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Research Paper

TRIBOLOGICAL CHARACTERISTICS OF ACRYLONITRILE-BUTADIENE-STYRENE (ABS) THERMOPLASTIC COMPOSITES

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The selection of material and methods for wear applications is an important part for both technological advancement and manufacturing activities. Materials application, performance and manufacturability are all key parts for the selection of wear resistance applications. Wear materials are used to reduce dimensional changes due to unwanted material removal, reduce frictional losses, to tailor the physical performance of a component and to provide physically stable working surface. Acrylonitrile-Butadiene-Styrene (ABS) is a widely used thermoplastic. ABS polymers have a high toughness, satisfactory rigidity, and good resistance to heat, chemical, and environmental stress cracking. Molded articles with high dimensional stability and good surface quality can be produced by simple processing technique. It is essential to carryout investigations to characterize ABS thermoplastic composites for its wear behavior for tribological applications.

Keywords: ABS, Friction and wear, Design of Experiments, Central Composite Design, Analysis of Variance

INTRODUCTION

Composite materials have generally considerable research interest during recent times. They are replacing many conventional engineering materials due to their specific properties of strength and stiffness. The applications are either weight critical or performance critical as seen in automobile and aerospace industries. The concept of combining two or more constituent materials to form a composite and to make the best use of the more desirable properties of the constituents has opened up several avenues for intelligent exploitation of composite materials.

A composite material is made by combining two or more materials to give a unique combination of properties. The above

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definition is more general and can include metals alloys, plastic co-polymers, minerals, and wood. Fiber-reinforced composite materials differ from the above materials in that the constituent materials are different at the molecular level and are mechanically separable. In bulk form, the constituent materials work together but remain in their original forms. The final properties of composite materials are better than constituent material properties (*Composite Material Handbook*).

Based on the nature of matrix, the composites can be Ceramic Matrix Composites (CMCs), Metal Matrix Composites (MMCs) or Polymer Matrix Composites (PMCs). Polymer Matrix Composites have matrices of thermoplastic or thermosetting polymers. A large number of resin formulations, curing agents and fillers provide an extensive range of possible properties. PMCs are increasingly being employed as structural materials in civil, defense, aerospace, automotive and industrial applications where the weight reduction can contribute toward saving in fuel and other materials (*Composite Material Handbook*). Many common thermoplastics are too stiff by themselves, limiting their commercial applications. ABS represents industrially the most important thermoplastic two-phase system with an amorphous structure. The ABS polymers are based on three monomers: Acrylonitrile, Butadiene, and Styrene. Acrylonitrile-Butadiene-Styrene (ABS) is a widely used thermoplastic. In ABS, acrylonitrile causes an improvement in chemical resistance and weatherability, butadiene has the character of rubber toughness, and styrene offers glossiness and processability. The compositions of the various components can be controlled to meet the requirements of a variety of applications. Acrylonitrile Butadiene Styrene is a common thermoplastic. It is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. ABS polymers have a high toughness, satisfactory rigidity, and good resistance to heat, chemical, and environmental stress cracking. Molded articles with high dimensional stability and good surface quality can be produced by simple processing technique.

FRICTION AND WEAR

Friction and wear are terms that most people use in their daily lives. Most people accept the cost of sport shoes wearing out after 4 months of use; people accept wear of roadways and flooring; people accept 30,000 miles as the limiting use of an automobile before fan belts, brakes, and other components start to wear out. This guide reviews current friction and wears fundamentals and describes the bench tests that are most often used to study and solve tribology problems. Tests are compared and critiqued. Information is presented to help the reader select a test that he or she might use to address a tribology concern that they are responsible for solving. The overall objective of the guide is to lower the annual cost of wear, and unwanted friction through appropriate tribo testing.

Friction

Friction is an energy dissipation process that accompanies a body or substance in relative motion in contact with another body or substance. When a solid body slides on another solid, it takes energy to put the body in motion and keep it moving. Friction is the resistance to movement of one body over another body. The word comes from Latin verb fricare, which means to rub. This energy is dissipated at the rubbing surfaces, usually in the form of heat or deformation. When a solid body is moved through a fluid, the energy required to produce motion is dissipated by movement of the fluid as in waves or even results in heating.

