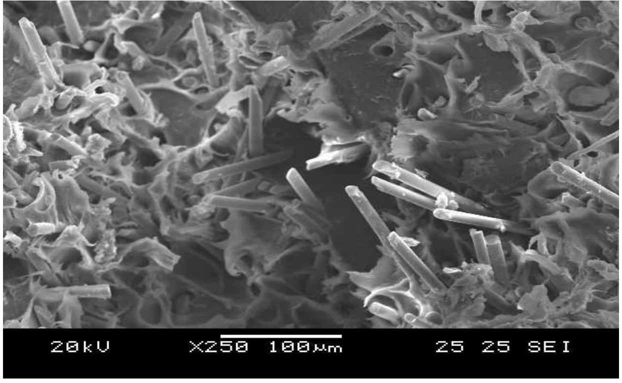

Fig. 5.3 Fiber Pullouts and Fracture of Fibers from the Matrix

From the Fig. 5.1 it was found that WR decreases with addition of coconut fiber reinforcement. This indicates that the improper stress transfer and distribution by the matrix to the fibers which in turn decreases the wear rate of the composite. When the coconut fiber content increases beyond best possible value, the fiber gets agglomerated as depicted in the Fig. 5.4 and the interfacial adhesion between the matrix and fiber is not enough to sustain the loading resulting in higher wear [23].

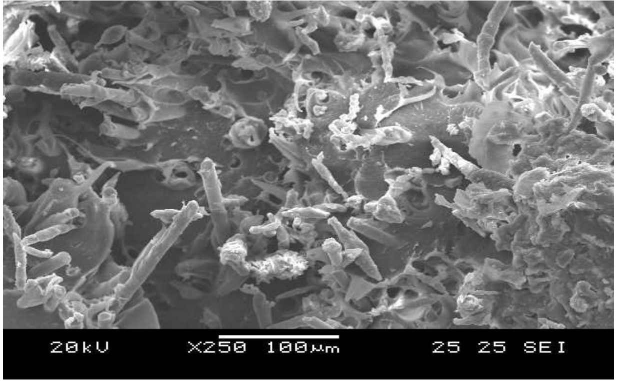

Fig. 5.4 Agglomerated and Interfacial Adhesion between Matrix and Fiber

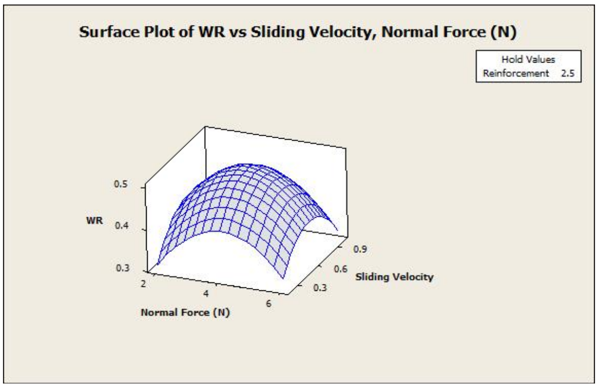

Fig. 5.5 Influences of Normal Force and Sliding Velocity on WR

The Fig.5.5 shows the surface plot of WR with respect to normal force and sliding velocity. It is clearly seen from the surface plot, the wear rate increases with increasing sliding velocity up to the focus value. This could be happened, because of sliding of two mating surfaces, during the test condition the frictional heat generated at the contacting region makes bonding gets diffused at interfacial regions of the fibers and matrix. Due to this the specimen had deformed like pits, severe fiber fracture and deep grooves were observed from the SEM image Fig.5.6, [24].

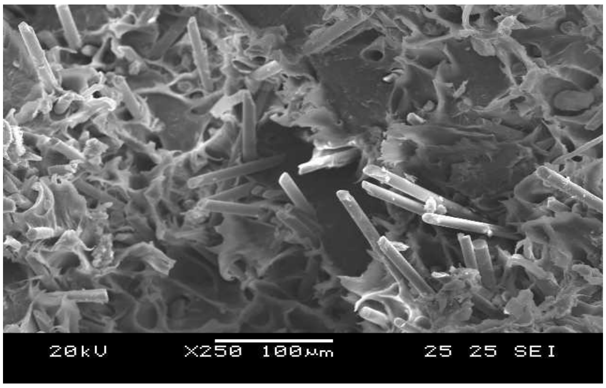

Fig. 5.6 Pits, Severe Fiber Fracture and Deep Grooves

Further increasing of sliding velocity the wear rate is decreased, because of the repeated cycles of contact are not necessary in adhesive and abrasive wear for the generation of wear particles. Due to the reason of ascertained a large area is subjected to plastic deformation. However, the smoother area of contact provides less resistance to friction and lesser wear as shown in Fig. 5.7 [25]. When the number of contact cycles is high, there is a state where a plastically deformed region appears beneath the interface without reaching the surface. Repeated friction under the normal force causes that accumulation of local plastic strain around some stress concentration points, pits, grooving and cracks are generated.

