The Investigation into Tribological Properties of Carbon Fiber Reinforced Composite

by

Mohd Nurhadi bin Arifin

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

DECEMBER 2008

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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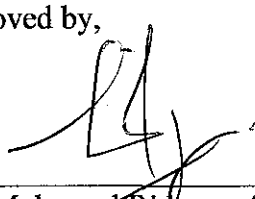
Approved by,



(Mr. Muhamad Ridzuan Abdul Latif)

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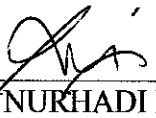
TRONOH, PERAK

December 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.



MOHD NURHADI BIN ARIFIN

ABSTRACT

Carbon fiber reinforced composites can be considered as a good candidate material for tribological applications because of their complex interwoven nature of the fiber that makes it difficult to break. Since this advanced composite are relatively new in tribological applications, studies need to be done to discover its friction and wear properties. The main purpose of doing this research is to investigate the friction and wear properties of carbon fiber reinforced composite. The samples of this composite were prepared from carbon fiber prepreg. Tests have been conducted to evaluate the friction and wear behaviour of the composite. The first test conducted was the hardness test using an Indentec 9150 LKV hardness testing machine. Wear tests were conducted using a TABER® 5131 Abraser. The purpose of doing this test was to evaluate the resistance of surface to abrasive wear. Before and after the test, the surface roughness of the composite was measured using a Perthometer Concept. The adhesive wear mode of the composite was also tested by using a Ducom® Multispecimen Tester. Finally, the studies on worn surface topography were done using a Scanning Electron Microscope (SEM) to understand its wear mechanisms. Based on the results obtained, the woven reinforcement composite proved to be better in performance for both abrasive and adhesive wear.

ACKNOWLEDGEMENTS

First and foremost, thank god for His grace and mercy throughout the progress of this Final Year Project. I would like to acknowledge my family for always being there to provide financial and moral support. I would also like to take this exceptional opportunity to honorably thank my Final Year Project supervisors, Mr. Muhamad Ridzuan Abdul Latif and Assoc. Prof. Dr Mustafar bin Sudin for giving me their personal time every week in the effort to further educate and guide me on the project undertaken while contributing reading materials which serves as reference They also introduced me the aspects needed to do my FYP and the methods which are to be used to analyze the project so that the needed result can be obtained. Besides, I would also like to express my special thanks to the lecturers and others who have directly and indirectly contributed to the project by giving valuable information on how to conduct and improve the project. Without such assistance from these people, this Final Year Project might not be as successful as it is.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Advanced polymer composites are generally understood to be materials consisting of a polymer matrix reinforced with high-strength continuous fibers of a predefined orientation. The reinforcements are typically fibers, particles or flakes. The matrix in most common cases is a resin system or adhesive that binds the reinforcements together. The reinforcement material and the matrix are combined at a macroscopic level where the reinforcement is immersed in the matrix. The two materials bond conjointly to make one system that is commonly referred to as a composite [1]. Depending on the orientation of the fiber, the composite can be stronger in a certain direction or equally strong in all directions. The complex interwoven nature of the fiber makes it very difficult to break. Therefore, they are considered to be good candidate materials for tribological applications; from sporting equipment to aircrafts components [2]. Since advanced composites are still new in tribological applications, studies need to be done to discover its friction and wear properties. In this research, the focus is on studying the tribological properties of carbon fiber reinforced composite with the fiber types as the variable parameters.

1.2 Problem Statement

Although the carbon fiber reinforced composite have been used in some tribological applications, the understanding of their friction and wear behavior is very limited. Very few studies on the tribological behavior of this composite have been published. Recently, the friction and wear behavior of this composite based on fiber types and orientation are still being studied to discover the optimum composite structure that can be designed for high performance product. This is important because every type

and orientation of carbon fiber will give different impact to the tribological properties of this composite [2].

1.3 Significance of Study

On completing the experiment, the final data will enable the friction and wear behavior of the composite based on their fiber types to be analyzed and understood. This information can be used as a guideline for choosing an optimum fiber type according to tribological application requirement. Other than that, durability of the composite when exposed to wear and friction can be identified.

1.4 Objective

The main objective of this research is to analyze the friction and wear properties of the carbon fiber reinforced composite that are affected by the fiber types. This objective will be accomplished by conducting tribological tests for the samples of carbon fiber reinforced composite by using TABER® 5131 Abraser, TABER® Linear Abraser and DUCOM® Multi Specimen Tester. The other objective is to produce experimental data which can be used as a guideline for choosing an optimum fiber type for tribological applications of the composite.

1.5 Scope of Study

The scope of study for this project is related to the tribological properties of carbon fiber reinforced composite focusing on fiber types. After all the information related to this project was gathered, some samples from carbon fiber prepreg with variable fiber types were prepared. Then, tribological tests will be conducted on those samples at UTP laboratory.

After completing the tests, the optimum type of the fiber for tribological application will be identified. Comparison of wear rate between each fiber types will be done in order to study their tribological properties. The microstructure of the samples before and after testing will be analyzed to know their surface characteristics. The coefficient of friction for the composite also will be determined.

Finally, complete research information will be gathered based on the findings during the tests. Data that relate the fiber fabric with their friction and wear properties will be recorded properly for future references.

CHAPTER 2
LITERATURE REVIEW

2.1 Carbon Fiber Reinforced Composite

Carbon fiber reinforced composite materials can be divided into two main categories normally referred to as short fiber reinforced materials and continuous fiber reinforced materials. Continuous reinforced materials will often constitute a layered or laminated structure. The woven and continuous fiber styles are typically available in a variety of forms. They can be pre-impregnated with the given matrix (prepreg), dry, unidirectional tapes of various widths, plain weave, harness satins, braided, or stitched. The short and long fibers are typically employed in compression molding and sheet molding operations. These come in the form of flakes, chips, and random mate [2].

The main purpose of the reinforcement is to provide superior levels of strength and stiffness to the composite. In a continuous fiber reinforced composite, the fibers provide virtually the entire strength and stiffness. Each layer or "ply" of a continuous fiber composite typically has a specific fiber orientation direction. These layers can be stacked such that each layer has a specified fiber orientation, thereby giving the entire laminated stack highly tailorable overall properties [2].

The role of the matrix is to support the fibers and bond them together in the composite material. It transfers any applied loads to the fibers, keeps the fibers in their position and chosen orientation. The matrix also gives the composite environmental resistance and determines the maximum service temperature of the composite [2].

2.2 Carbon Fiber

The search for advanced fibers led to the development of carbon and graphite fibers. These fibers are currently the best known and most widely utilized in high performance resin base composites. Primarily developed for military aerospace applications, these materials have found wide-spread commercial and industrial applications. This situation has resulted in the availability of a wide variety of fibers having various levels of engineering properties at costs once thought unachievable. These materials are now available on a world wide basis at competitive prices and are now experiencing increasing levels of interest for applications such as commercial aerospace, ground transportation and the infrastructure. The production of carbon/graphite fibers is well suited to large scale continuous operation where economies of scale operate effectively and the stability of operating conditions provides a narrow band of fiber mechanical properties. Carbon fibers are produced commercially by the thermal decomposition of organic precursor fibers such as rayon or polyacrylonitrile (PAN). The process involves highly controlled steps including heat treatment and tension, to transform the organic precursor into a highly ordered carbon or graphitic structure. Carbon and graphite fibers are also produced from pitch base precursor materials. Although the potential for low cost exists, complex processing steps involved in the pitch treatment have prevented the production of really low cost fibers. US manufactured pitch base carbon and graphite fibers while having a very high modulus, up to 830GPa (120 x 106psi), have demonstrated low tensile properties and thus have not been seriously considered for high performance structural applications. The new high strength, high modulus carbon fibers have smaller diameters thus requiring higher levels of support from the resin under compression loading [3].

2.3 Epoxy Resin

Nowadays, epoxy resins are used far more than all other matrices in advanced composite materials [3]. In chemistry, epoxy or polyepoxide is a thermosetting epoxide polymer that cures (polymerizes and crosslinks) when mixed with a catalyzing agent or "hardener". Most common epoxy resins are produced from a reaction between epichlorohydrin and bisphenol-A. Although epoxies are sensitive to moisture in both their cured and uncured states, they are generally superior to

polyesters in resisting moisture and other environmental influences. They also offer lower cure shrinkage and better mechanical properties. Even though the elongation-to-failure of most cured epoxy is relatively low, for many applications epoxies provide an almost unbeatable combination of handling characteristics, processing, flexibility, composite mechanical properties, and acceptable cost [3]. **Figure 1** below shows the different matrices which are compared in terms of temperature and mechanical performance.

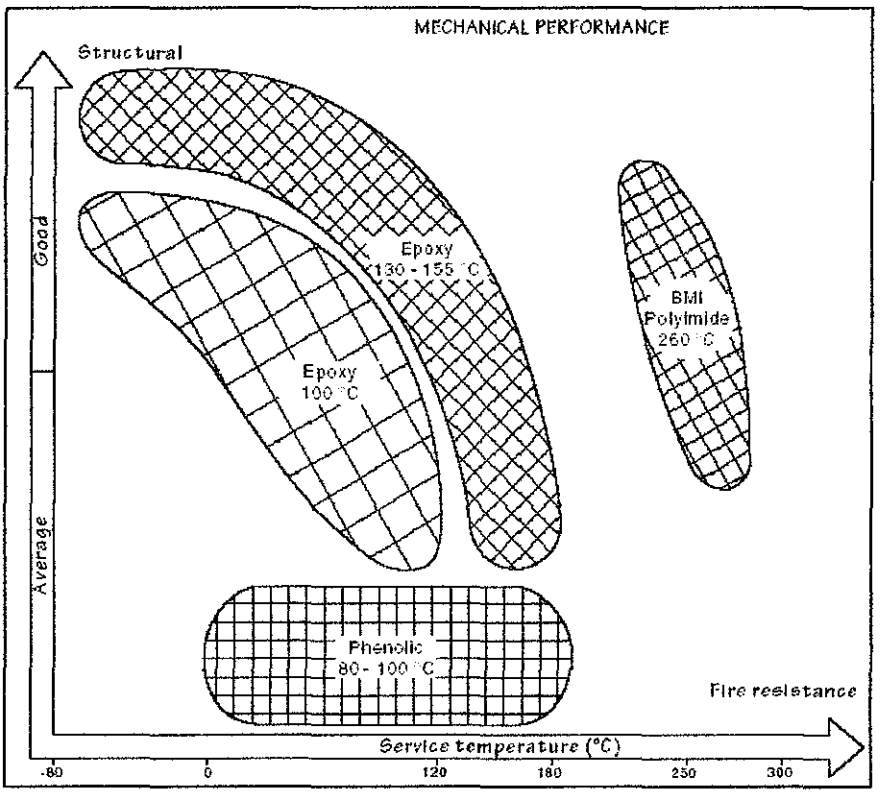


Figure 1 Temperature & mechanical performance for different matrices [4].

2.4 Basic Concept of Prepreg

The form of carbon fiber composite that used in this research is prepreg (refer to APPENDIX F). Prepreg is ready-to-mold or –cure material in sheet form which may be fiber, cloth, or mat impregnated with resin. It have very precisely controlled fiber-resin ratios, highly controlled tack and drape, controlled resin flow during the cure process, and, in some processes, better control of fiber angle and placement [3].

2.5 Prepreg Types

In market today, prepreg are available in two forms which are unidirectional (UD) and woven which is shown in **Figure 2** [4].

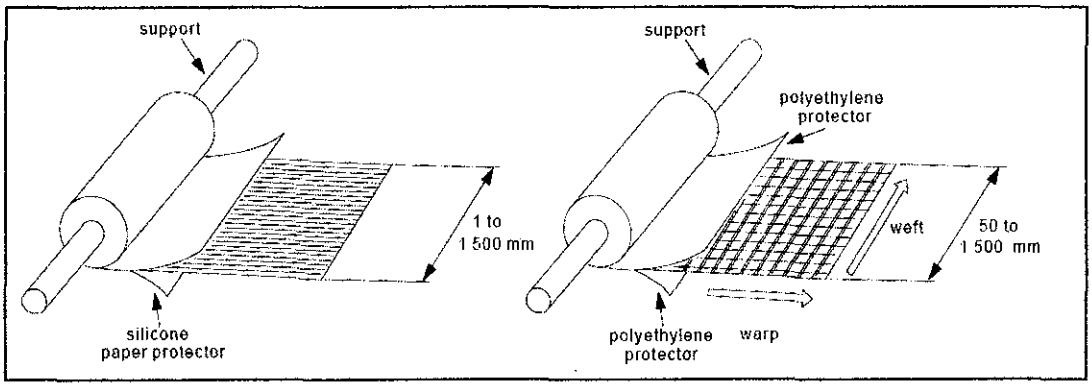
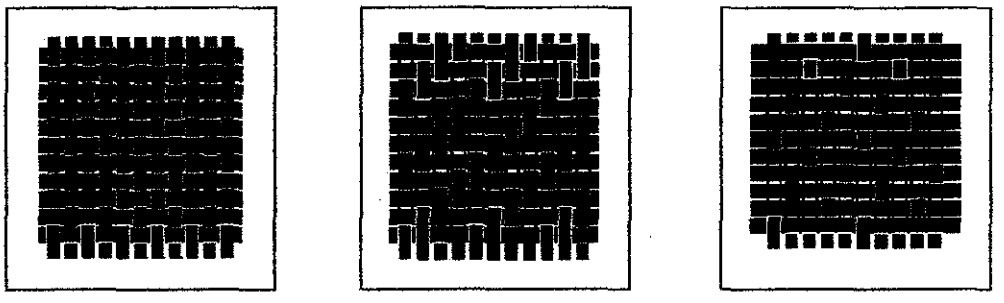


Figure 2 Prepreg Forms (UD & Woven) [4].

2.5.1 Woven Carbon

Woven carbon is a fabric introduced in recent years which has become an excellent alternative to fiberglass and Kevlar - only mils thick with great strength. The thickness of a woven carbon ply is approximately 0.324mm. In addition to its great strength, carbon fabric also has very low density and is very stiff. Although it is quite costly, the material saving is appreciable since only one course of carbon is required for 3 or 4 of fiberglass. It cuts considerably easier than Kevlar. Carbon prepregs, which are standard carbon weaves impregnated with either polyester or epoxy resins, have been used by major manufacturers to cut production time on composite parts. The required equipment and precise production controls for proper cure of prepregs make them difficult to adapt to homebuilt applications. The excellent qualities of the carbon fabric itself give it an immediate waiting market in the aircraft building field. Carbon fabric is available in the three different main styles as shown in **Figure 3.**



(a) (b) (c)

Figure 3 (a) Plain Style, (b) Twill Style & (c) Satin Style [5].

2.5.2 Carbon UD

The construction of carbon fiber in UD form is such that the fibers are oriented in a straight or linear manner with no twist and are able to be maintained in that condition while being impregnated by hand. The fabric is formed from rovings or "tows" of fibers similar to that used in making woven fabric. These fibers are locked into position by very fine fill (or cross machine direction) fibers which are encapsulated with an adhesive which is compatible with common impregnating resins. These fill fibers and the encapsulating adhesive will be visible in any clear resin. The resulting "pattern" is normal and should not be interpreted as poor wet-out of the reinforcing fibers [5]. The thickness of a UD ply is approximately 0.138mm.

2.6 Tribology

Tribolgy, which focuses on friction, wear and lubrication of interacting surfaces in relative motion, is a new field of science defined in 1967 by a committee of the Organization for Economic Cooperation and Development. 'Tribology' is derived from the Greek word 'tribos' meaning rubbing or sliding. After an initial period of skepticism, as is inevitable for any newly introduced word or concept, the word 'tribology' has gained gradual acceptance. As the word tribology is relatively new, its meaning is still unclear to the wider community and humorous comparisons with tribes or tribolites tend to persist as soon as the word 'tribology' is mentioned [6].

2.7 Friction

The force of friction or drag experienced when one solid body slides over another have its source in the same real contact areas associated with wear. When high spots contact and deform under localized contact stress these junctions resist tangential motion either by shearing of the junction or ploughing of a hard asperity through a softer surface. The frictional force resulting is a measure of the shear strength of the contact junctions. As sliding progresses, a steady frictional force is maintained by making and shearing many tiny cold welds between the surfaces [7].

It has long been known that the friction force of solids is proportional to normal load and independent of the apparent area of contact. Leonardo da Vinci demonstrated in the fifteenth century that a rectangular wooden block would slide down a ramp with the same friction force no matter whether it stood on end or on its broadest face. Modern friction theory is based on the principle that true area of contact increases proportionally with- load and that friction force is proportional to load and to the true area of contact (shear area). If friction is proportional to the area of junctions being sheared the following simple relation can be assumed [7].

$$F = SA$$

where

F = friction force,

A = true area of contact,

S = shear strength of the junction interface or the weaker of the two constituents of the junction,

The adhesion theory for friction assumes that at contact junctions adhesion occurs and friction forces are the sum of forces to shear each junction. It can be shown that the real area of contact is inversely proportional to the hardness of the softer material and proportional to the normal load [7].

$$A = W/P$$

where

A = true area of contact,

W = normal load,

P = indentation hardness,

The previous equation can be combined with the following

$$F = SW/P$$

or

$$F/W = S/P$$

and

$$F/W = \mu \text{ or coefficient of friction.}$$

The above simple relation shows analytically that the coefficient of friction is proportional to shear strength at the junction of the softer member of the junction, inversely proportional to the hardness of the softer material and is independent of area. This is a useful set of principles to keep in mind when confronting the complexities of friction phenomena in real life. It turns out that one of the factors S is difficult to define and accounts for wide variations in friction levels for the same material combinations [7].

If one considers closely the meaning of the terms in the equation $\mu = S/P$ something of an anomaly shows up. This is because the equation seems to imply that in order to have low friction, the rubbing materials must be hard and have low shear strength [7].

The junction shear strength S probably represents a complex term not just associated with the yield properties of the weaker member of a sliding pair. If a friction-adhesive junction is weak and shearing takes place at the interface and not through subsurface material, the condition of the surface has a decided effect on the friction level. There

are many ways of weakening the junction interface in fact; a "natural" surface is so contaminated with adsorbed gases and solids that contact in air environment generally involves poor adhesive junctions [7].

2.8 Wear

Wear is the consequence of the way in which surfaces come into contact. The process begins at highly stressed localized contact points. It is at these concentrated contacts that fracture, shearing, or flow takes place and a minute piece of the surface is separated to become debris. The process is complex and can follow several mechanisms depending on the composition and properties of the surface, surrounding environment, and forces involved. In general, what takes place is microscopic in scale and statistical in nature. There are a number of general wear processes that have identifying characteristics so that they can be classified [7].

Adhesive Wear: Contacting asperities cold weld and shear off below the weld interface causing transfer of material from one surface to the other or the formation of wear particles about the size of the asperity contacts [7].

Abrasive Wear: Hard asperities or particles penetrate a softer surface and cut material out by a micromaching process [7].