A problem in dealing with friction is that people often say that a material is low friction. A material cannot have a co-efficient of friction. It is a system effect. This co-efficient is unique to a system. It takes into consideration factors such as:

- Surface texture,
- Sliding speed,
- Contact geometry,
- Type of motion (reciprocity, continuous, etc.),
- Environment,
- Mating materials,
- Mechanical properties of mating materials,
- Separating films/particles and,
- Contaminants.

Wear

Wear refers to the progressive removal of material from a surface and plastic deformation of material on a surface due to the mechanical action of the other surface (Kenneth, 2007). The necessity for relative motion between the operating surfaces and initial mechanical contact between asperities leads an important role between mechanical wear compared to other processes with similar outcomes (Kenneth, 2007).

The Organization for Economic Cooperation and Development (OECD) defines wear as "the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface".

Wear Mechanism

Wear is a surface damage that results in removal of materials from the surfaces which are in relative motion. Surface damage in this context is defined as topographical or micro structural changes, or both, in a surface layer. Material can be removed from a solid surface in only three ways: by melting, by chemical dissolution, or by the physical separation of atoms from the surface. The last method can be accomplished either by the one-time application of a high strain or by cyclic strainingat lower magnitudes. Perhaps biggest challenge in solving wear problems in that of anticipating the type(s) of wear to which component will be subjected (Williams, 2005).

In principle, a tribosystem may exhibit damage of single type, but generally the pattern is a combination of two or more types. The types of damage that will in practice influence a layer are:

- Surface damage without exchange of material: structural changes, plastic deformation and surface cracking.
- Surface damage involving loss of material: shear fracture, extrusion, chip formulation, chip formation, tearing, brittle fracture, fatigue fracture, chemical dissolution and diffusion.

- Surface damage involving gain of material: pickup of loose particles, material transfer from counter surface and corrosion.

Friction and Wear Tests

The Tribometer uses a pin-on-disk system to measure wear. It consists of a pin on disc, loading panel and friction and wear monitor. The sliding wear of pure ABS and carbon powder filled ABS are carried out with different loads by varying time and sliding distances. To evaluate the performance of these composites under dry sliding and lubrication conditions, wear tests will be carried out in a pin-on-disc type friction and wear monitoring test rig as per ASTM G 99-95a. The counter body is usually a disc made of hardened ground steel. The specimen is held stationary and disc is rotated while a normal force is applied through a lever mechanism.

Figure 1: Set Up to Perform an Abrasive Wear Test on Pin-on-Disc

Standard Methodology

Design of Experiments

Design of experiments can be defined as "The simultaneous evaluation of two or more factors for their ability to affect the resultant average or the variability of the particular product or process characteristics". To accomplish this in an effective and statistically proper fashions, the level of the factors are varied in a strategic manner, the result of particular test combinations are observed, and the complete set of the results are analyzed to determine the influential factors and preferred levels, and weather increase or decrease of those levels will potentially lead to further improvement. It is important to note that this is an iterative process; the first round through DOE process will many times leads to subsequent rounds of experimentation. The beginning round often referred to as a screening experiment is used to find the few important influential factors out of many possible factors involved with a product or process design (Douglas, 2010).

To use the statistical approach in designing and analyzing an experiments, it is necessary for everyone involved in the experiment to have a clear idea in advance of exactly what is to be studied, how the data are to be collected, at least a qualitative understanding of how these data are to be analyzed. An outline of the recommended procedure is shown below (Douglas, 2010).

- Recognition of and statement of the problem.
- Choice of factors, levels, and ranges.
- Selection of the response variable.
- Choice of experimental design.

- Performing the experiment.
- Statistical analysis of the data.
- Conclusions and recommendations.

Central Composite Design (CCD)

Design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors on performance output. The most important stage in the design of experiment lies in the selection of the control factors. Therefore, a number of factors are included so that non-significant variables can be identified at earliest opportunity. Two parameters viz., normal load and time each at two levels are considered in this study in accordance with Central Composite Design (CCD) (Philip, 1995).

Central Composite Design (CCD) is one of the methods of response surface design. CCD is very effective experimental technique in studies involving large number of factors. A set of experimental design that can look at k factor an n observation with each factor at two levels is called two level factorial designs, which can prove good and efficient when a linear relationship prevails between the factors and response.

Figure 2 shows the geometric form of the design when it is rotated by 450. It can be noticed that the levels of each factor have been increased from three levels without increasing the total number of Test combination (Tc) which is still equal to nine. The design as represented in geometric form in Figure 3 is called Central Composite Design (CCD) for it is made up of a central point and optimal joining of the 2^2 factorial designs with one factor-at-a-time design.