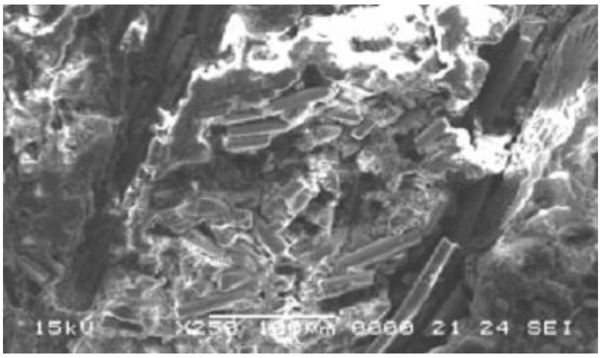

Fig. 5.7 Stress Concentration Points, Pits, Grooving and Cracks

B. Influencing of Input Parameter on COF

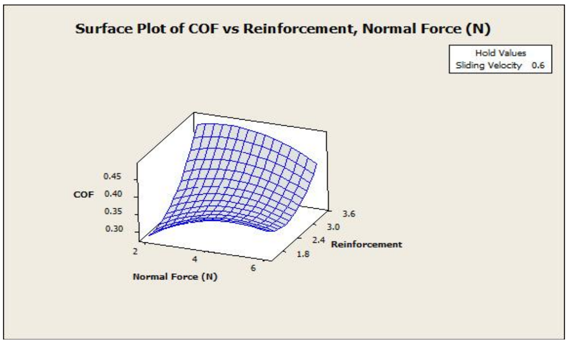

Fig. 5.8 Influences on Normal Force and RF on COF

Fig. 5.8 shows that the COF on normal force and reinforcement. It is evident from the figure that, initially the coefficient of friction increased with normal force, however further increase in normal force it decreases because of temperature between the counter surfaces was increases. Due to the rubbing action of surface it increase in temperature, thermal gradient is developed subsequently thermal stresses were generated. It leads to polishing the surface and debonding of fibers from the matrix, fibers get loose from the matrix, which in result shear easily occurs due to repeated axial thrust and reduction in friction coefficient is observed [26].Similar trend of decrease in coefficient of friction with increase in normal force is also observed by past researchers [27-28].

The minimum coefficient of friction is observed at lower volume fractions of coconut fiber is owing to the rolling action of sample debris may reduce the friction coefficient of the composites [29-30]. At higher volume fractions of fibers less amount of debris formation may cause higher coefficient of friction [31].

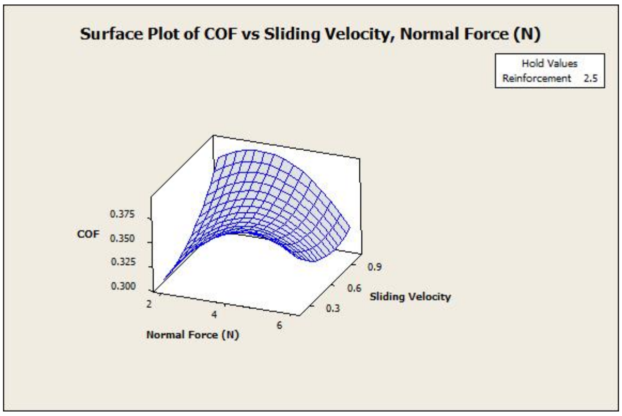

Fig.5.9 Influences on Normal Force and Sliding Velocity on COF

The effect of sliding velocity on COF is shown in Fig. 5.9. It is evident from the figure that initially; coefficient of friction decreases with increasing of sliding velocity however further increase in sliding velocity, the COF increases. The similar observation was observed by past researchers [32-33]. The decrease. in coefficient of friction may be due to the fact that under dry sliding condition increased sliding velocity increases the temperature at the interface. This increase in temperature causes thermal penetration, which results in weakness in bond at the fiber-matrix interface. Consequently the fibers become loose and trim easily due to the axial force of the pin.

With increase in sliding velocity as the wear process is continued the rough profiles of the counterparts and the composite were smoothened as a result, a transfer film formed on the surface of the counterparts. Consequently, lower coefficients of friction were obtained. Further increase in sliding velocity stronger fiber matrix bonding keeps the broken fibers in the composite surface, thus preventing the early formation of third body abrasives leads to higher COF. This mechanism is in accordance with that proposed [34].