Chemical Wear: Corrosion of a surface produces a product that is fractured and chipped off under the high localized stress at asperity contacts. Removal of the corrosion product destroys a protective layer and the corrosion process is speeded up. Wear debris is broken up corrosion product [7].

Galling Wear: A severe form of combined adhesive wear and abrasive wear in which a few strong adhesive junctions grow in size and remain junctions between the moving surfaces by a subsurface shear process. The junctions grow to visible size and eventually break, freeing a large work-hardened particle that can imbed in one surface and plough the mating surface. The result is a severely roughened surface and heavy wear rate [7].

Most real wear situations involve a combination of the above general classifications. However, in this research the wear mechanism is focusing on adhesive and abrasive wear [7].

2.8.1 Adhesive Wear

True adhesive wear is most often found in nonlubricated or dry contact conditions and mostly with metals. It is also more prevalent when the contacting surfaces are about the same hardness. Adhesive wear occurs in lubricated contact but on a much reduced scale. Adhesive wear is common in nonlubricated electrical contacts, product assembly conveyor systems bearings, and gears operating in space vacuum [7].

A simple mathematical model for adhesive wear has been developed and it is based on the assumption that wear occurs by shearing of the true contact area between two contacting surfaces and that the true contact area is a function of the contact stress yield point of the surface of the softer material (the mean contact yield stress is about 3X tensile yield point). Thus, the lower the yield point the larger the true area of contact for a given load and the larger the wear. Further, since each asperity contact during motion of the surfaces has a statistical probability of producing a wear particle, the wear is proportional to the total sliding distance. A simple equation has been derived on the basis of these assumptions where [7]

$$V = KLW/P_m$$

where

V = volume of wear;
L = distance slid;
W = load;
Pm = indentation yield point
K = wear constant

The implication here that wears is proportional to load and distance of sliding and inversely proportional to the hardness of the softer material has been verified experimentally. The principle that wear is proportional to load holds as long as the wear process is the same. Increasing the load to the point where the mode of surface

damage changes can be accompanied by an order of magnitude change in wear rate. The wear constant, K, has been interpreted as a measure of the probability of each asperity contact producing a wear particle. The wear constant is not universal for all materials but has a wide range covering several orders of magnitude [7].

2.8.2 Abrasive Wear

Abrasive wear is most prevalent when a hard and soft material combination exists or lubrication is present. Lubricants serve to reduce the strength of the junction between contacting asperities and reduce the level of adhesive wear in a sliding combination. One prevalent example of abrasive wear is the wear of magnetic recording heads by tape. The magnetic particles in the tape act as a very fine abrasive [7].

The contact condition in abrasive wear involves hard asperities penetrating the softer surface of the contacting pair. When one surface moves relative to the other, material is removed by cutting from the penetrating asperities. If the asperities are assumed to be conical in geometry, and volume removed a function of the V-shaped groove formed by ploughing the cone through soft material, the following equation can be derived analytically [7]:

$$V = K\left(\frac{2\cot\theta}{P_m}\right) WL$$

where

V = volume of wear;

L = distance of sliding;

W = load;

Pm = indentation yield point

K = wear constant

θ = cone angle

For abrasive wear, the wear varies inversely with the abraded material hardness and directly with distance traveled, load, and sharpness of the abrading asperities or particles. The asperities can be hard phases in the abrading surface, or abrasive

particles imbedded in the surface. Loose abrasive particles between the surfaces will cause very little wear unless they imbed in one or the other surfaces. The wear coefficient K is a factor related to the proportion of abrading asperities or particles that cut or remove material. In practice, for instance, measuring the abrasivity of abrasive cloths or papers, it is found that material removal is not a simple function of material hardness but depends on the relative hardness of the abrasive and abraded material [7].

Abrasive particle size and shape also influence wear. Above a critical diameter, wear is insensitive to particle size or cone diameter. Below this critical size, wear rate decreases with decreasing size. The critical size has been reported in the range of 50 - 1.50 p from experimental studies. The particular size depends on the mechanical properties of the abraded material and the geometry of abrading agents [7].

2.9 Wear Mechanism of UD and Woven Fiber

For the investigation into tribological properties of carbon fiber reinforced composite, fiber orientation play an important role. There are three major fiber orientations relative to the sliding interface. Shown in **Figure 4** are the fiber orientations that play the role in tribological application. They are parallel, anti-parallel and normal [6].

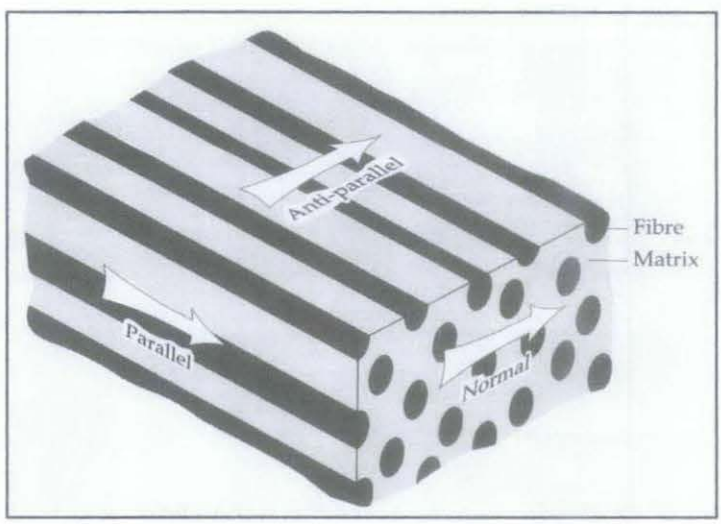


Figure 4 Orientation of Reinforcement Fibers to the Sliding Counterface

The wear mechanisms involved in this composite with the three different fiber orientations are similar but the process is different [6]. The wear process of the parallel and anti-parallel orientations is shown in **Figure 5**.

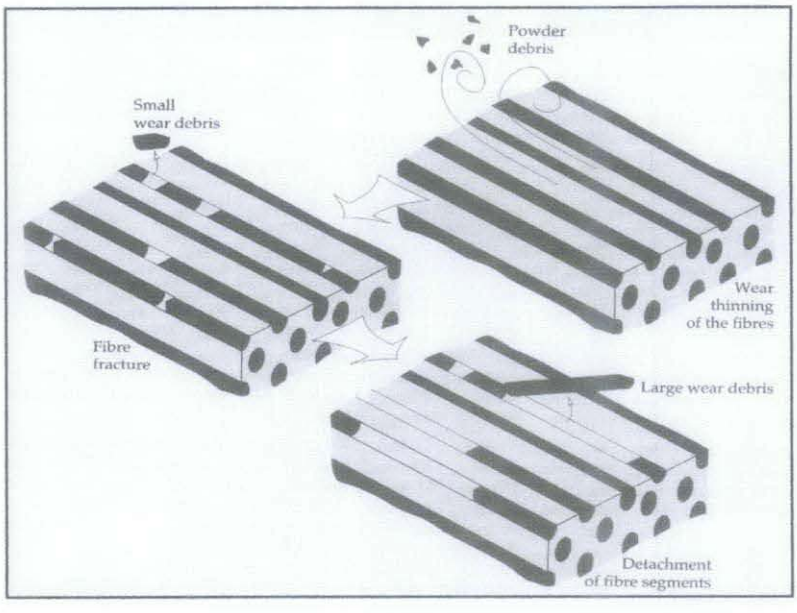


Figure 5 Wear Process of Parallel and Anti-Parallel Fiber Lays.

Wear of the matrix and fiber proceed at the same rate until the depth of about half of the fiber diameter is worn away and the fibers start to detach in short segments from the matrix.

It can be seen from **Figure 5** the wear debris originating from the fibers range from fine powder to complete segments of fiber as the wear proceeds. In contrast wear debris from the matrix tend to be uniformly fine. It is possible that a fine transfer film of the matrix polymer may cover the exposed fibers and reduce the overall coefficient of friction.

The wear mechanism of normally oriented fibers is different since partially worn fibers remain firmly attached in the matrix. During the process of wear the fibers are subjected to repeated bending which causes them to gradually debond from the matrix. A simultaneous process of cracking and fragmentation at the fiber ends allows material to be eventually released as wear debris [6]. The mechanism of wear through normal fiber orientation is schematically shown in **Figure 6**.

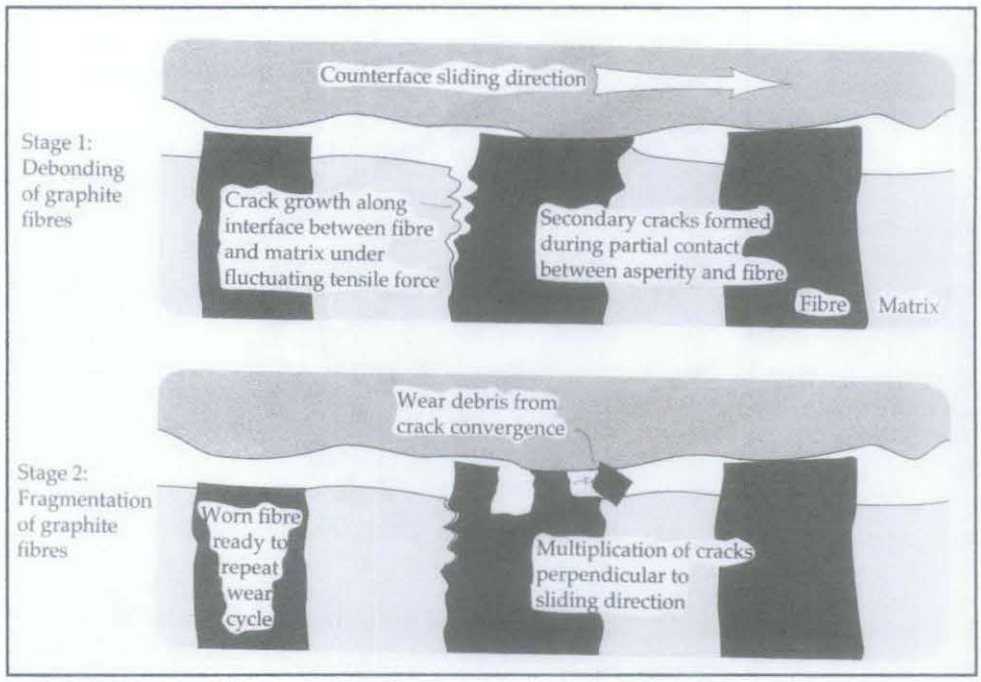


Figure 6 Mechanism of Wear Through Normal Fiber Orientation

Polymer composites with parallel fiber orientation are the most preferable followed by the anti-parallel types. Polymer composites with the normal fiber orientation give a low wear rate but at the risk of sudden seizure. The reason for this is that the exposed normal fibers tend to gouge into the counterface and initiate severe wear seizure.

Unidirectional and woven reinforcement do not offer dramatic improvements over chopped fiber reinforcement for wear against smooth steel counterfaces. Wear rates under these conditions are usually controlled by crack propagation between fibers and matrix. The woven or unidirectional reinforcements offer far more favorable crack propagation conditions than short chopped fibers where many crack are formed for each fiber segment. This result in rapidly wear by crack propagation to release wear particles. Woven fiber reinforcements, particularly made of tough materials, are useful in controlling abrasive wear. As mentioned already, brittle fibers cause rapid abrasive wear so the selection of fiber material is crucial to the characteristics of the composite [6].

2.10 Applicable ASTM Standards (G99 ASTM Standards)

2.10.1 Test Specimens and Sample Preparation

In this standard, the test method may be applied to variety of materials. The only requirement is that specimens having the specified dimensions can be prepared and that they will withstand the stresses imposed during the test without failure or excessive flexure. The materials being tested shall be described by dimensions, surface finish, material type, form, composition, microstructure, processing treatments, and indentation hardness (if appropriate). For the surface finish, a ground roughness of 0.8 μm (32 μin) arithmetic average or less is usually recommended. Care must be taken in surface preparation to avoid subsurface damage that alters the material significantly. Special surface preparation may be appropriate for some test programs [8].

2.10.2 Test Parameters

Table 1 below shows the test parameters that should be considered when using this standard.

Table 1 Description of Test Parameters for ASTM G99

Test Parameters	Description
Load	Values of the force in Newtons at the wearing contact.
Speed	The relative sliding speed between the contacting surfaces in meters per second.
Distance	The accumulated sliding distance in meters.
Temperature	The temperature of one or both specimens at locations close to the wearing contact.
Atmosphere	The atmosphere (laboratory air, relative humidity, argon, lubricant, etc.) surrounding the wearing contact.

2.11 Related Research Done

The influence of weave of carbon fabric in polyetherimide composites in various wear situations has been studied by Jayashree Bijwe and Rekha Rattan. They used the different weave styles which were plain, twill and satin as the variable parameter. In their research, three composites containing 55 volumes % of carbon fiber were fabricated by impregnation technique followed by compression molding. Based on their research, the twill weave proved to be the best for enhancing most of the mechanical properties of the composites followed by satin and plain. In case of tribo-performance, however, the role of weave varied with wear modes. No weave performed best or poorest in all wear modes.

CHAPTER 3

METHODOLOGY

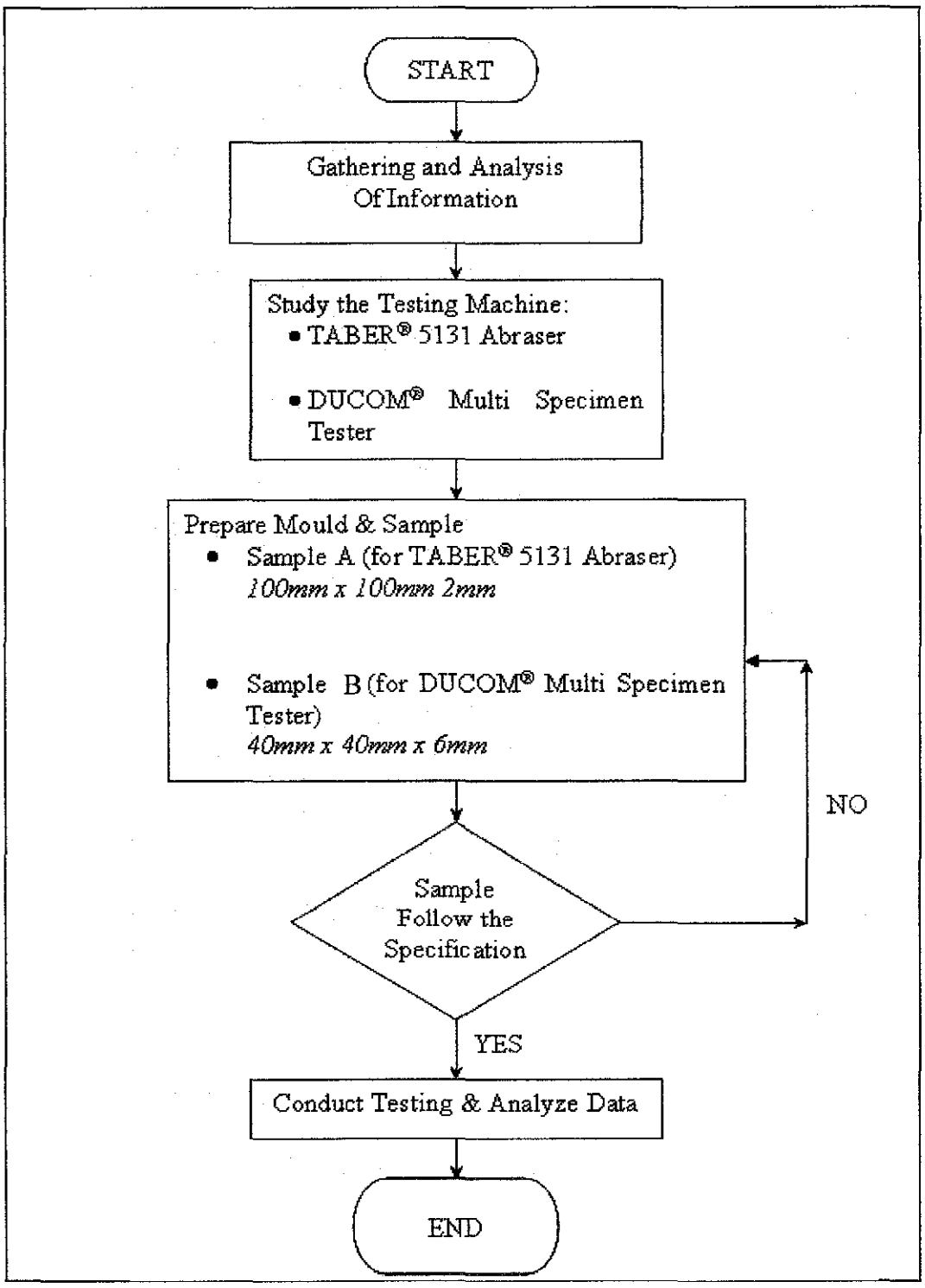


Figure 7 Final Year Project Process Flow

3.1 Gathering and Analysis of Information

Information gathering is made from various sources such as internet, books, journal, and also related personnel who are expert in this field. Internet and online journals give the general ideas about the carbon fiber reinforced composite development and the area of research done worldwide. Furthermore, the books borrowed from the Information Resource Centre helps to know the basic understanding the fundamentals of this composite.

3.2 Study the Testing Machine (TABER® 5131 Abraser, TABER® Linear Abraser & DUCOM® Multi Specimen Tester)

Before preparing the samples and conducting the tests, the features and mechanism of the testing machine need to be studied. The main purpose of doing this is to know how to operate the machine. Other than that, the ability and precision of the machine also can be determined.

3.2.1 TABER® 5131 Abraser

3.2.1.1 Description

The purpose of TABER® 5131 Abraser machine is to characterize rub-wear action which is produced by contact of the test sample, turning on a vertical axis, against the sliding rotation of two abrading wheels [9].

3.2.1.2 Operation

Up to ½" thick specimens can be mounted to a rotating turntable and subjected to the wearing action of two abrasive wheels, which are applied at a specific pressure. The wheels are driven by the sample in opposite directions about a horizontal axis displaced tangentially from the axis of the sample. One abrading wheel rubs the specimen outward toward the periphery and the other, inward toward the center. The resulting abrasion marks form a pattern of crossed arcs over an area approximately 30 cm^2 [9].

3.2.1.3 Specifications

The parameters for TABER® 5131 Abraser can be altered, which enables the user to determine the optimal setting for each product or material [9]. Shown in Table 4 below are the parameters and their description:

Table 2 Parameters for TABER® 5131 Abraser

Parameters	Description
Load	• Standard range includes 250g, 500g and 1000g • Optional counter weights increase range to 75g, 125g, 325g, 375g, 825g, and 875g.
Abradants	• Wide selection of Taber wheels available (resilient or vitrified) • Specialty wheels custom formulations.
Vacuum level	• Programmable from keypad • Adjustable vacuum nozzle clearance • Range from 50% to 100%
Test Duration	• Programmable up to 50,000 cycles
Conditions	• Wet or dry

3.2.2 DUCOM® Multi Specimen Tester

3.2.3.1 Description

The purpose of this multi specimen tester machine is to characterize friction and wear in sliding contact with variety of contact geometries. This equipment characterizes sliding contact between two materials over a wide range of test parameters. The contact could be in term of point, line or area. For the point contact, the test will be ball-on-balls or ball-on-disc while for the line contact; the test will be cylinder-on-disc. Lastly, for the area contact, the test will be pin-on-disc or washer-on-flat. In my research, the pin-on-disk method will be used to analyze the wear and friction characteristic of the carbon fiber reinforced composite [11].