Figure 2: Geometric Form of CCD

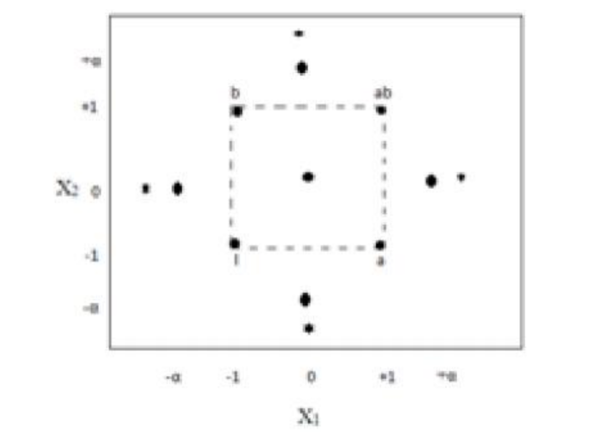
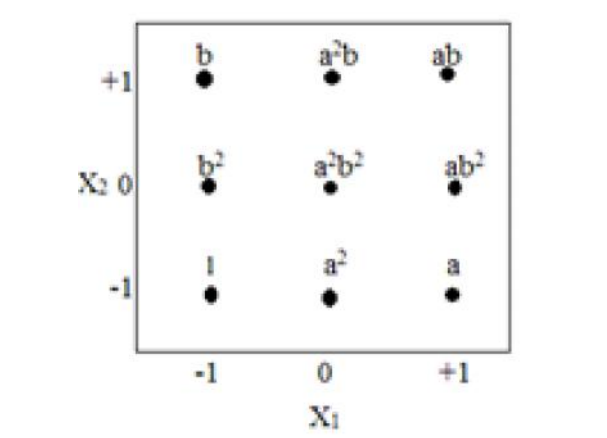


Figure 3: 2^2 Factorial Designs with One Factor-at-a-Time Design



The experimental design based on CCD allows investigation of factor up to fourth order quartics relationship due to the existence of five levels of each factor. The real value of the design is the increased scope of the experiment central composite design are easy to construct since they are based on two level factorials (2^k) and one-factor-at-a-time techniques. The general representation of CCD is:

No. of test combinations (Tc) = $2^{k-p} + 2*k + 1$

Here, k = no. of factors and p = the fractionalization element

Table 1 provides details of factors and their range considered in the present investigation.

Table 1: Details of Factor and Their Range

Factors		Range
Load, N	X_1	10 to 80
Time, Sec	X_2	500 to 1000

The distance (~) of the star (*) points from the centre is determined using equation

$$\sim = 2^{k/4} = (2^2)^{1/4} = 1.414$$

These factors and their levels in CCD experimental plan are summarized on Table 2.

Table 2: Factors and Their Levels in CCD Experimental Plan

Factors		Levels				
		–1.414	**–1**	**0**	1	+1.414
Load, N	X_1	10	20	45	70	80
Time, sec	X_2	500	573.2	750	926.8	1000

Note: No. of test combinations (tc) = $2^{k\text{-}p} + 2{*}k + 5$
tc = $2^{2\text{-}0} + 2{*}2 + 5 = 13$.

RESULTS AND ANALYSIS

Results and Analysis of ABS Under Dry Sliding Condition

From Table 3, CCD experimental plan and the wear test results of ABS thermoplastics are shown. Analyses are made using popular software specifically used for design of experiment applications known as Minitab. Before any attempt is made to use this simple model as a predictor for the measure of performance, the Regression models, Analysis of variance (ANOVA), main effects and the possible interactions between the control factors must be considered. Thus factorial design incorporates a simple means of testing for the presence of the interaction effects.