C. Optimization based on RSM for Polyamide with Coconut Fiber

Optimization procedure in RSM is initiated by picking several starting points, from which, searching for the optimal factor is continued. Two types of solutions are obtained for the search: (1) local solution, for each starting point, there is a local solution. These solutions are the “best” combination of factor settings found for that particular starting point. (2) Global solution, there is only one global solution, which is the best of all the local solutions. The global solution is the “best” combination of factor settings for achieving the desired responses. The optimum operating conditions for achieving desirable wear performance are obtained using the response surface optimizer module available in the statistical software, Minitab® (version 16).

The objective of using RSM is not only to investigate the response over the entire factor space, but also to locate the region of interest where the response reaches its optimum or near optimal value. Based on the developed second order response surface equations for correlating the various tribological process parameters effects with the WR and COF values, optimality search can be obtained. An analysis for the optimization of the process parameters has been carried out using RSM optimization technique. Desirability for the whole process optimization has been calculated to show the feasibility of optimization, i.e. to explore whether all the parameters are within their working range or not. The goal was to minimize the WR and COF, while both are considered at a time. As the composite desirability is close to one, it can be concluded that the parameters are within their working range.

Optimization plot for the both responses is shown in Fig.5.10. The optimum values from the plot are WR = 0.3943 mm^3/Nm, COF is 0.3173 μ and the relevant parameters normal force, sliding velocity and volume fractions of reinforcement are 6.0 N, 0.7818 m/sec and 2.3485 $\%V_f$ respectively.

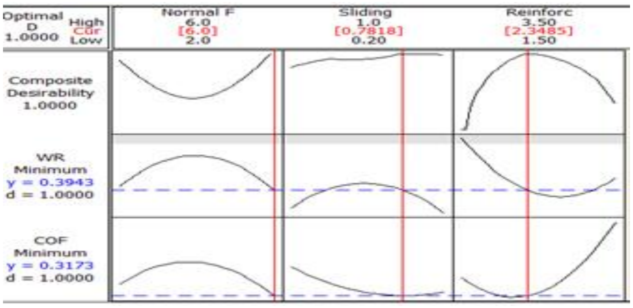

Fig. 5.10 Optimal chart obtained through RSM for Polyamide composite using Coconut Fiber as Reinforcement

In this study, after determining the optimum conditions and predicting the response under these conditions, a new experiment was designed and conducted with the optimum values of the tribological parameters. Verification of the test results at the selected optimum conditions for WR and COF are shown in Table 5.1. The predicted tribological performance was compared with the actual tribological performance and a good agreement was obtained. From the analysis of Table 3, it can be observed that the calculated error is small. The error between experimental and predicted values for WR and COF lie within 2.18 % and 3.49 %, respectively. Obviously, this confirms outstanding reproducibility of the experimental conclusions.

Table .3 Validation Test Results for Polyamide Composite using Coconut Fibers

Sl.No	Normal Force, N	Sliding Velocity, m/sec	Reinforcement, V_f	WR mm^3/Nm			COF μ		
				Predicted	Actual	%Error	Predicted	Actual	%Error
1	6	0.78	2.34	0.3943	0.3814	2.18	0.3173	0.3065	3.49

IV. CONCLUSION

The experiments were conducted on a pin on disc wear testing machine for polyamide matrix composites. The second order polynomial model developed for WR and COF. Increase in the normal force results in the increase of the wear rate because of bonding between the coconut fiber and matrix is insufficient to resist normal force resulting matrix damage thus wear rate increases. Further increase in normal force wear rate decreases which results in less tangential frictional force acting between the mating surfaces of sample and disc leads to less wear rate. Addition of coconut fiber reinforcement results the improper stress transfer and distribution by the matrix to the fibers, which in turn decreases the wear rate and at higher fiber content the fiber gets agglomerated resulting in higher wear rate.

The coefficient of friction increased with normal force, however further increase in normal force it decreases. Due to the rubbing action of surface which leads to polishing the surface and debonding of fibers from the matrix, that results in reduction of friction coefficient. With increase in sliding velocity the rough profiles of the counterparts and the composite were smoothened as a result, a transfer film formed on the surface of the counterparts. Consequently, lower coefficients of friction were obtained. Further increase in sliding velocity stronger fiber matrix bonding keeps the broken fibers in the composite surface, thus preventing the early formation of third body abrasives leads to higher COF.

The optimization has been carried out using RSM and the corresponding optimized values obtained were WR is 0.3943 mm^3/Nm, COF is 0.3173 μ, and the relevant parameters normal force, sliding velocity and reinforcements are 6.0 N, 0.7818 m/sec and 2.3485 $\%V_f$ respectively.

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