3.2.3.2 Operation

A range of pin holder is available to hold various pin geometries. The pin holder will be attached on a rotating shaft. The sample will be put on the bottom of the pin and mounted. So that, the sample will be fix. It is pressed on to the rotating pin with test load. The frictional torque developed is measured with a torque cell. The main components of multi specimen tester are shown in Appendix D. Test load, speed of rotation, test duration and temperature can be varied. Test can be run either dry or lubricated. In my research, the test will be conducted in dry environment [11].

3.2.3.3 Specifications

When using this machine, user can set the parameters by key in the values. This enables the user to choose the optimal setting to test the sample [11]. **Table 6** below shows the parameters for the DUCOM® Multi Specimen Tester.

Table 3 Parameters for the DUCOM® Multi Specimen Tester.

Parameter	Unit	Min	Max	LeastCount	Remarks
Normal Load	N	5	1000	1	D,R
Frictional Torque	Nm	0	10	0.01	D,R
Shaft Speed	RPM	200	2000	1	D,R
Wear	micrometer	0	2000	1	D,R
Test Duration	Hours	0	9999	0.1	
Stage Temperature	° C	Ambient	120	1	PID controlled

3.3 Mould and Sample Preparation

During this stage, mould will be set up to prepare the samples that suite with the wear and friction testing machines at UTP laboratory. The samples must be prepared properly because it will affect the result of the tests. There are 5 processes in samples and mould preparation stage. This stage was done at Composite Technology research Malaysia Sdn Bhd (CTRM). **Figure 8** on the next page shows the process of preparing mould and sample.

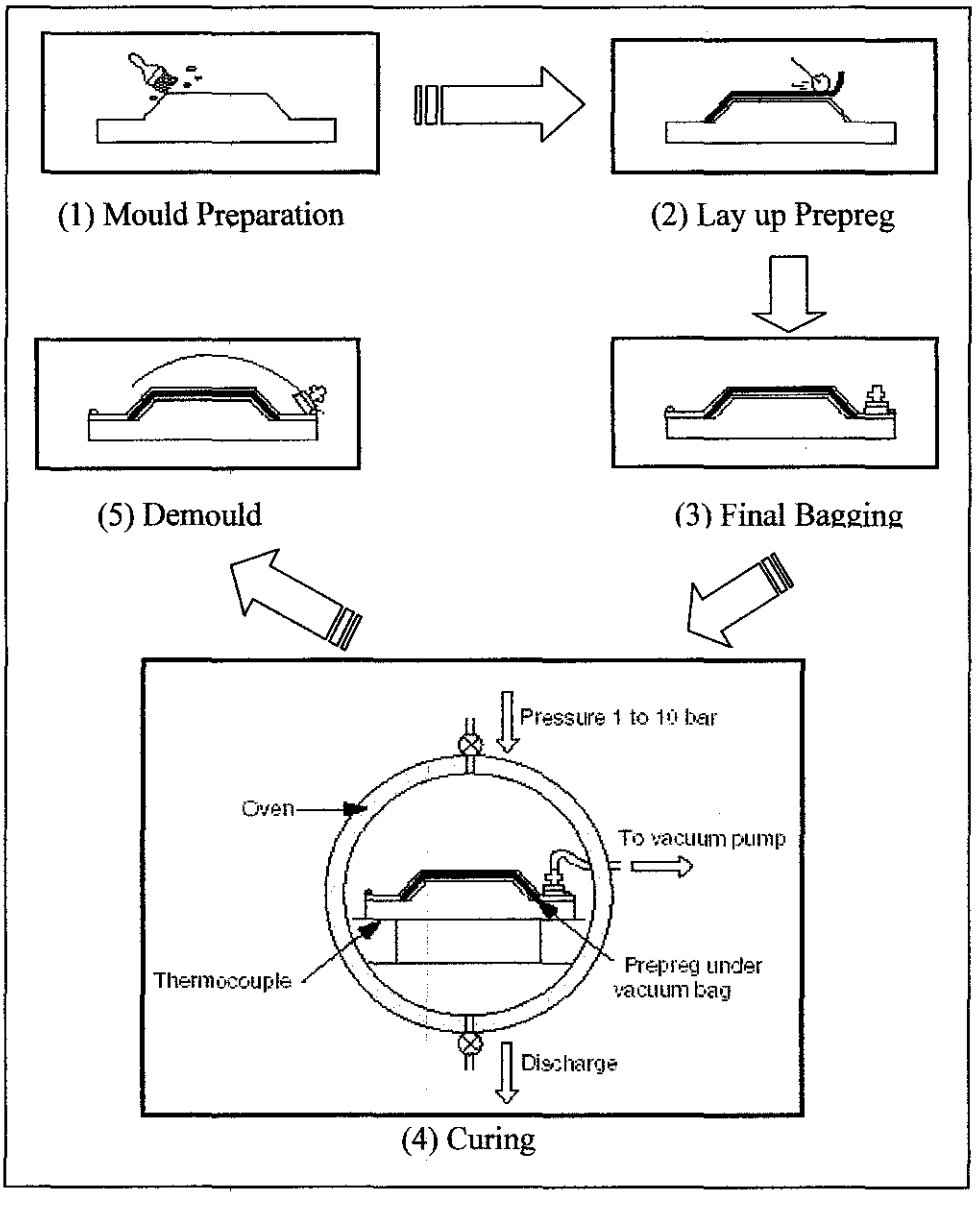


Figure 8 Steps for Sample and Mould Preparation

3.3.1 Mould Preparation and Application of Release Agent

Before using the mould, it must be prepared properly. The mould surface should be cleaned by wiping it with solvent and soaked clean cloths. If there is oxidation or dirt exists, which cannot be removed by this procedure, type S Scotch-Brite is used to sand gently. Once the mould surface is clean, the release agent is applied according to the specification for the material. Once the release agent is dry, the mould surface is rubbed with a white lint free cloth until all roughness and opaqueness disappears.

3.3.2 Lay up

Lay up is the main process for the sample preparation. First step of the process is removing the material from its bags and making visual inspection. The purpose is to make sure that the material is in good condition. Then, the separating backer's film needs to be removed and released in the warp or weft direction. This material must be handled carefully. The location of the plies should be placed properly on the mould, considering the warp direction and its face. After several plies have been laid up, debulk process is applied, where the plies are bagged under vacuum bag for several minutes to ensure the plies are consolidated well between each other. This is done several times during the lay up process.

3.3.3 Final Bagging (Debulking and Vacuum Bagging)

Before the samples are cured in the autoclave, they will go through a process called "final bagging". The purpose of this process is to ensure that the materials are properly bagged and debulked in order to eliminate air trap inside the samples. During the debulking process, the plies are hold in their position while squeezed into contact with the surface of the mould. The purpose of the debulking process is to consolidate all the plies that have been laid down and prevent wrinkles. So, the air trap between the plies can be removed.

3.3.4 Curing Process

Another important process is curing. During this process, composite panels are 'cooked' according to the required temperature and pressure for it to cure appropriately. This is commonly done in an autoclave. Each material has its own curing recipe which includes the period, temperature and pressure of the cure. After the autoclave is ready, the panel and mould will be placed inside the autoclave. The curing process will start after the autoclave's door is sealed properly and all safety measures have been taken.

3.3.5 Demould Process

After the panel has been cured, it will be demoulded to remove the panel from the mould. The demould process should be done carefully and without using any sharp tools because it can cause a permanent indentation to the mould. Normally after completing demould process, the mould will be cleaned and stored before it can be used again for the next manufacturing cycle.

3.4 Conduct Testing and Analyze Data

3.4.1 Hardness Test

A Rockwell hardness tester (Indentec 9150 LKV) was used to measure the hardness of each sample under a load of 60kg by using R scale (HRR). The diameter of the ball shaped indenter was 12.7 mm (1/2 inch). The Rockwell scale characterizes the indentation hardness of materials through the depth of penetration of an indenter under a major load on a material sample and compared to the penetration made by a minor load. [12]

In this test, eighteen samples were tested. The samples were categorized into two groups which are determined by the wear test that will be conducted next. For hardness test, sample A was divided into nine sub areas as shown in **Figure 9**. Each sub area was tested and one additional test is carried out at a random point on the sample. Finally, the arithmetic average was taken from each test as the final value. While, for sample B and C, each of them was divided into four sub area as shown in **Figure 9**. As for sample A, each sub area was tested and the arithmetic average was taken from each test as the final value. Then, the graph of the arithmetic average of the hardness for each test was plotted. This graph was plotted for each group of sample as shown in **Figure 11 and 12**.

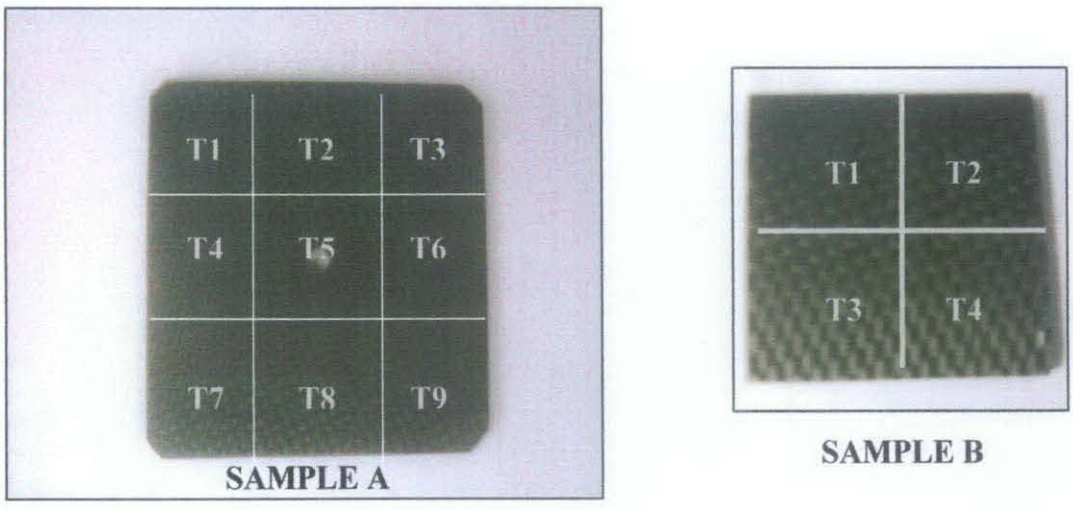


Figure 9 The Sub Area for Hardness Test of Sample A and Sample B

Below is the procedure for the hardness test:

1. Firstly, the power supply is switched ON. Then, the indenter is advanced to its forward position (nearest to operator).
2. The specimen is raised until its surface touch the indenter tip.
3. The specimen is brought into contact with the indenter to apply the pre-load. This is done by turning the hand wheel clockwise.
4. The pre-load position is indicated by a horizontal bar at the display board on control panel. It is in the correct position when the horizontal bar touched the end of the fixed bar.
5. Then, an audible bleep will be heard and vertical movement of the indenter should be stopped.
6. At the end of the load cycle, the hardness number will be displayed.
7. The hardness reading is recorded.
8. The specimen is released by turning the hand wheel counterclockwise.
9. For next reading the test is performed at different spot.

3.4.2 Abrasive Wear Test

A wear tester (Taber 5131 Digital Abrasers) was used to evaluate the resistance of the carbon fiber UD and woven reinforcement surfaces to rubbing abrasion. The abrasive test wheels that used in this test are H-18 Calibrade. This non-resilient, vitrified wheel of medium abrasive property is suitable to be used with 250, 500, or 1000 gram load. In this test, both the UD and woven reinforcement samples were being tested with 250g, 500g and 1000g load under 500 wear cycles. Below is the testing procedure for the wear test:

1. Firstly the power is turned ON.
2. SELECT TEST CYCLES key is depressed. Then '500 cycles' is selected.
3. SET VACUUM LEVEL key is depressed. Then '100% vacuum' is selected.
4. The sample is weighted and mounted. Abrasive test wheels and weights are selected.
5. START key is depressed to begin the test.
6. The CYCLES COMPLETED key is automatically activated once the START key is depressed.
7. The abraser will automatically stop at 500 revolutions.
8. The counter is reset to zero by depressing RESET CYCLES COMPLETED key.
9. The sample is removed and reweighed.
10. Abrasive test wheels are refaced for the next test if necessary.

3.4.3 Surface Profiling for Abrasive Wear Test

Surface profiler equipment (Perthometer Concept) was used to measure the surface texture of the samples. In order to obtain the surface roughness of the samples, the direction of the measurement stylus was projected as shown in **Figure 10**. This means four measurement were taken for each sample.

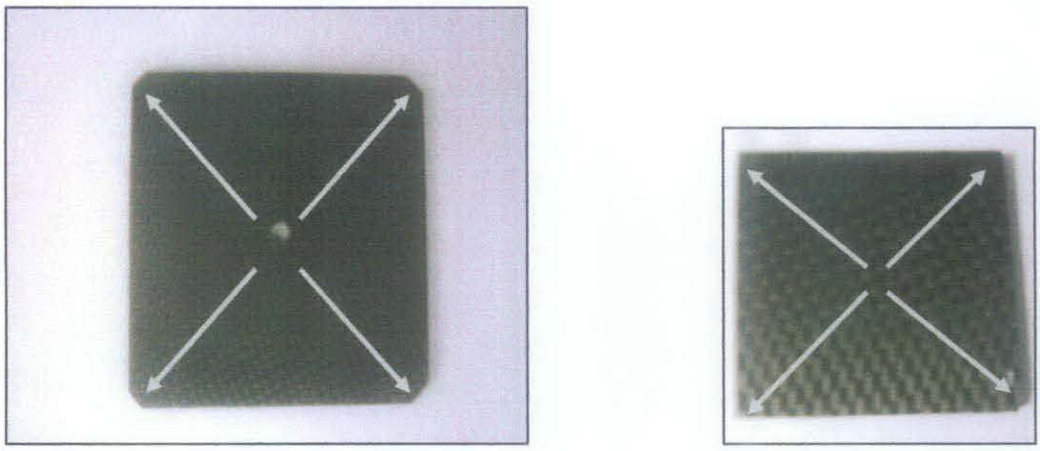


Figure 10 Direction of Measurement Stylus for Surface Roughness Measurement.

The surface roughness which was measured is the surface where the wear test will be conducted. The arithmetic average of surface roughness value for each sample was taken as the final value and the graph of arithmetic average of absolute roughness value for each sample was plotted. Below is the procedure for measuring the surface roughness by using Perthometer Concept:

1. The dongle is checked whether it is connected to parallel port.
2. The drive unit is checked whether it is connected to the computer.
3. Then the computer is switched ON.
4. The CONCEPT program on the desktop is entered by double clicking on its icon.
5. The required measuring conditions are set.
6. The red button (ON) is twisted and pulled up.
7. The 'measurement station view' is clicked.
8. The sample is placed on the stage under the sensor.
9. The down arrow button is pressed to lower the sensor. It is stopped before it touches the sample.
10. Then initialize icon is clicked.
11. The single measurement is chosen for the test.
12. "Start measurement' icon is clicked.
13. After the first measurement, the ample bit is moved so that the surface roughness of the new sample can be measured.
14. For the next sample, the 'measurement station view' is clicked again and the procedures are repeated.
15. Finally the measurement is saved under the roughness folder.

3.4.4 Adhesive Wear Test

In case of sliding against smooth metallic surface generally dominant wear mode is adhesive wear. Studies in multi-pass and dry condition were conducted on a single pin-on-disc machine in which pin of mild steel slid against rotating disc of the composite. The details of this machine are discussed in the literature review. Prior to the experiment, 4mm mild steel ball was slid against the composite disc. The operating parameters were: velocity, 200rpm; variable load (20, 40, 60, 80 and 100N) and sliding time 0.2h. Below is the testing procedure for the wear test:

1. The Ducom® Multispecimen Tester is set up and "WINCOM 2006" program is run on the computer.
2. "Run continuously" and "power" icon on the toolbar of the program is clicked to turn on the machine.
3. The desire test time, speed, type, temperature and trip value for safety is set.
4. File name such as id for the specimen is entered. Then, acquire is clicked.
5. All parameter must be in zero modes before the test is started.
6. Balancing load is applied at the leverage arm by putting 5kg weighing mass on the balancing mechanical load.
7. The sensor of the machine must be touched the disc holder.
8. The load is applied by putting the dead weight.
9. The load icon is adjusted into desired value by sliding the weighting mass slowly.
10. "Run" icon is clicked to start the test.
11. It is advisable to run the test for 110 minutes for warm up.
12. The test is rerun with the same setting.
13. "Power turn off" icon is clicked after finishing the test.
14. The sample is removed from the holder.
15. The PC and machine power supply are shutdown after using it.

3.4.5 SEM Studies on Worn Surfaces in Selected Wear Modes

Studies on worn surface topography were done to understand wear mechanisms. In this study, the mode used was Secondary Electron Imaging (SEI). Below is the procedure for the SEM studies:

1. The samples need to be coated before it was scanned under the SEM machine. The purpose of the coating is to create conductive surface on the non-metal material.
2. After coating, the samples will be patched to the holder using a carbon tape. Carbon tape was used because it is conductive.
3. Then, the samples will be put inside the sample chamber. In this chamber, the air will be sucked out and leave the space inside it in vacuum atmosphere.
4. The image of the samples are digitally captured and displayed on a computer monitor and saved to a computer's hard disk

CHAPTER 4
RESULT AND DISCUSSION

4.1 Hardness Test

Hardness is a resistance to penetration, wear, a measure of flow stress and resistance to cutting and scratching [13]. It is generally known that, when fibres or other types of reinforcement are incorporated into a resin, the presence of the reinforcement can affect the curing process; this can affect the properties of the cured resin [14]. This will contribute to the properties of the composite including hardness. **Figure 11** shows the hardness value of Sample A for each test (sub area). The highest value of hardness for UD reinforcement is 127.4 while the lowest value is 126.0. The average value for the hardness of this reinforcement is 126.83 and the standard deviation is 0.42. For woven reinforcement, the highest value of hardness is 123.33 while the lowest value is 121.1. The average value for the hardness of this reinforcement is 122.03 and the standard deviation is 0.63. **Figure 12** shows the hardness value of Sample B for each test (sub area). The highest value of hardness for UD reinforcement is 124.57 while the lowest value is 123.43. The average value for the hardness of this reinforcement is 124.07 and the standard deviation is 0.41. For woven reinforcement, the highest value of hardness is 126.8 while the lowest value is 125.87. The average value for the hardness of this reinforcement is 126.38 and the standard deviation is 0.41.