Table 3: CCD Experimental Plan and the Wear Test Results of ABS Under Dry Sliding Condition

tc	Coded Variables		Natural Variables		Responses	
	A	B	Load, N	Time, sec	Wear, g	COF
1	–1	–1	20	573.2	0.0003	0.502
a	+1	–1	70	573.2	0.0008	0.451
b	–1	+1	20	926.8	0.0009	0.406
ab	+1	+1	70	926.8	0.0014	0.441
$-\sim_a$	–1.414	0	10	750	0.0002	0.497
$+\sim_a$	+1.414	0	80	750	0.0019	0.447
$-\sim_b$	0	–1.414	45	500	0.0003	0.474
$+\sim_b$	0	+1.414	45	1000	0.0014	0.490
zero	0	0	45	750	0.0011	0.528
zero	0	0	45	750	0.0012	0.475
zero	0	0	45	750	0.0012	0.586
zero	0	0	45	750	0.0011	0.552
zero	0	0	45	750	0.0010	0.496

Analysis of Variance (ANOVA)

ANOVA is performed to evaluate the relative importance of the factors and the error variance (Madhav, 1989). The results of the ANOVA are shown in Table 4 below. The P-value for the model and F statistic in the ANOVA indicates that there is a difference in the mean percentage increase in wear between the two factors. The P-value is the probability that the test statistic will take on a value that is at least as extreme as the observed value of the statistic. Once the P-value is known, it is easy to determine how significant the data are without the data analyst formally imposing a preselected level of significance.

Statistically, there is a tool which provides a decision at some confidence level as to whether these estimates are significantly different. This tool is called an F-test, named

Table 4: ANOVA-General Linear Model

General Linear Model: Wear versus Load, Time

Factor Type Levels Values

Analysis of Variance for wear, gms, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Load	1	0.0000014	0.0000014	0.0000014	26.11	0.001
Time	1	0.0000009	0.0000009	0.0000009	17.11	0.003
Load*time	1	0.0000000	0.0000000	0.0000000	0.00	1.000
Error	9	0.0000005	0.0000005	0.0000001		
Total	12	0.0000029				

S = 0.000235537   R-Sq = 82.76%   R-Sq (adj) = 77.02%

Term	Coef	SE Coef	T	P
Constant	0.000985	0.000065	15.07	0.000
Load	0.000426	0.000083	5.11	0.001
Time	0.000344	0.000083	4.14	0.003
Load*time	0.000000	0.000118	0.00	1.000

Unusual Observations for wear, gms

Obs	wear, gms	Fit	SE Fit	Residual	St Resid
4	0.001400	0.001755	0.000179	-0.000355	-2.31 R

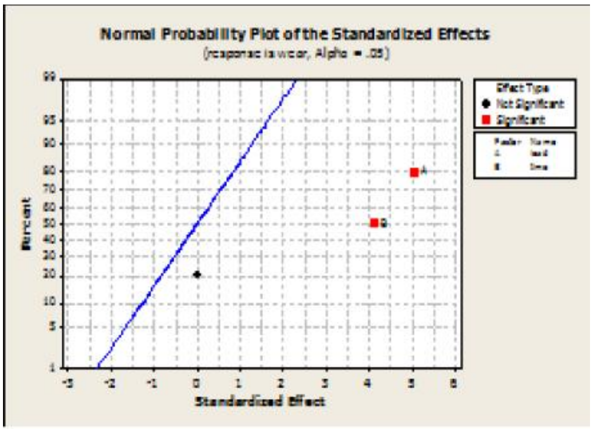
R denotes an observation with a large standardized residual.

after Sir Roland Fisher. Each combination of confidence, numerator degrees of freedom and denominator degrees of freedom has an F-ratio associated with it. *F*~, *v*1, *v*2 is the format for determining an explicit F-value (Philip, 1995). Using ~ = 0.05, the critical value of F for load and time is F0.05, 1, 9 = 5.12. Because 26.11>5.12 and 17.11>5.12, it concludes that the factors load and time significantly affects the wear. The P-value is considered for determining the significant factors. The values of P less than 0.050 indicate model terms are significant. In this case factors X_1 (load) and X_2 (Time) are significant model terms, the AB (load-time) interaction value greater than 0.050 indicates insignificant model terms.

In addition to the basic analysis of variance, the program displays some additional useful information. The quantity "R-squared" explains about 82.76% of the variability in wear. The "adjusted" R2 is a variation of the ordinary R2 statistic that reflects the number of factors in the model. The "predicted R-squared" of 0.8276 is in reasonable agreement with the "adjusted R-squared" of 0.7702. Clearly, it must have 0 < R2 < 1, with larger values being more desirable (Douglas, 2010).

The normal probability plot of these effects is shown in Figure 4. All of the effects that lie along the line are negligible, whereas the large effects are far from the line. The significant effects that emerge from this analysis are the main effects A (load) and B (time) and the interaction AB.