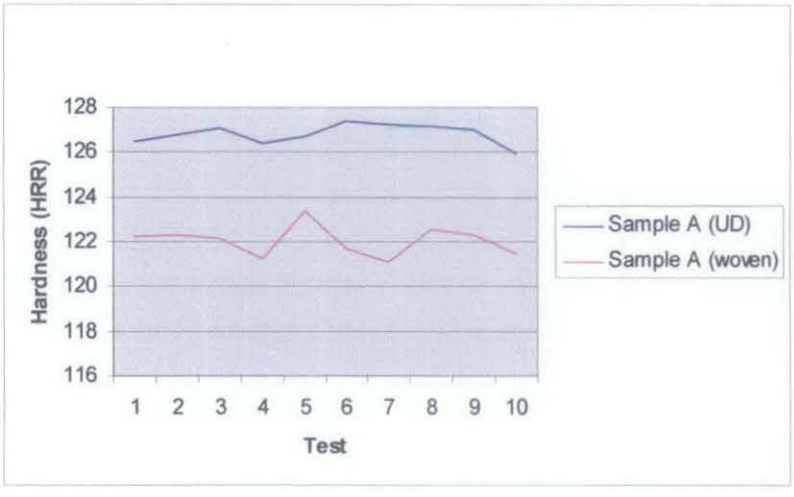


Figure 11 Hardness of Sample A for Each Test (Sub Area)

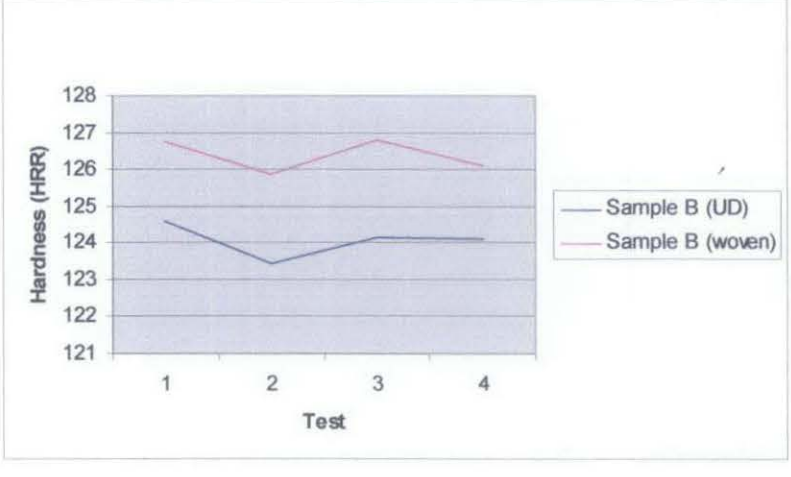


Figure 12 Hardness of Sample B for Each Test (Sub Area)

Hardness is one of the key factors which influence the sliding behavior of different materials combinations. However, in many discussions the only hardness value considered is that of the softer of the two materials in a tribological pair. This is usually the case when a simple linear wear equation as describe in the literature review. Observations on many materials combinations demonstrate that the effects of hardness are much more complex. Hardness varies with position and time. It can depend on temperature, sliding speed and the chemical environment. The sign of hardness gradients adjacent to the sliding surface affects sliding behavior. Transfer and subsequent mechanical mixing strongly influence local hardness. Changes in hardness can affect transitions in friction and wear. Relative hardness values can help to explain differences in debris and in smooth and rough sliding.

4.2 Abrasive Wear Test

Based on the result obtained as shown in **Figure 13**, the weight loss for both the unidirectional and woven carbon fiber is increasing when the applied load during the test is raised. In case of abrasive wear the basic mechanism is shearing forces being very serve during abrasion tend to cut the fibers at first instance. Whether they will be cut or not definitely depends on how rigidly they are held between crossover points. The shearing force is directly proportional with the applied load.

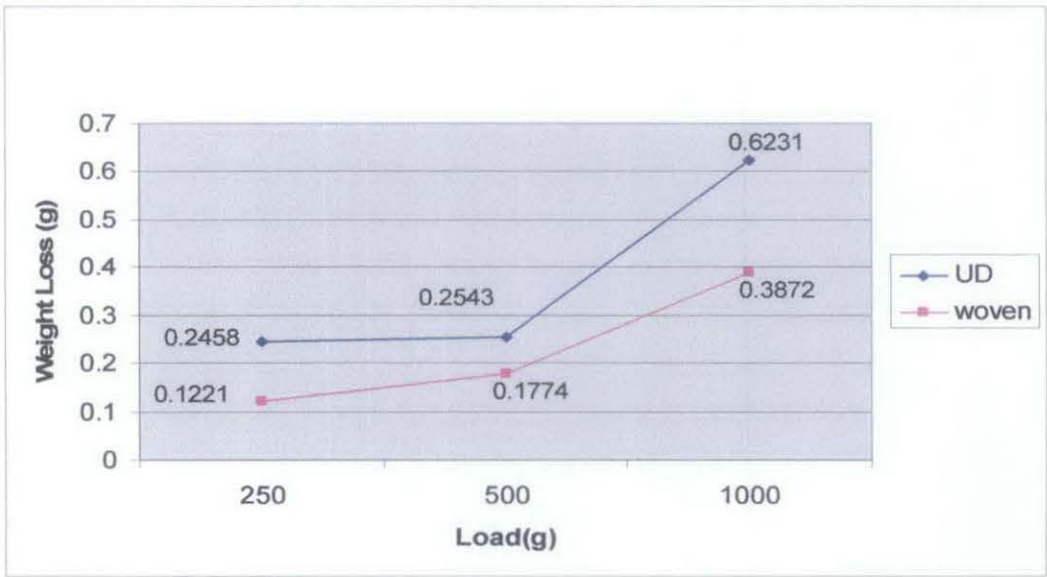


Figure 13 Weight Loss for Sample A after Abrasive Wear Test

Secondly, the UD carbon fiber experienced more weight loss compared to woven carbon fiber. The result of weight loss for Sample A after the test is further refined by calculating the Taber Wear Index (APPENDIX E). The result is shown in **Figure 14**. Theoretically, wear debris being quite large which causes entrapment of wear debris in the pockets or beneath the crimp points is not possible. Debris if produced, get removed from the surface contributing to "positive" wear. Thus, the abrasive wear of such composites is mainly controlled by the ease with which fibers are broken which in turn depends on how tightly they are held between the crossover points. Fibers under or over crossover points are under more tension and are more vulnerable to breakage. So, this shows that UD carbon fiber could be easily broken compare to woven carbon fiber.

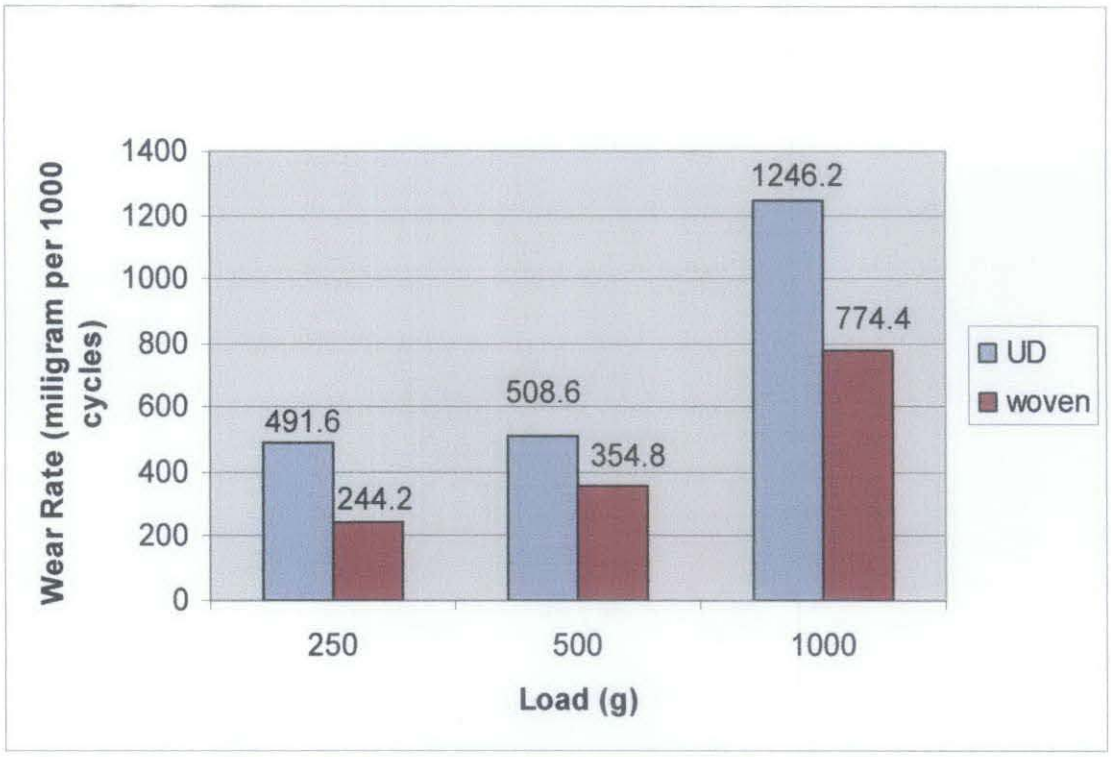


Figure 14 Wear Rate for Sample A for Abrasive Wear Test

4.3 Surface Profiling for Abrasive Wear Test

Roughness is a measure of the texture of a surface. It is observed by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth [15]. Next is the measurement result of surface roughness for samples before and after the wear test.

Table 4 Surface Roughness of Sample A (UD) Before and After Wear Test

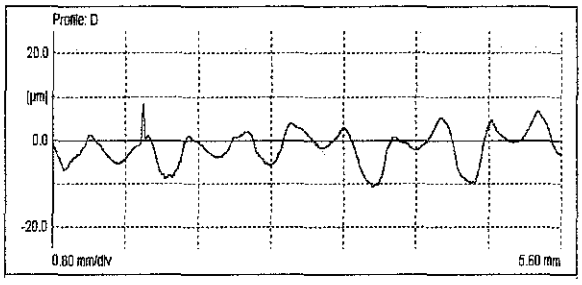
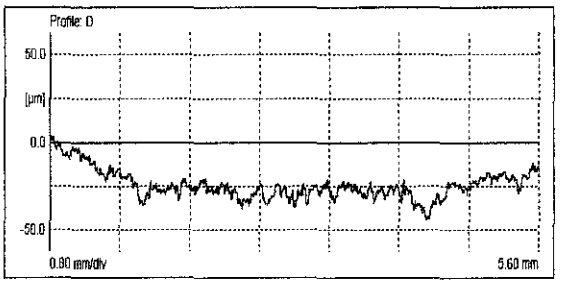
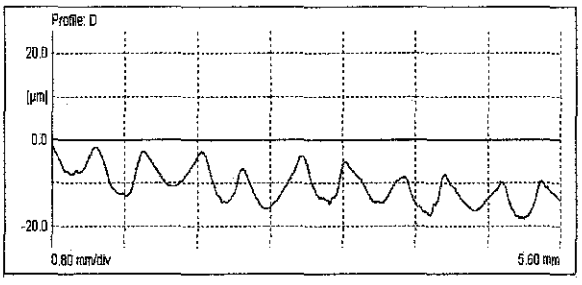
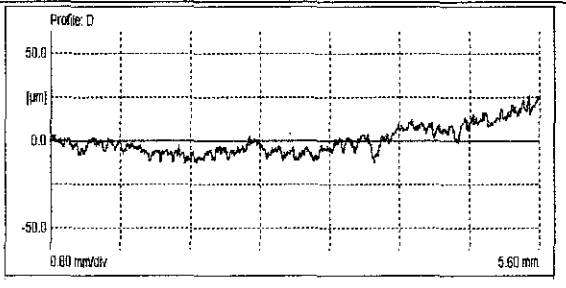
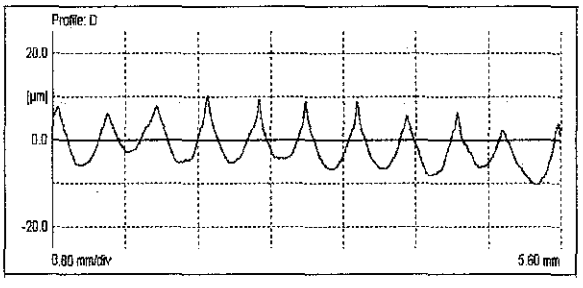
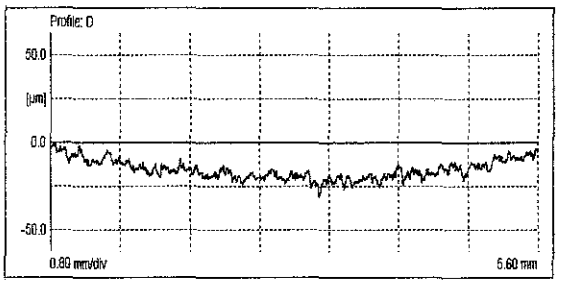
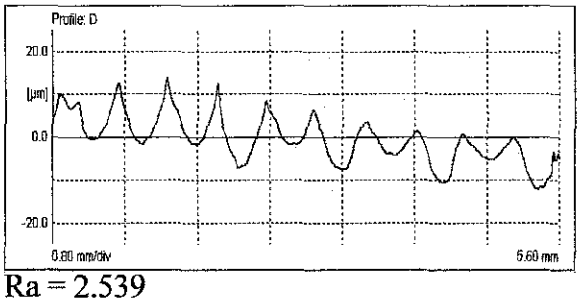
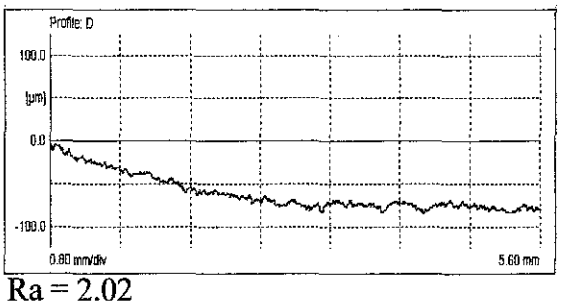
SAMPLE A (UD) 1 – 250g load	
BEFORE	AFTER
	
Ra = 2.154	Ra = 2.61
	
Ra = 2.107	Ra = 1.92
	
Ra = 2.716	Ra = 1.73
	
Ra = 2.539	Ra = 2.02
Ra (average) = 2.379	Ra (average) = 2.07

Table 5 Surface Roughness of Sample A (UD) Before and After Wear Test

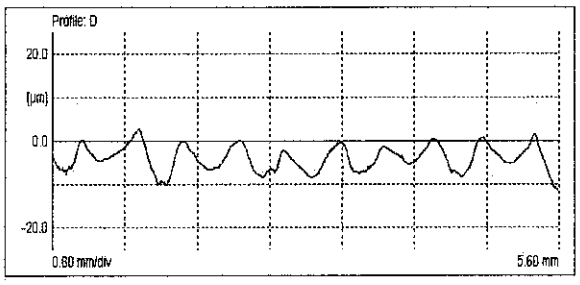
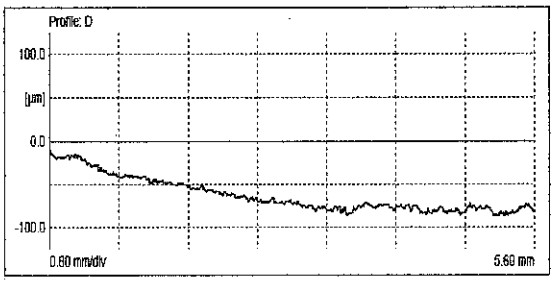
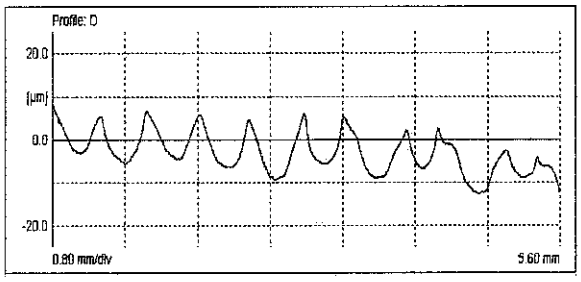
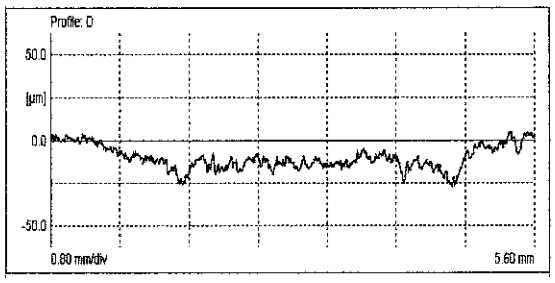
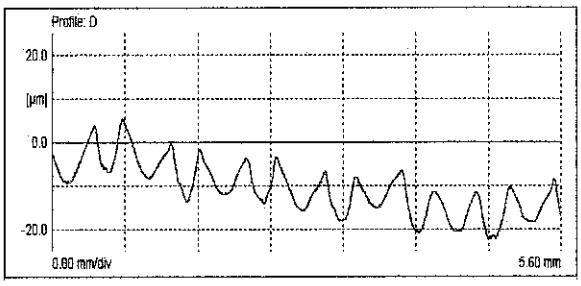
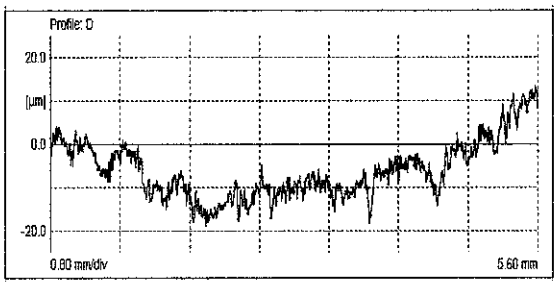
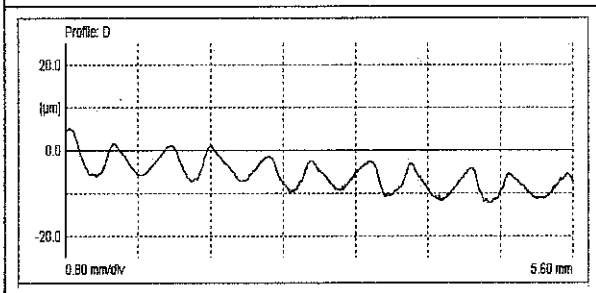
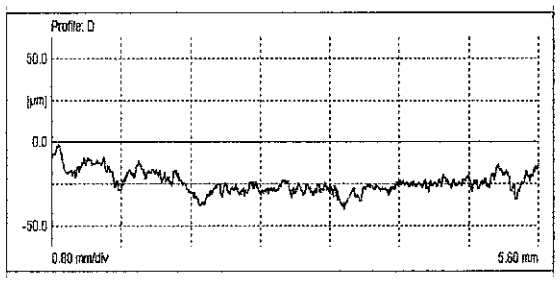
SAMPLE A (UD) 2-500g load	
BEFORE	AFTER
	