Figure 4: Normal Probability Plot of Standardized Effects



The effects of the factors are defined to be the change in response produced by the change in the level of factor. This is frequently called a main effect because it refers to the primary factors of interest in the experiment.

To assist practical interpretation of this experiment, Figure 5a presents plots of the two main effects load and time and the AB (load-time) interactions shown in Figure 5b. The main effect plots are just graphs of the marginal response averages at the levels of the two factors. Notice that all two variables have positive main effects; that is, increasing the

Figure 5a: Main Effect Plot

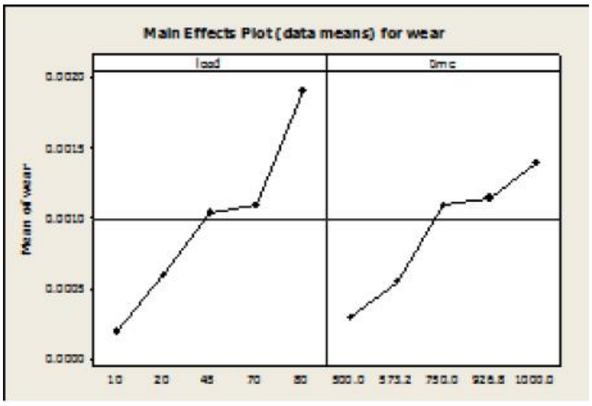


Figure 6a: Surface Plot

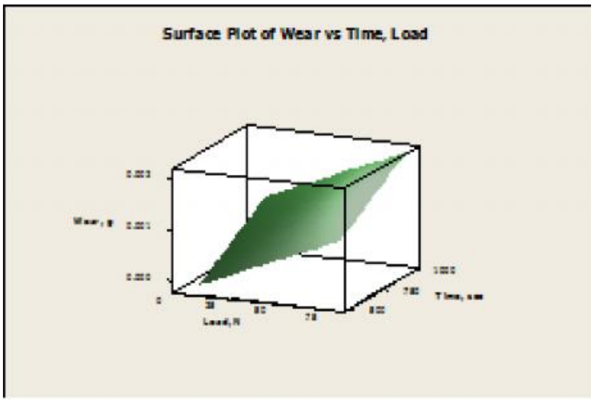


Figure 5b: Interaction Plot

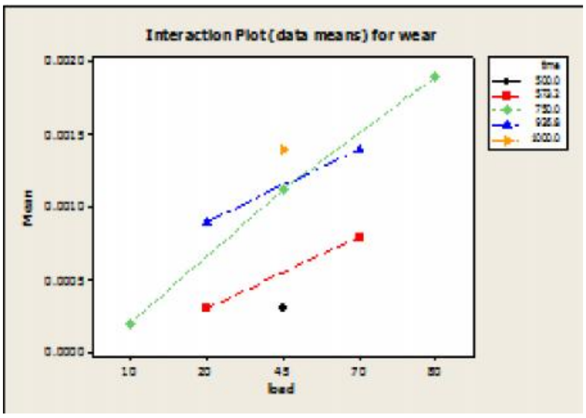
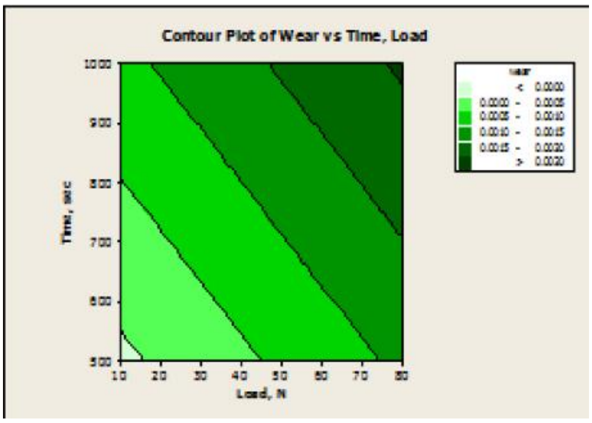


Figure 6b: Contour Plot



variable moves the average deviation from the fill target upwards.

In Figure 6a shows a plot of the plane of wear generated by the various combinations of load and time. This three dimensional graph is called a response surface plot. Figure 6b shows the contour lines of the constant response wear in the load and time plane. Notice that because the response surface is a plane, the contour plot contains parallel straight lines.