Ra = 1.858	Ra = 1.60
	
Ra = 2.671	Ra = 2.33
	
Ra = 1.991	Ra = 1.73
	
Ra = 1.753	Ra = 2.00
Ra (average) = 2.06825	Ra (average) = 1.915

Table 6 Surface Roughness of Sample A (UD) Before and After Wear Test

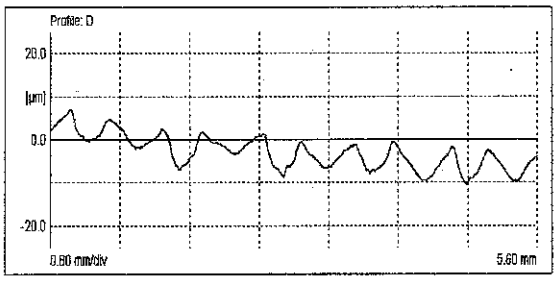
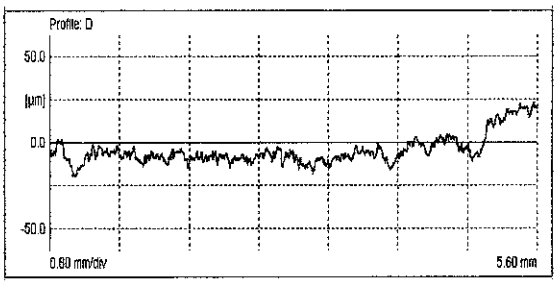
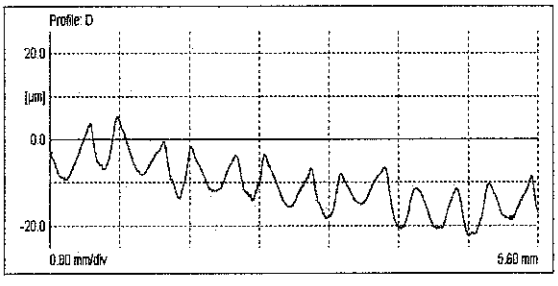
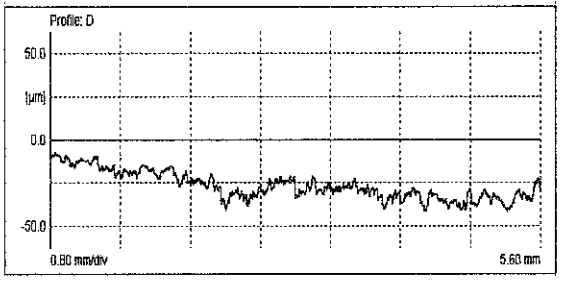
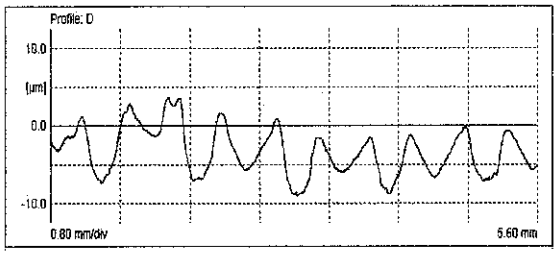
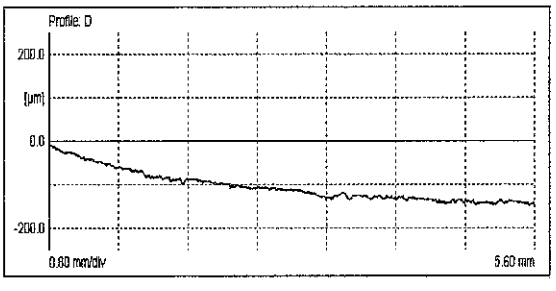
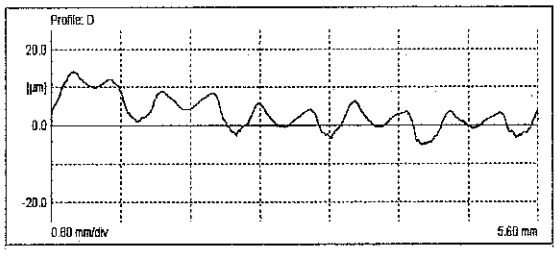
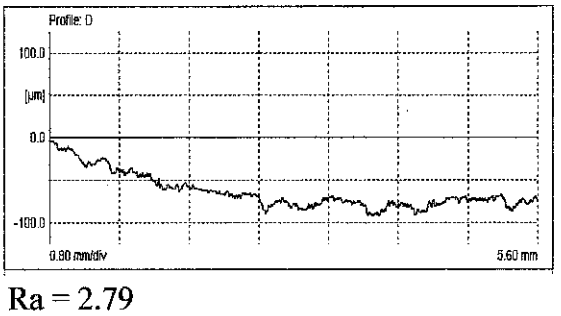
SAMPLE A (UD) 3-1000g load	
BEFORE	AFTER
	
Ra = 1.592	Ra = 2.04
	
Ra = 1.688	Ra = 2.21
	
Ra = 1.719	Ra = 1.99
	
Ra = 1.670	Ra = 2.79
Ra (average) = 1.66725	Ra (average) = 2.2575

Table 7 Surface Roughness of Sample A (Woven) Before and After Wear Test

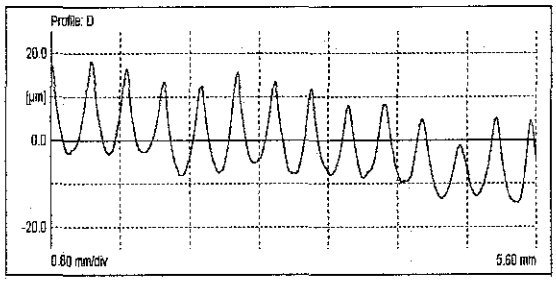
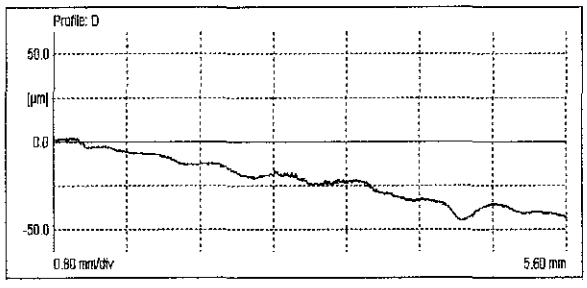
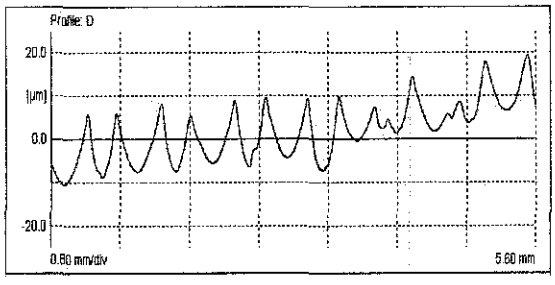
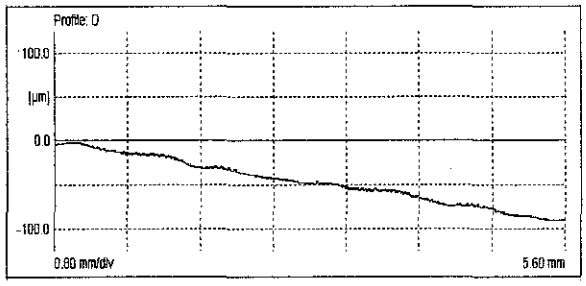
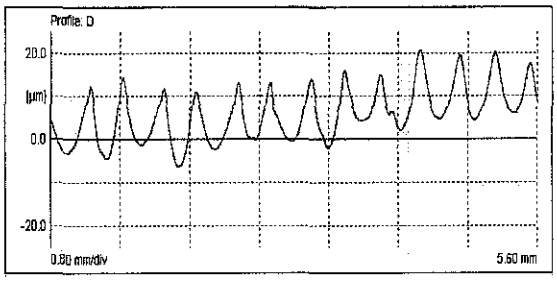
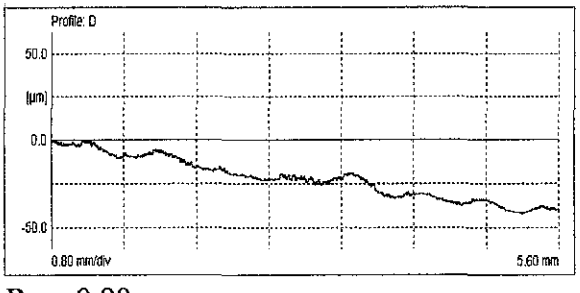
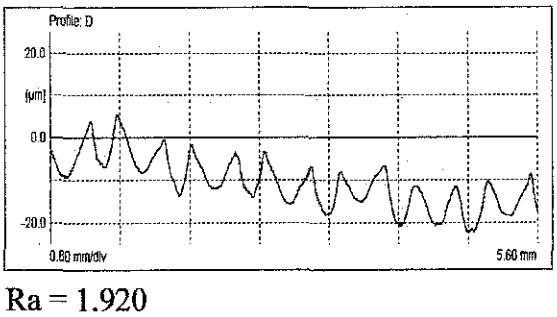
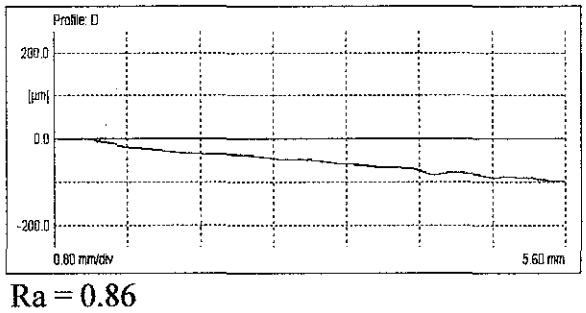
SAMPLE A (Woven) 1-250g load	
BEFORE	AFTER
	
Ra = 5.018	Ra = 0.91
	
Ra = 3.058	Ra = 0.80
	
Ra = 3.943	Ra = 0.90
	
Ra = 1.920	Ra = 0.86
Ra (average) = 3.48475	Ra (average) = 0.8675

Table 8 Surface Roughness of Sample A (Woven) Before and After Wear Test

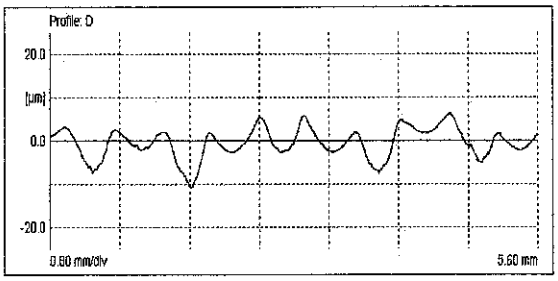
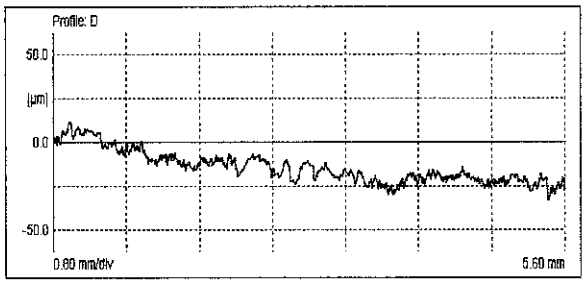
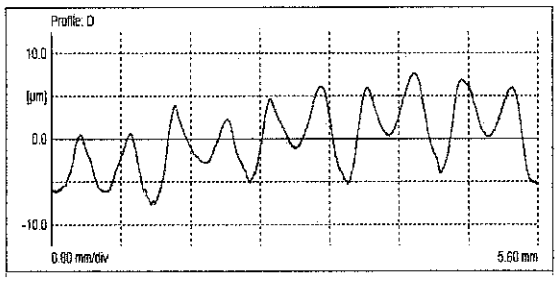
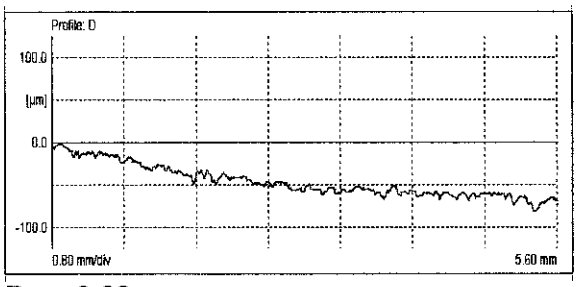
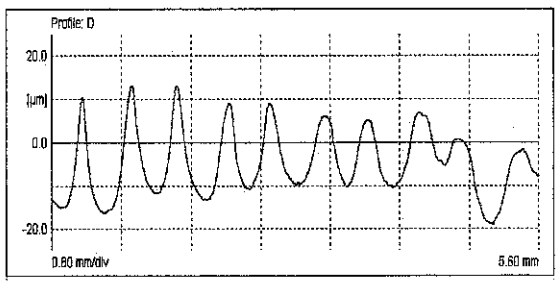
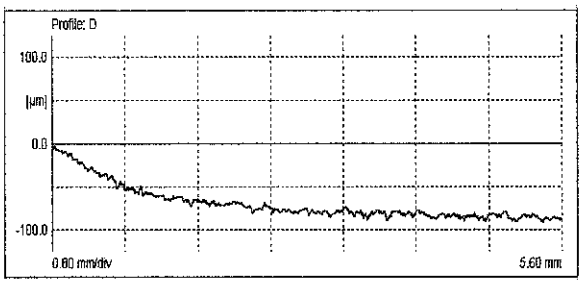
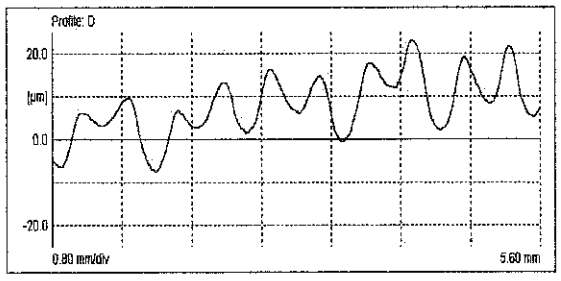
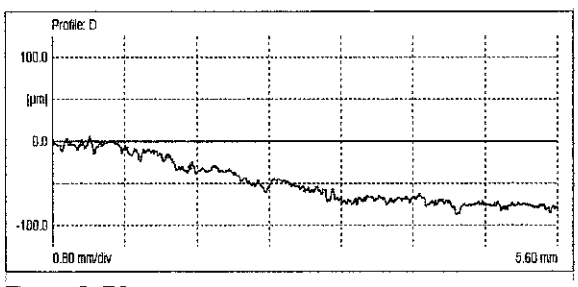
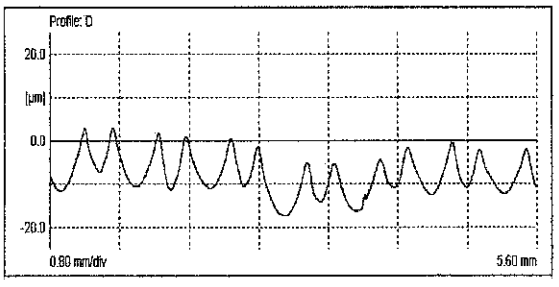
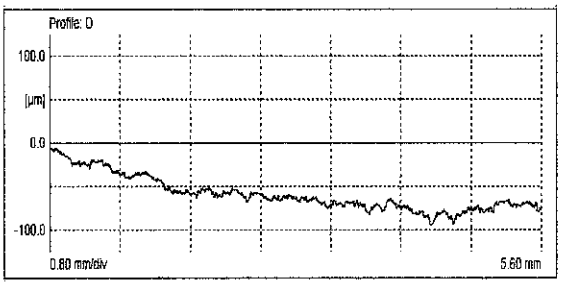
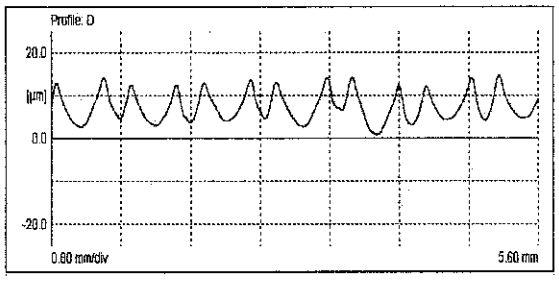
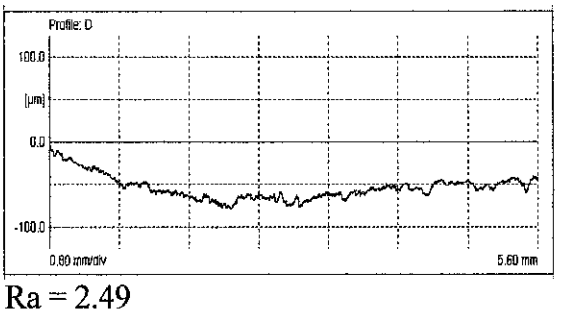
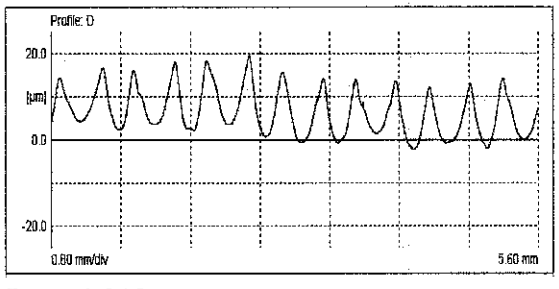
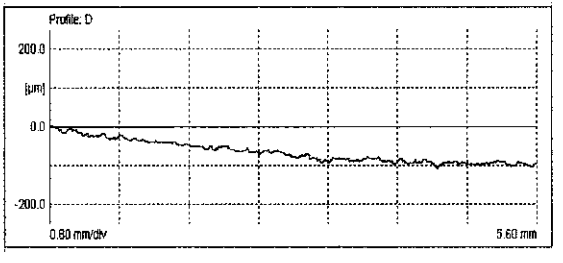
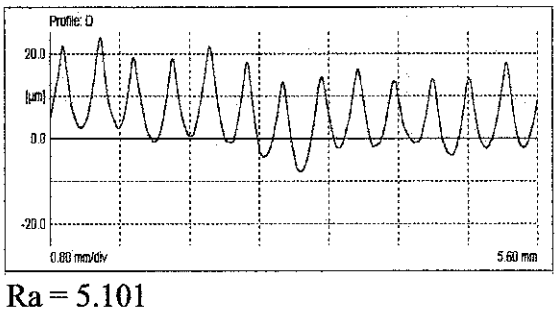
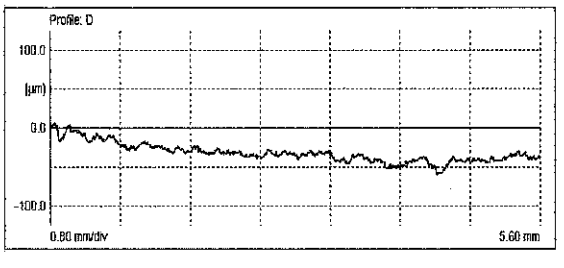
SAMPLE A (Woven) 2-500g load	
BEFORE	AFTER
	