Frequently, the initial estimates of the optimum operating conditions for the system will be far from the actual optimum. In such circumstances, the objective is to move rapidly to the general vicinity of the optimum. It is usually assume that a first order model is an adequate approximation to the true surface in a small region of the wear. The method of steepest ascent is a procedure for moving sequentially in the direction of the maximum increase in the response.

Results and Analysis of ABS Under Lubrication Condition

The tests were carried out under lubricating condition by using SAE 10 W oil. Sufficient amount of oil was maintained during the test for oil to remain continuously in contact with the specimen and the disc surface (George, 2005; and Scientific Journal of Riga Technical University, 2010). CCD experimental plan and the wear test results of pure ABS under lubricated conditions are provided in Table 5.

Table 5: CCD Experimental Plan and the Wear Test Results of ABS Under Lubrication Condition

tc	Coded Variables		Natural Variables		Responses	
	A	B	Load, N	Time, sec	Wear, g	COF
1	–1	–1	20	573.2	0.0001	0.169
a	+1	–1	70	573.2	0.0005	0.198
b	–1	+1	20	926.8	0.0004	0.202
ab	+1	+1	70	926.8	0.0007	0.166
$-\sim_a$	–1.414	0	10	750	0.0001	0.153
$+\sim_a$	+1.414	0	80	750	0.0011	0.180
$-\sim_b$	0	–1.414	45	500	0.0002	0.156
$+\sim_b$	0	+1.414	45	1000	0.0009	0.199
zero	0	0	45	750	0.0004	0.152
zero	0	0	45	750	0.0003	0.211
zero	0	0	45	750	0.0004	0.174
zero	0	0	45	750	0.0005	0.180
zero	0	0	45	750	0.0003	0.151

Analysis of Variance (ANOVA)

The ANOVA are summarized in Table 6. It can be seen that the percentage of load and time significantly affect the wear. Using ~ = 0.05, the critical value of F for load and time is F0.05, 1, 9 = 5.12. Because 23.54 > 5.12 and 11.69>5.12. The values of P less than 0.050 indicate model terms are significant. In this case factors A (load) and B (Time) are significant model terms, but the AB (load-time) interaction value greater than 0.050 indicates insignificant model terms.

In addition to the basic analysis of variance, the program displays some additional useful

Table 6: ANOVA-General Linear Model

General Linear Model: Wear versus Load, Time

```
Factor Type Levels Values

Analysis of Variance for wear, using Adjusted SS for Tests

Source      DF    Seq SS     Adj SS     Adj MS      F      P
Load         1  0.0000006  0.0000006  0.0000006  23.54  0.001
Time         1  0.0000003  0.0000003  0.0000003  11.69  0.008
Load*Time    1  0.0000000  0.0000000  0.0000000   0.11  0.753
Error        9  0.0000002  0.0000002  0.0000000
Total       12  0.0000011


S = 0.000154063   R-Sq = 79.70%   R-Sq(adj) = 72.93%

Term            Coef    SE Coef      T      P
Constant     0.000454  0.000043  10.62  0.000
Load         0.000264  0.000054   4.85  0.001
Time         0.000186  0.000054   3.42  0.008
Load*Time   -0.000025  0.000077  -0.32  0.753

Unusual Observations for wear

Obs     wear       Fit     SE Fit   Residual  St Resid
  6  0.001100  0.000828  0.000088  0.000272     2.16 R

R denotes an observation with a large standardized residual.
```

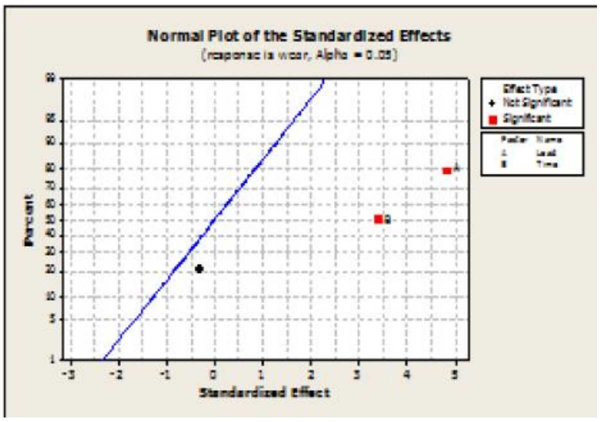
information. The quantity "R-squared" explains about 79.70% of the variability in wear. Clearly, it must have 0 ≤ R2 ≤ 1, with larger values being more desirable. The "adjusted" R2 is a variation of the ordinary R2 statistic that reflects the number of factors in the model. The "predicted R-Squared" of 0.7970 is in reasonable agreement with the "adjusted R-squared" of 0.7293.