Ra = 1.762	Ra = 2.18
	
Ra = 2.037	Ra = 2.32
	
Ra = 4.667	Ra = 1.88
	
Ra = 3.221	Ra = 2.73
Ra (average) = 2.92175	Ra (average) = 2.2775

Table 9 Surface Roughness of Sample A (Woven) Before and After Wear Test

SAMPLE A (Woven) 3-1000g load	
BEFORE	AFTER
	
Ra = 2.800	Ra = 2.58
	
Ra = 2.339	Ra = 2.49
	
Ra = 4.012	Ra = 2.78
	
Ra = 5.101	Ra = 2.76
Ra (average) = 2.379	Ra (average) = 2.6525

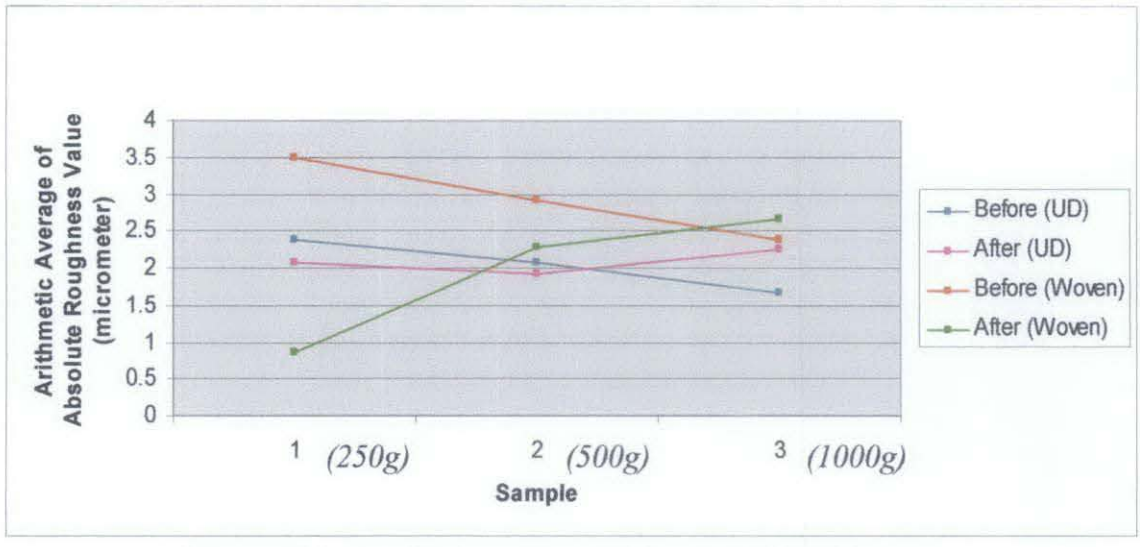


Figure 15 Arithmetic Average of Absolute Roughness

Surface roughness limits the contact between solid bodies to a very small portion of the apparent contact area. Contact between solid bodies at normal operating loads is limited to small areas of true contact between the high spots of either surface. The random nature of roughness prevents any interlocking or meshing of surfaces. True contact area is therefore distributed between a numbers of micro-contact areas. If the load is raised, the number of contact areas rather than the 'average' individual size of contact area are increased. This will result wear of the material. **Figure 15** shown after undergo the wear test with 250 gram load; the value of surface roughness for both unidirectional and woven reinforcement samples is lower compare to reading before wear test. Then, the value of surface roughness is increase for Sample B which is experienced abrasive wear under 500 gram load but the value still low compare to the reading before wear test. Finally, for Sample C which is being tested with 1000 gram load, the surface roughness of both types of samples is increasing and for this time, the value exceeds the value before the samples are being tested. This phenomenon is discovered through analyzing the samples by using Scanning Electron Microscope (SEM).

4.4 Adhesive Wear Test

Histogram in **Figure 16** shows the coefficient of friction (μ) of the composite under various loads, respectively in adhesive wear modes. As seen from **Figure 16,** the friction performance of the composites under selected loads decrease from the lowest to highest load. For each applied load, the woven reinforcement provides better friction performance compare to UD reinforcement. The highest value of coefficient for woven reinforcement is 0.27 (under 20N load) while the lowest value is 0.22 (under 100N load). The average value of coefficient of friction for woven reinforcement is 0.242. For the UD reinforcement, the highest value of coefficient of friction is 0.25 (under 20N load) while the lowest value is 0.21 (under 100N load). The average value of coefficient of friction for UD reinforcement is 0.23.

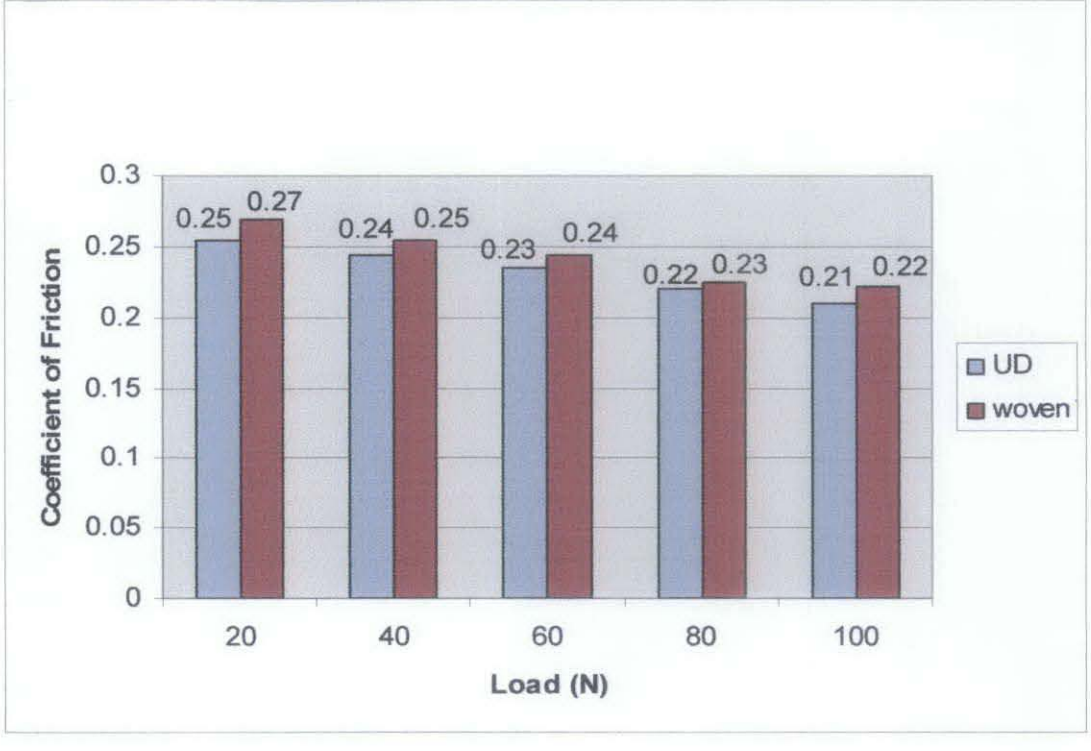


Figure 16 Coefficient of Friction under Various Loads

Figure 17 shows the weight loss for sample B after adhesive wear test. Based on the result obtained, the weight loss for both the unidirectional and woven carbon fiber is increasing when the applied load during the test is raised. For each applied load, the UD carbon fiber experienced more weight loss compare to woven carbon fiber When load increases, extent of frictional heat apart from mechanical stresses also increases which lead to increase in the extent of fiber breakage (micro-cracking, micro-cutting

and pulverization of fibers followed by peeling off or pulling out of fibrous debris) that increases disproportionately. This was observed in SEM studies of the composites in details.

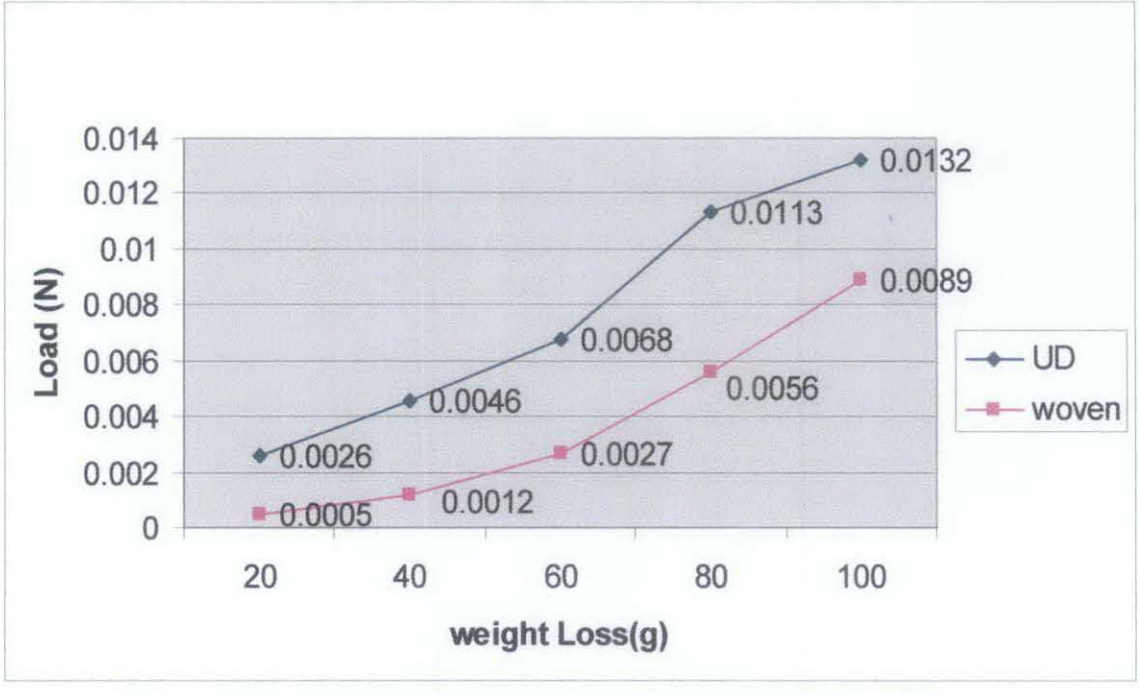


Figure 17 Weight Loss for Sample B after Adhesive Wear Test

4.5 SEM Studies

Table 10 SEM Images for Abrasive Wear Mode under 250g Load

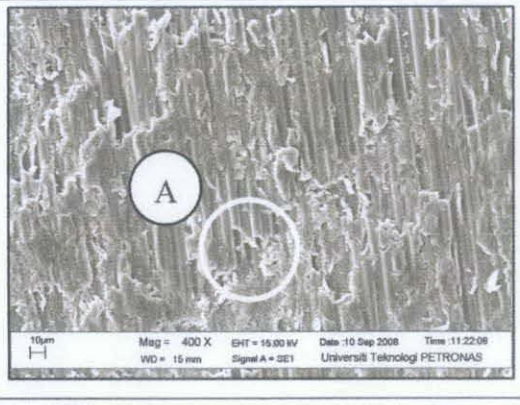
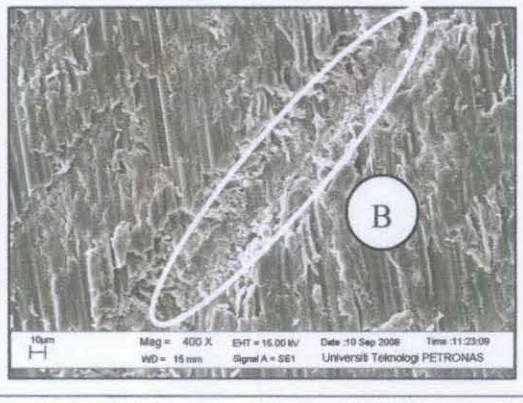
Wear mode : Abrasive Load : 250g	
Woven Reinforcement Sample	UD Reinforcement Sample
	
A – Fibers between crossover points are broken and peeled off. Such peeled off fibers lying on surface are easily crushed in consecutive abrasion cycle.	B – Furrows due to abrasion in matrix-rich portion.

Table 11 SEM Images for Abrasive Wear Mode under 500g Load

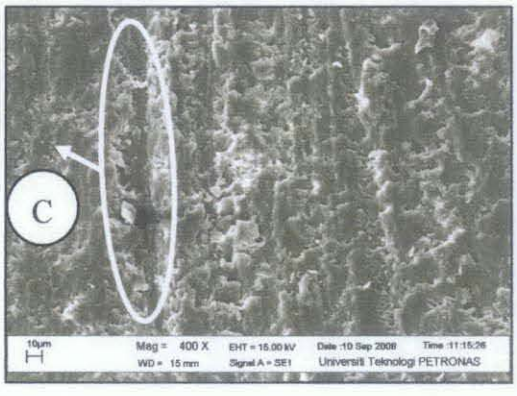
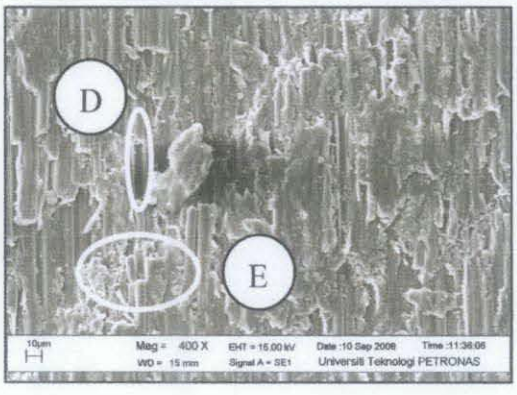
Wear mode : Abrasive Load : 500g	
Woven Reinforcement Sample	UD Reinforcement Sample
	
C- Lot of patches of back transferred resin, enhanced debonding in fiber-matrix interphase.	D – A small portion of fibers is removed after pulverization leaving behind cavity. E – Fibers between crossover points are broken and peeled off. Such peeled off fibers lying on surface are easily crushed in consecutive abrasion cycle.

Table 12 SEM Images for Abrasive Wear Mode under 1000g Load

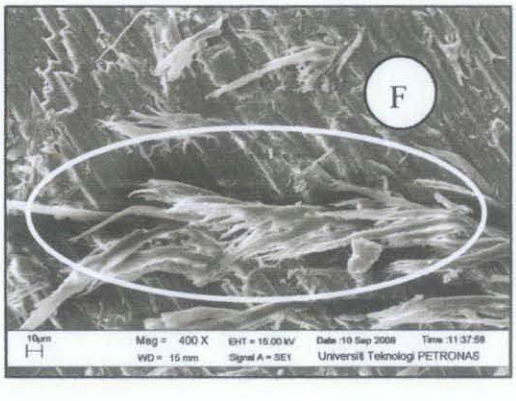
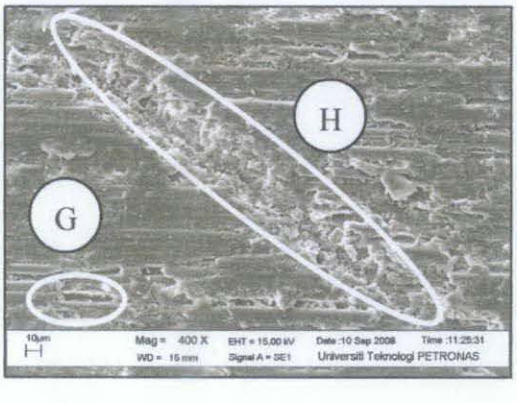
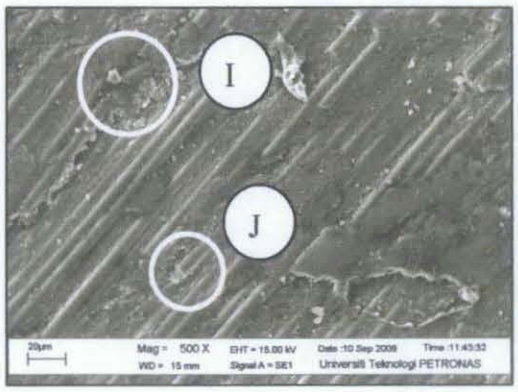
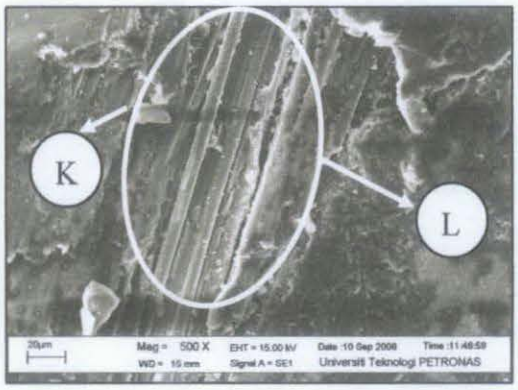
Wear mode : Abrasive Load : 1000g	
Woven Reinforcement Sample	UD Reinforcement Sample
	
F – Fibers micro-cut, lifted and an disoriented	G - Furrows due to abrasion in matrix-rich portion. H – A small portion of fibers is removed after pulverization leaving behind cavity.

Table 13 SEM Images for Adhesive Wear Mode under 100N Load

Wear mode : Adhesive Load : 100N	
Woven Reinforcement Sample	UD Reinforcement Sample
	
I, J – Fiber damage and cutting but no pulverization.	K, L – Lot of patches of back transferred resin, enhanced debonding in fiber-matrix interphase.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Based on the result of the experiment, for abrasive wear test, the weight loss for UD and woven reinforcement composite increased when the applied load was raised. Based on wear rate, the composite with woven reinforcement proves the best performance compare to UD reinforcement composite. So, woven fiber reinforcements, particularly made of tough materials, are useful in controlling abrasive wear. For adhesive wear test, the woven reinforcement proves the best performance based on the weight loss and coefficient of friction. However, the friction performance for the UD and woven reinforcement is decreasing from the lowest to the highest applied load. Same as the abrasive wear test, when the applied load is raised, the weight loss for both types of composites will increase.

5.2 Recommendations

For the future study, it is suggested to investigate the tribological properties of the composite in both, longitudinal and transverse directions. This can improve the understanding of wear and friction behavior of the composite in more detail. Other than that, for better understanding of surface topography, the SEM images should be captured at different direction of the fiber. This is because each direction of the fiber will experience different effect due to the wear.