The normal probability plot of these effects is shown in Figure 7. All of the effects that lie along the line are negligible, whereas the large effects are far from the line. The important effects that emerge from this analysis are the main effects A (load) and B (time) and the interaction AB.

Figure 8a presents plots of two main effects and the (load-time) interaction. The main effect plots are just graphs of the marginal response averages at the levels of the two factors.

Notice that all two variables have positive main effects; that is, increasing the variables

Figure 7: Normal Probability Plot of Standardized Effects



moves the average deviation from the mean. The interaction between the load and time is fairly small, as shown the shape of the three curves in below Figure 8b.

Figure 8a: Main Effect Plot

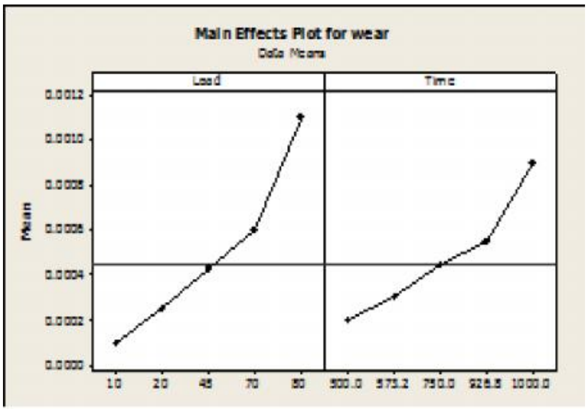
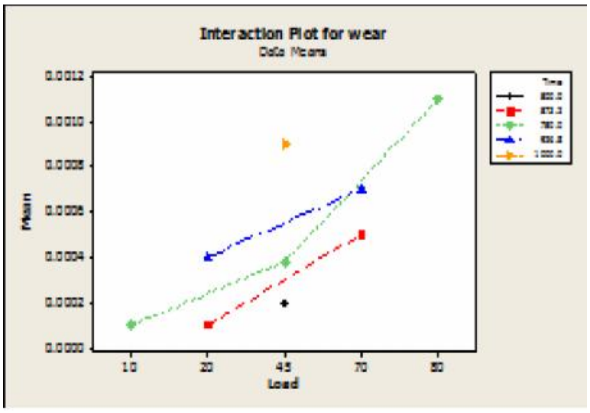


Figure 8b: Interaction Plot



In Figure 9a, plots of the plane of wear values generated by the various combinations of load and time. This three dimensional graph is called a response surface plot. Figure 9b shows the contour lines of constant response wear in the load and time plane. Notice that because the response surface is a plane, the contour plot contains parallel straight lines. Examination of this response surface indicates that maximum wear of 0.0011 gm is achieved around 80 N loads and time of 750 sec.

Figure 9a: Surface Plot

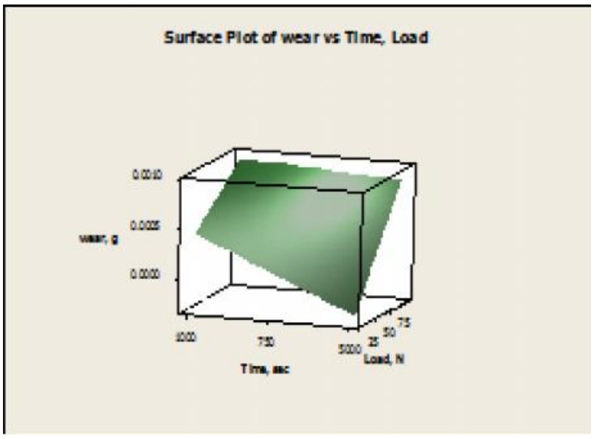
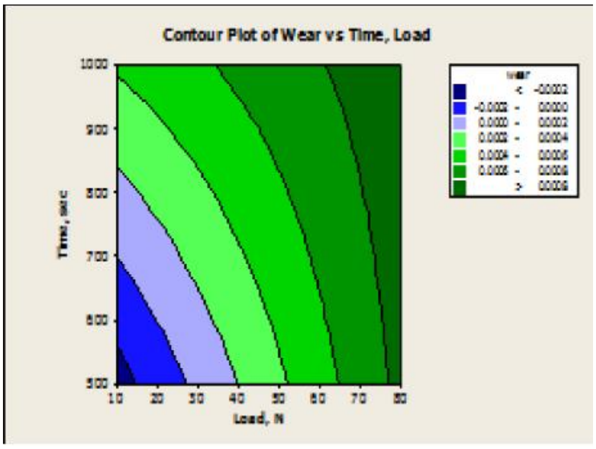


Figure 9b: Contour Plot



COMPARATIVE STUDY

A comparative study of ABS has been taken for both dry and lubricating conditions. Wear failure of polymers is controlled by a number of factors, which include sliding speed, normal load co-efficient of friction, adhesive property of the transfer film and thermal properties of polymers. Comparative study of pure ABS under dry sliding and lubricating conditions are discussed here.

Effect of Friction and Wear of Pure ABS by Varying Load

Effect of friction and wear of pure ABS by varying load under dry sliding and lubricating conditions are illustrated in Figures 10a and 10b. Polymers in the presence of lubricant molecules, plasticize, which reduce friction, but wear can be high because of the decrease in the mechanical strength of the polymer due to plasticization (Sinha, 2002). The impact of these interactions on the mechanical properties and failure of an affected polymer are many. One effect can be plasticization of the polymer by the adsorbed chemical. Plasticization of a polymer can result in the polymer being transformed from a rigid, glassy material to a soft flexible material (Donald, 2002).

Figure 10a gives an idea about the wear behavior of pure ABS under dry sliding and lubricating conditions. From the above figure it is obvious that the wear under lubricating is less as compared to dry sliding condition. Pure ABS exhibits superior wear properties in lubricating condition than in dry sliding condition.

Figure 10b confirms the variation of the co-efficient of friction with load at constant velocity.

Figure 10a: Wear of ABS Under Dry Sliding and Lubricating Conditions

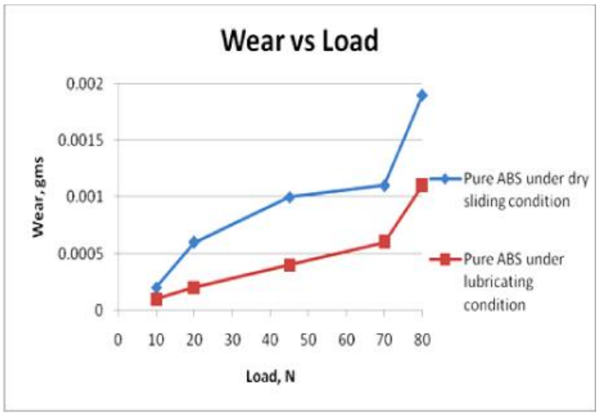
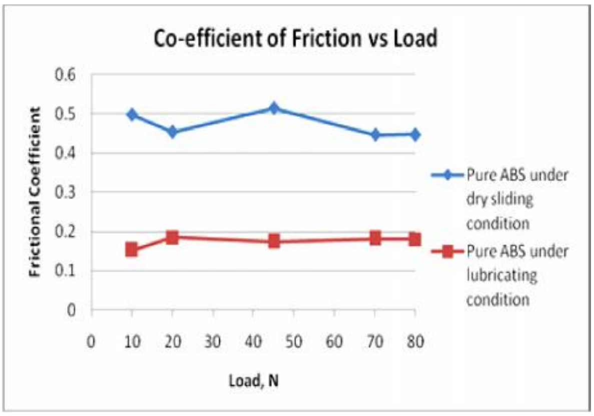


Figure 10b: Co-efficient of Friction of ABS Under Dry Sliding and Lubricating Conditions



From the above graph it is clear that, pure ABS has the minimum value of co-efficient of friction is observed in oil lubricated condition. This is due to lubricant interacts with polymer molecules and forms a chemically bonded monolayer on the outer surface of the polymer. This can drastically reduce the co-efficient of friction when the polymer slides against a hard surface.

CONCLUSION

The experimental and statistical analysis are carried out for the friction and wear behavior of under dry sliding and lubricating conditions leads to the following conclusions.

Pure ABS exhibits superior wear properties in lubricating condition than in dry sliding condition and the co-efficient of friction of pure ABS has minimum under lubricating condition and it remains constant at higher loads.

Besides this study concerning the influence of characteristic properties of ABS, these investigations will not only help in understanding friction and wear behavior but also assist in design and fabrication of materials for tribological applications based on ABS.

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