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APPENDICES

APPENDIX A

GANTT CHART

	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic															
2	Preliminary Research Work															
3	Submission of Preliminary Report															
4	Seminar 1 (compulsory)															
5	Determine the Suitable Test for Project															
6	Submission of Progress Report															
7	Seminar 2 (compulsory)															
8	Study About the Testing Machine															
9	Submission of Interim Report Final Draft															
11	Oral Presentation															

Suggested milestone
Progress

Appendix 1: Gantt Chart FYP 1

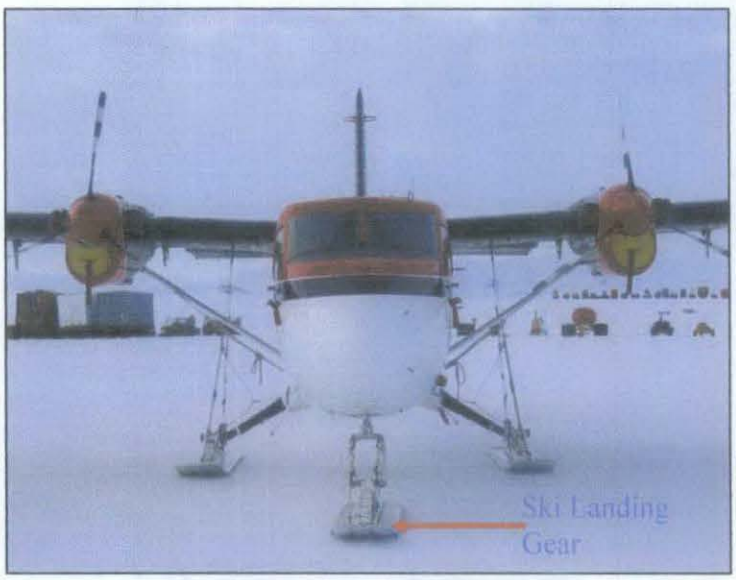
	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Conduct Abrasive Wear Test															
2	Submission of Progress Report 1															
3	Conduct Adhesive Wear Test															
4	Submission of Progress Report 2															
5	Seminar (compulsory)															
6	Analyze Data															
7	Poster Exhibition															
8	Final Report Writing															
9	Submission of dissertation (soft bound)															
10	Oral presentation															
11	Submission of Project Dissertation (hard bound)															

Suggested milestone
Progress

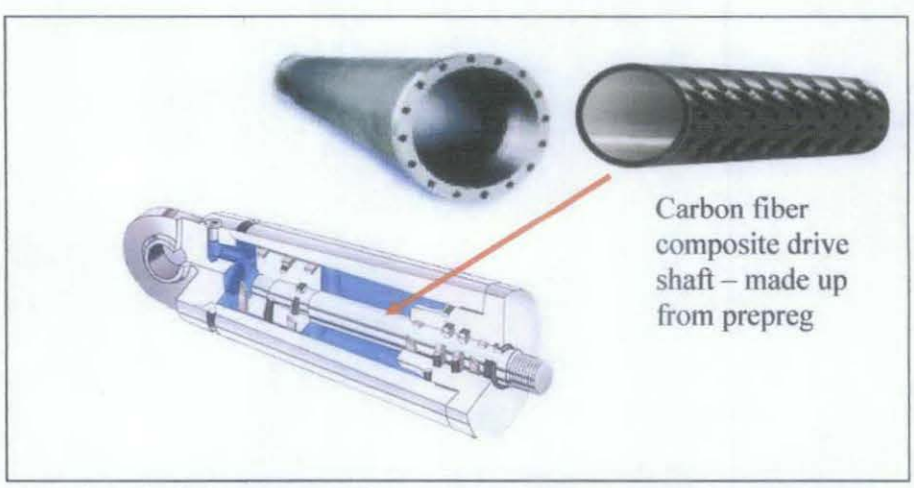
Appendix 1: Gantt Chart FYP 2

APPENDIX B

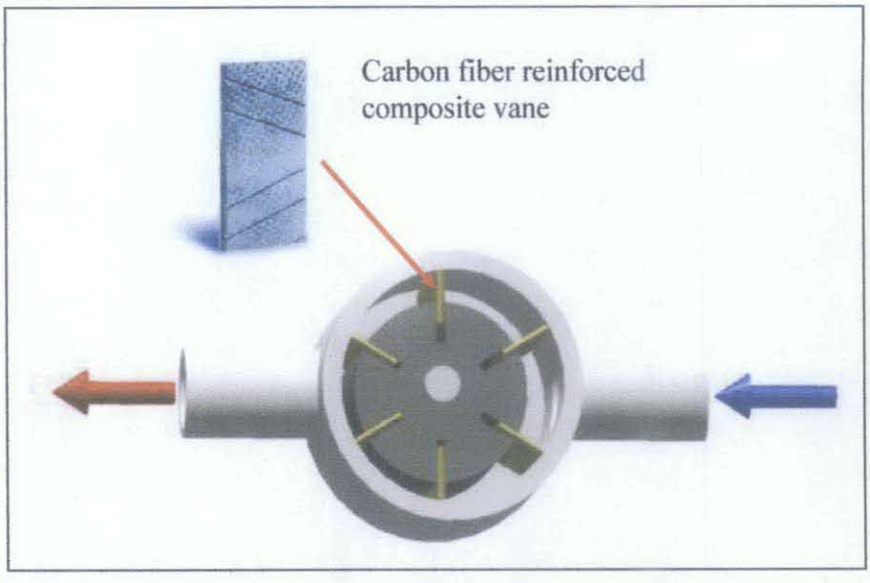
TRIBOLOGICAL APPLICATIONS OF CARBON FIBER REINFORCED COMPOSITE



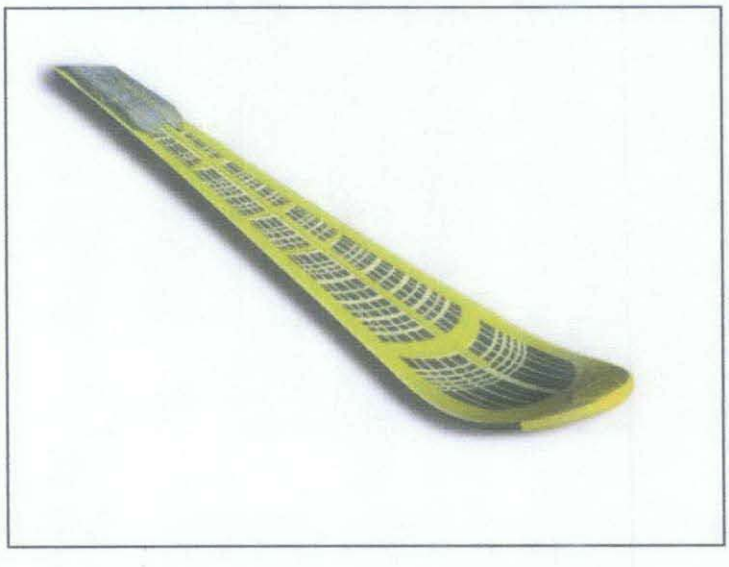
Ski Landing Gear for Aircraft



Drive Shaft for Pumps, Mixers, and Other Large Rotating Equipment



Vanes for Rotary Industrial Pump

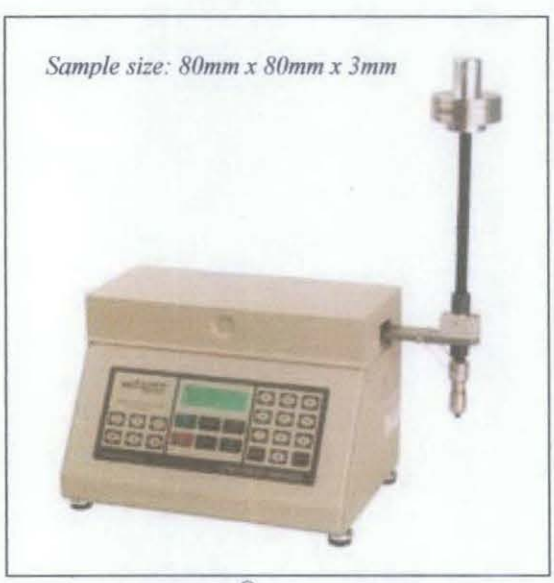


Basic Material for Ski

APPENDIX C

TABER® 5131 ABRASER AND TABER® LINEAR ABRASER

TABER® 5131 Abraser

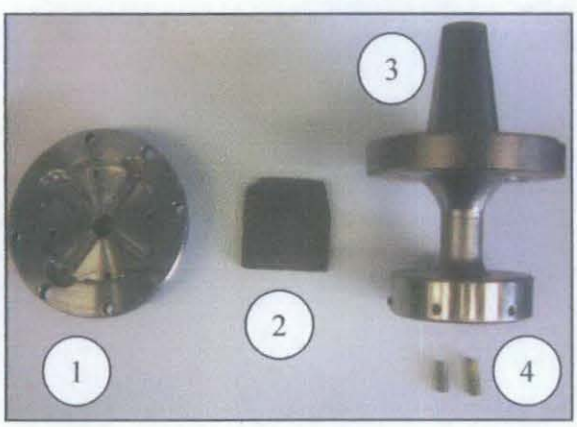


TABER® Linear Abraser

APPENDIX D

MAIN COMPONENTS OF DUCOM® MULTI SPECIMEN TESTER

DUCOM® Multi Specimen Tester



1) Sample Mounting
2) Sample (40mm x 40 mm x 6mm)
3) Pin Holder
4) Pin

Main Components of DUCOM® Multi Specimen Tester

APPENDIX E

COMMON METHODS OF EVALUATING RESULTS FROM THE TABER® 5131 ABRASER

WEAR MEASUREMENT	DESCRIPTION
Visual End Point	Test ends when there is a clearly marked change in specimen appearance or other characteristic. When the abrasion test end-point is described in a material specification, the end-point may consist of pass/fail criteria such as yarn breakage, loss in coating, loss of luster, napping, pilling, color loss, or other changes in appearance. Specimens are typically compared with a known standard of the material tested.
Weight Loss	• Measure in milligram • Indicates the weight of material that has been removed by abrasion. • Firstly, the specimen will be weighted before abrasion. • After abrasion, the material will be weighted again $L = A - B$ Where L = weight loss A = weight of test specimen before abrasion B = weight of test specimen after abrasion
Taber Wear Index	• Indicates the rate of wear and it is calculated by measuring the loss in weight (in milligrams) per thousand cycles. • The lower wear index of the specimen, the better its abrasion resistance is. $I = \frac{(A - B)(1000)}{C}$ Where I = wear index A = weight of test specimen before abrasion B = weight of test specimen after abrasion C = number of cycles
Volume Loss	For specimens of different specific gravities. Using a correction factor, you can obtain a true indication of wear resistance

Depth of Wear	Measure the depth of the wear with an instrument such as an optical micrometer.
Wear Cycles per Mil	Wear cycles per mil represents the wear cycles required to break through a coating of a certain thickness. W = D/T Where W = wear cycles per mil D = cycles required to wear coating through to substrate T = thickness of coating, mils (0.001) to one decimal place
Residual Breaking Force (textile fabrics)	The effective strength of the fabric, or force required to break a specific width of fabric. To determine the individual breaking force of the abraded specimen use the procedure described in the ASTM D5034 and D5035 Standard Test Method for Breaking Strength and Elongation of Textile Fabrics. To work, you must change the distance between clamps to 25mm and horizontally place the path of abrasion on the abraded specimen midway between the clamps. Report the breaking load to the nearest 0.5kg.
Average Breaking Strength (textile fabrics)	Calculated by averaging the breaking strength of the abraded specimens and the unabraded specimens, as determined by the Residual Breaking Force.
Percentage Loss in Breaking Strength (textile fabrics)	To determine the breaking load of the original fabric and the abraded specimen, use the procedure noted above (ASTM D5034 and D5035). Calculate the percentage loss in breaking strength to the nearest 1% for each lengthwise and widthwise directions. AR% = 100* (X-Y) / X

APPENDIX F

MATERIAL DATA

HexPly® 8552

Epoxy matrix (180°C/356°F curing matrix)

Product Data

Description

HexPly® 8552 is a high performance tough epoxy matrix for use in primary aerospace structures. It exhibits good impact resistance and damage tolerance for a wide range of applications.

HexPly® 8552 is an amine cured, toughened epoxy resin system supplied with unidirectional or woven carbon or glass fibres.

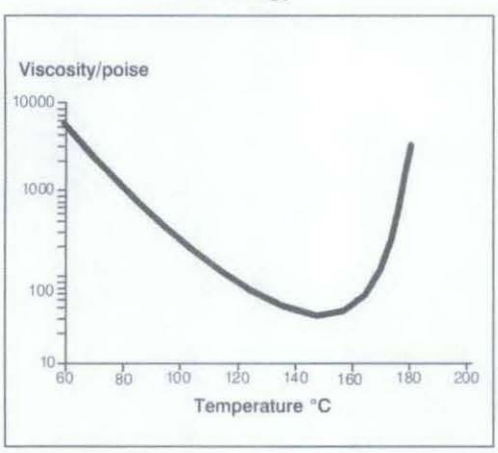
HexPly® 8552 was developed as a controlled flow system to operate in environments up to 121°C *(250°F)*.

Benefits and Features

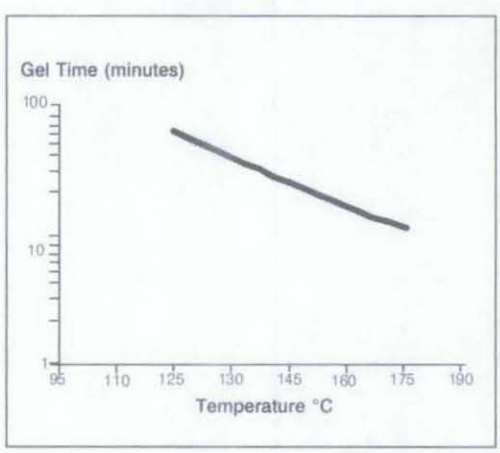
- Toughened epoxy matrix with excellent mechanical properties
- Elevated temperature performance
- Good translation of fibre properties
- Controlled matrix flow in processing
- Available on various reinforcements
- Excellent drape and tack

Resin Matrix Properties

Rheology



Gel Time



HexPly® 8552

repreg Properties - HexPly® 8552 UD Carbon Prepregs

ysical Properties

	Units	AS4	IM7
Fibre Density	g/cm³ *(lb/in³)*	1.79 *(0.065)*	1.77 *(0.064)*
Filiament count/tow		12K	12K
Resin density	g/cm³ *(lb/in³)*	1.30 *(0.047)*	1.30 *(0.047)*
Nominal Cured Ply Thickness 8552 /35%/134	mm *(inch)*	0.130 *(0.0051)*	0.131 *(0.0052)*
Nominal Fibre Volume	%	57.42	57.70
Nominal Laminate Density	g/cm³ *(lb/in³)*	1.58 *(0.057)*	1.57 *(0.057)*

echanical Properties

Test	Units	Temp °C *(°F)*	Condition	AS4	IM7
0°Tensile Strength	MPa *(ksi)*	-55*(-67)*	Dry	1903 *(267)*	*2572 (373)*
		25*(77)*	Dry	2207 *(320)*	2724 *(395)*
		91*(195)*	Dry	-	**2538 *(368)****
90°Tensile Strength	MPa *(ksi)*	-55*(-67)*	Dry	-	174 *(25.3)*
		25*(77)*	Dry	81 *(11.7)*	111 *(16.1)*
		93*(200)*	Dry	75 *(10.9)*	**92 *(13.3)****
0°Tensile Modulus	GPa *(msi)*	-55*(-67)*	Dry	134 *(19.4)*	163 *(23.7)*
		25*(77)*	Dry	141 *(20.5)*	164 *(23.8)*
		91*(195)*	Dry	-	**163 *(23.7)****
90°Tensile Modulus	GPa *(msi)*	-	-	-	-
		25*(77)*	Dry	10 *(1.39)*	12 *(1.7)*
		93*(200)*	Dry	8 *(1.22)*	**10 *(1.5)****
0°Compression Strength	MPa *(ksi)*	-55*(-67)*	Dry	1586 *(230)*	-
		25*(77)*	Dry	1531 *(222)*	1690 *(245)*
		91*(195)*	Dry	1296 *(184)*	1483 *(215)*
0°Compression Modulus	GPa *(msi)*	-55*(-67)*	Dry	124 *(18)*	-
		25*(77)*	Dry	128 *(18.6)*	150 *(21.7)*
		91*(195)*	Dry	122 *(17.7)*	162 *(23.5)*
0° ILSS (Shortbeam shear)	MPa *(ksi)*	-55*(-67)*	Dry	164 *(23.8)*	-
		25*(77)*	Dry	128 *(18.5)*	137 *(19.9)*
		91*(195)*	Dry	122 *(14.7)*	**94 *(13.6)****
		25*(77)*	Wet	117 *(16.9)*	115 *(16.7)*
		71*(160)*	Wet	84 *(12.2)*	**80 *(11.6)*****
		91*(195)*	Wet	78 *(11.3)*	-
In-plane Shear Strength	MPa *(ksi)*	25*(77)*	Dry	114 *(16.6)*	120 *(17.4)*
		93*(200)*	Dry	105 *(15.2)*	**106 *(15.4)****

Bold 93°C *(200°F)* **Bold* 104°C *(220°F)*** **Bold** 82°C *(180°F)***

HexPly® 8552

reg Properties - HexPly® 8552 Woven Carbon Prepregs (AS4 Fibre)

cal Properties

	Units	AGP193-PW	AGP 280-5H
bre Type	-	AS4 3K	AS4 3K
bre density	g/cm³ *(lb/in³)*	1.77 *(0.065)*	1.77 *(0.065)*
eave	-	Plain	5HS
ass	g/m² *(oz/yd²)*	193 *(5.69)*	286 *(8.44)*
eight Ratio, Warp : Fill		50 :50	50 :50
ominal cured ply thickness 37% resin content	mm *(inch)*	0.195 *(0.0076)*	0.289 *(0.0114)*
ominal Fibre Volume	%	55.29	55.29
ominal Laminate Density	g/cm³ *(lb/in³)*	1.57 *(0.057)*	1.57 *(0.057)*

anical Properties

est	Units	Temp°C *(°F)*	Condition	AGP193-PW	AGP280- 5H
Tensile trength	MPa *(ksi)*	-55*(-67)* 25*(77)* 91*(195)*	Dry Dry Dry	766 *(111)* 828 *(120)* -	828 *(120)* 876 *(127)* 903 *(131)*
D°Tensile trength	MPa *(ksi)*	-55*(-67)* 25*(77)* 93*(200)*	Dry Dry Dry	710 *(103)* 793 *(115)* 759 *(110)*	752 *(109)* 800 *(116)* 772 *(112)*
Tensile lodulus	GPa *(msi)*	-55*(-67)* 25*(77)* 91*(195)*	Dry Dry Dry	66 *(9.5)* 68 *(9.8)* -	70 *(10.2)* 67 *(9.7)* 69 *(10)*
D°Tensile lodulus	GPa *(msi)*	-55*(-67)* 25*(77)* 93*(200)*	Dry Dry Dry	66 *(9.6)* 66 *(9.5)* 68 *(9.8)*	67 *(9.7)* 66 *(9.5)* 65 *(9.4)*
Compression trength	MPa *(ksi)*	-55*(-67)* 25*(77)* 91*(195)*	Dry Dry Dry	959 *(139)* 883 *(128)* 759 *(110)*	- 924 *(134)* **752 *(109)***
Compression lodulus	GPa *(msi)*	-55*(-67)* 25*(77)* 91*(195)*	Dry Dry Dry	60 *(8.7)* 60 *(8.7)* 61 *(8.8)*	- 64 *(9.3)* **67*(9.7)***
ILSS Shortbeam hear)	MPa *(ksi)*	-55*(-67)* 25*(77)* 91*(195)* 25*(77)* 71*(160)* 91*(195)*	Dry Dry Dry Wet Wet Wet	101 *(14.6)* 84 *(12.2)* 70 *(10.2)* 75 *(10.9)* 72 *(10.4)* 59 *(8.5)*	- 79 *(11.4)* - 69 *(10)* - -

old 93°C (200°F) Bold* 104°C (220°F) Bold** 82°C (180°F)

HexPly® 8552

epreg Properties - HexPly® 8552 Woven Carbon Prepregs (IM7 Fibre)

ysical Properties

	Units	SPG 196-P	SPG 370-8H
Fibre Type	-	IM7 6K	IM7 6K
Fibre density	g/cm³ *(lb/in³)*	1.77 *(0.064)*	1.77 *(0.064)*
Weave	-	Plain	8HS
Mass	g/m² *(oz/yd²)*	196 *(5.78)*	374 *(11.03)*
Weight Ratio, Warp : Fill		50 :50	49 :51
Nominal cured ply thickness @ 37% resin content	mm *(inch)*	0.199 *(0.0078)*	0.380*(0.0150)*
Nominal Fibre Volume	%	55.57	55.57
Nominal Laminate Density	g/cm³ *(lb/in³)*	1.56 *(0.056)*	1.56*(0.056)*

echanical Properties

Test	Units	Temp°C (°F)	Condition	SPG 196-PW	SPG 370-8H
0°Tensile Strength	MPa *(ksi)*	-55*(-67)*	Dry	979 *(142)*	965 *(140)*
		25*(77)*	Dry	1090 *(158)*	1014 *(147)*
		91*(195)*	Dry	-	-
90°Tensile Strength	MPa *(ksi)*	-55*(-67)*	Dry	862 *(125)*	903 *(131)*
		25*(77)*	Dry	945 *(137)*	959 *(139)*
		93*(200)*	Dry	**979 *(142)****	**879 *(130)****
0°Tensile Modulus	GPa *(msi)*	-55*(-67)*	Dry	85 *(12.3)*	86 *(12.5)*
		25*(77)*	Dry	85 *(12.3)*	86 *(12.4)*
		91*(195)*	Dry	-	-
90°Tensile Modulus	GPa *(msi)*	-55*(-67)*	Dry	80 *(11.6)*	81 *(11.7)*
		25*(77)*	Dry	80 *(11.6)*	81 *(11.7)*
		93*(200)*	Dry	**79 *(11.5)****	**79 *(11.5)****
0° ILSS (Shortbeam shear)	MPa *(ksi)*	-55*(-67)*	Dry	-	-
		25*(77)*	Dry	88 *(12.7)*	90 *(13)*
		91*(195)*	Dry	**69 *(10)****	***74 (10.8)****
		25*(77)*	Wet	80 *(11.6)*	83 *(12.1)*
		71*(160)*	Wet	**61 *(8.8)*****	***63 (9.1)*****
		91*(195)*	Wet	-	-

Bold 93°C (200°F) **Bold* 104°C (220°F)** **Bold** 82°C (180°F)**

ypical Neat Resin Data

olour	Yellow	
ensity	1.301 g/cc	*(0.0470 lb/in³)*
lass Transition Temperature, Tg dry	200°C	*(392°F)*
lass Transistion Temperature, Tg wet	154°C	*(309°F)*
ensile Strength	121 MPa	*(17.5 ksi)*
ensile Modulus	4670 MPa	*(0.677 msi)*

Curing Conditions

Cure cycle for monolithic components

1. Apply full vacuum (1 bar).
2. Apply 7 bar gauge autoclave pressure.
3. Reduce the vacuum to a safety value of 0.2 bar when the autoclave pressure reaches approximately 1 bar gauge.
4. Heat at 1- 3°C/min *(2-8°F/min)* to 110°C ± 5°C *(230°F ± 9°F)*
5. Hold at 110°C ± 5°C *(230°F ± 9°F)* for 60 minutes ± 5 minutes.
6. Heat at 1-3°C/min *(2-8°F/min)* to 180°C ± 5°C *(356°F ± 9°F)*
7. Hold at 180°C ± 5°C *(356°F ± 9°F)* for 120 minutes ± 5 minutes.
8. Cool at 2 - 5°C *(4-9°F)* per minute
9. Vent autoclave pressure when the component reaches 60°C *(140°F)* or below.

Cure cycle for honeycomb sandwich components

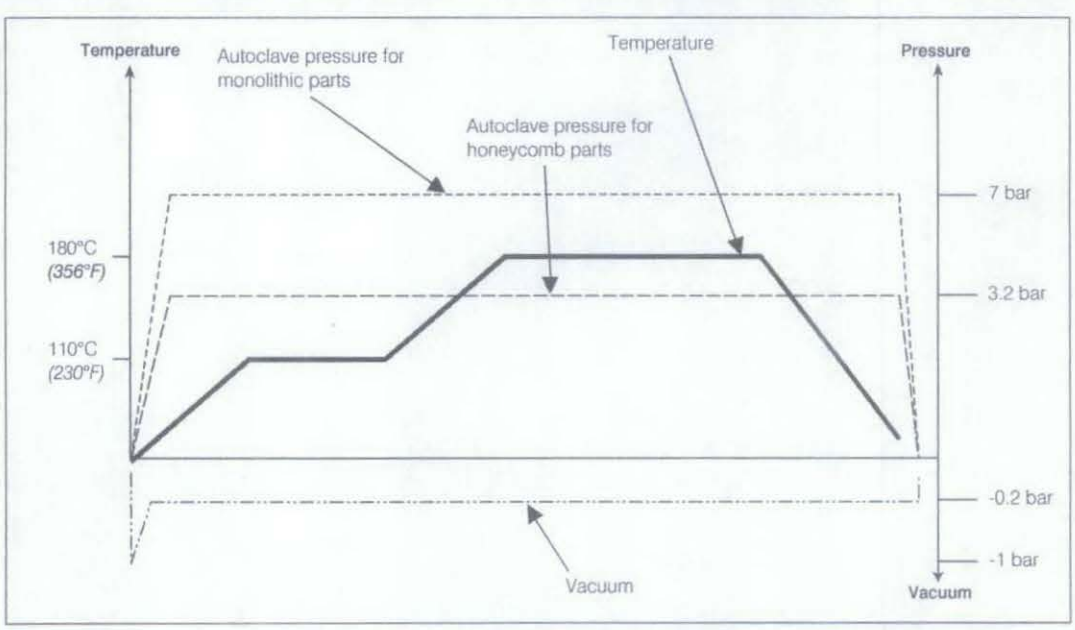
1. Apply full vacuum (1 bar).
2. Apply 3.2 bar gauge autoclave pressure.
3. Reduce the vacuum to a safety value of 0.2 bar when the autoclave pressure reaches approximately 1 bar gauge.
4. Heat at 1- 3°C/min *(2-8°F/min)* to 110°C ± 5°C *(230°F ± 9°F)*
5. Hold at 110°C ± 5°C *(230°F ± 9°F)* for 60 minutes ± 5 minutes.
6. Heat at 1-3°C/min *(2-8°F/min)* to 180°C ± 5°C *(356°F ± 9°F)*
7. Hold at 180°C ± 5°C *(356°F ± 9°F)* for 120 minutes ± 5 minutes.
8. Cool at 2 - 5°C *(4-9°F)* per minute
9. Vent autoclave pressure when the component reaches 60°C *(140°F)* or below.

Note: For both cure cycles – at each stage, use the temperature shown by the leading thermocouple.

Heat-up rates are dependent on component thickness, eg, slow heat-up rates should be used for thicker components and large tools. Accurate temperature measurements of the component should be made during the cure cycles by using thermocouples.

Performance testing should accompany alternative cure cycles to ensure suitability for the particular application.

Curing Cycle for Honeycomb and Monolithic Components



Prepreg Storage Life

Tack Life:	10 days at RT (23°C/*73°F*)
Out Life:	21 days at RT (23°C/*73°F*)
Shelf Life:	12 months at -18°C(*0°F*) (from date of manufacture)

Definitions:

Shelf Life:	The maximum storage life for HexPly® Prepreg, upon receipt by the customer, when stored continuously, in a sealed moisture-proof bag, at -18°C(*0°F*). To accurately establish the exact expiry date, consult the box label.
Tack Life:	The time, at room temperature, during which prepreg retains enough tack for easy component lay-up.
Out Life:	The maximum accumulated time allowed at room temperature between removal from the freezer and cure.

Precautions for Use

The usual precautions when handling uncured synthetic resins and fine fibrous materials should be observed, and a Safety Data Sheet is available for this product. The use of clean disposable inert gloves provides protection for the operator and avoids contamination of material and components.

Important

All information is believed to be accurate but is given without acceptance of liability. Users should make their own assessment of the suitability of any product for the purposes required. All sales are made subject to our standard terms of sale which include limitations on liability and other important terms.

For More Information

Hexcel is a leading worldwide supplier of composite materials to aerospace and other demanding industries. Our comprehensive product range includes:

- Carbon Fibre
- RTM Materials
- Honeycomb Cores
- Continuous Fibre Reinforced Thermoplastics
- Carbon, glass, aramid and hybrid prepregs
- Reinforcement Fabrics
- Structural Film Adhesives
- Honeycomb Sandwich Panels
- Special Process Honeycombs

For US quotes, orders and product information call toll-free 1-800-688-7734

For other worldwide sales office telephone numbers and a full address list please go to:

http://www.hexcel.com/contact/salesoffices

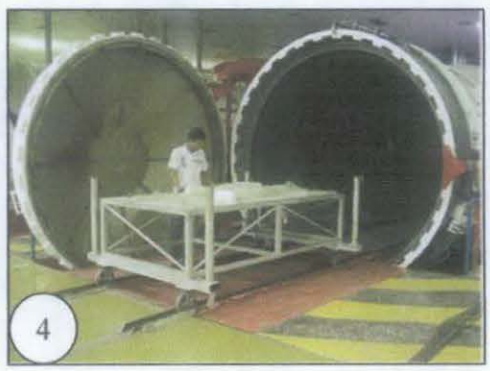
APPENDIX G

MOULD AND SAMPLE PREPARATION PROCESS

Mould Preparation

Lay up Prepreg

Final Bagging



Curing

Demould

APPENDIX H

RAW DATA FOR HARDNESS TEST

Sample	Hardness (HRR)									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
A(UD)1	127.5	126.9	127.6	126.8	126.9	127.8	127.5	127.4	128.0	126.8
A(UD)2	127.3	126.3	126.5	127.1	126.4	127.2	127.1	127.3	126.3	126.5
A(UD)3	124.6	127.2	127.1	125.4	126.8	127.2	127.1	126.9	126.7	124.6
Average	126.5	126.8	127.1	126.4	126.7	127.4	127.2	127.2	127.0	126.0

Sample	Hardness (HRR)									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
A(W)1	125.2	123.6	125.9	124.2	125.3	123.1	123.5	124.4	125.2	124.6
A(W)2	122.0	118.8	119.4	120.1	121.3	119.5	120.3	118.9	120.0	121.1
A(W)3	119.4	124.4	121.2	119.5	123.4	122.5	119.5	124.3	121.6	118.8
Average	122.2	122.3	122.2	121.3	121.7	121.1	122.5	122.3	122.3	121.5

Sample	Hardness (HRR)			
	T1	T2	T3	T4
B(UD)1	124.3	123.7	124.4	124.3
B(UD)2	124.4	123.0	124.2	123.2
B(UD)3	125.0	123.6	123.9	124.8
Average	124.6	123.4	124.2	124.1

Sample	Hardness (HRR)			
	T1	T2	T3	T4
B(W)1	127.6	127.5	127.5	127.4
B(W)2	126.4	126.7	125.6	125.6
B(W)3	126.3	123.4	127.3	125.3
Average	126.8	125.9	126.8	126.1

Sample	Hardness (HRR)			
	T1	T2	T3	T4
C(UD)1	125.1	124.2	124.6	125.1
C(UD)2	125.3	124.1	124.7	125.6
C(UD)3	124.0	124.5	124.6	125.3
Average	124.8	124.3	124.6	125.3

Sample	Hardness (HRR)			
	T1	T2	T3	T4
C(W)1	128.1	127.4	125.9	126.5
C(W)2	127.8	125.0	125.6	126.2
C(W)3	127.1	127.5	127.8	127.6
Average	127.7	126.6	126.4	126.5

APPENDIX I

RAW DATA FOR WEAR TEST

Sample	Wear cycle	Load (g)	Weight (g)		Weight Loss (g)
			Before	After	
A (UD) 1	500	250	27.960	27.7057	0.2543
A (UD) 2	500	500	27.5645	27.3187	0.2458
A (UD) 3	500	1000	27.1773	26.5542	0.6231

Sample	Wear cycle	Load (g)	Weight (g)		Weight Loss (g)
			Before	After	
A (Woven) 1	500	250	59.1391	59.0170	0.1221
A (Woven) 2	500	500	60.5906	60.4132	0.1774
A (Woven) 3	500	1000	60.4132	60.0260	0.3872

APPENDIX J

TEST RESULTS FOR ADHESIVE WEAR MODE

LOAD : 20N
REINFORCEMENT: CARBON UD
SPEED : 200rpm
CoF : **0.25369**

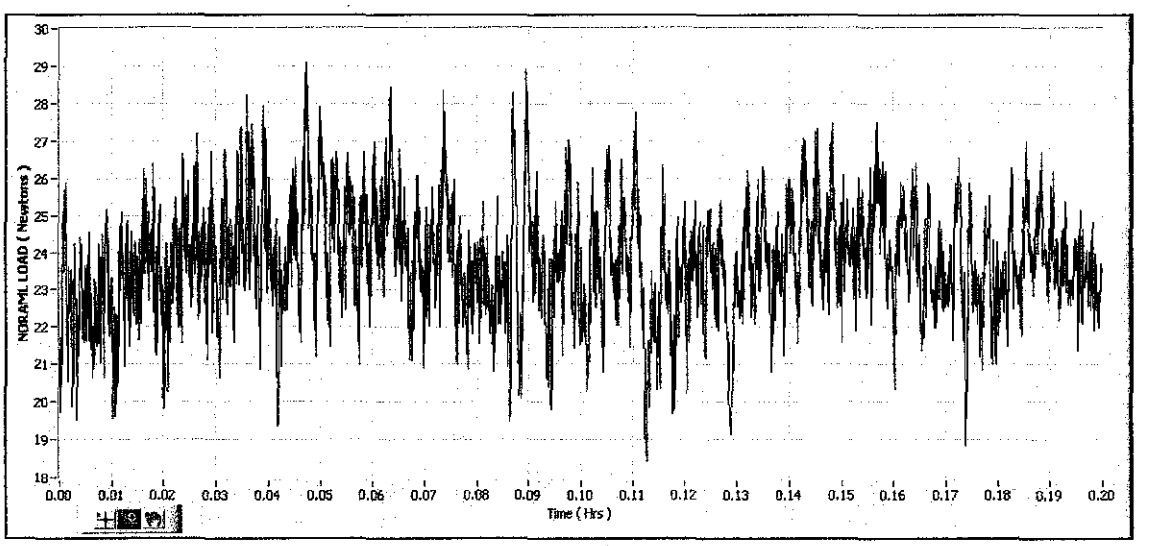


Figure 1

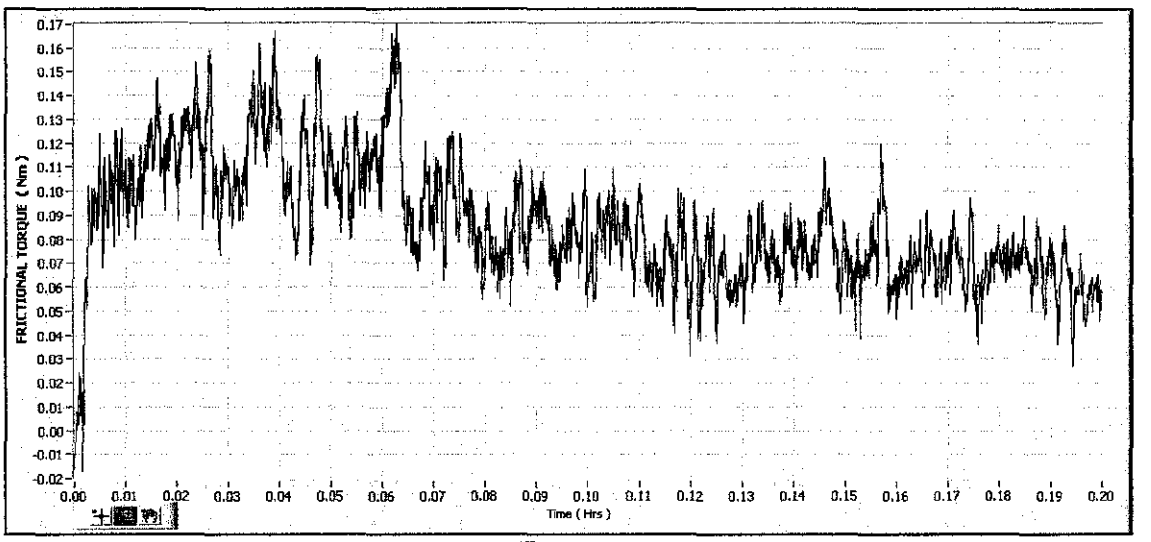


Figure 2

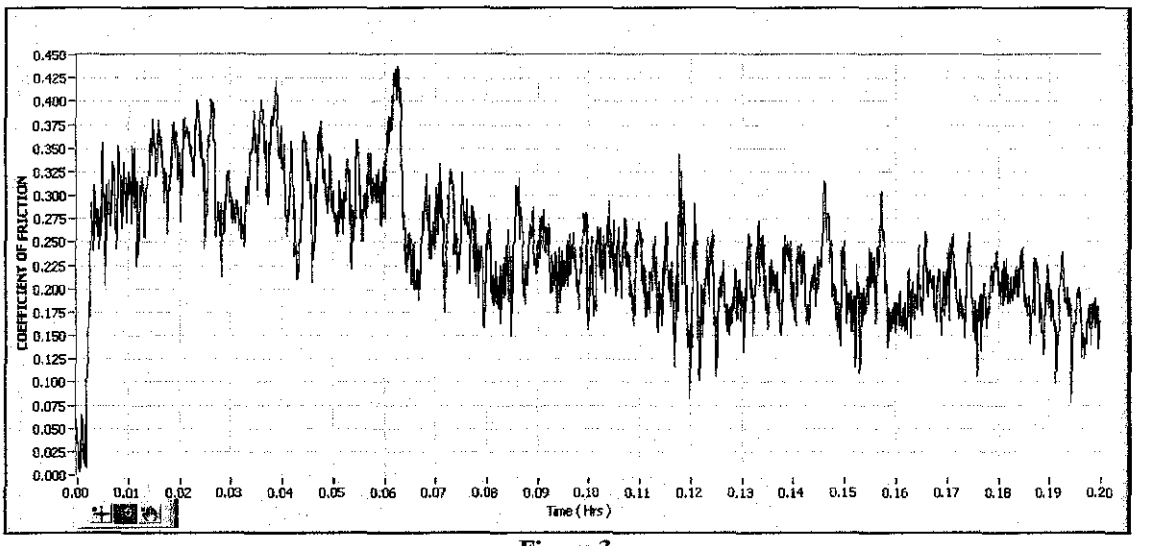


Figure 3

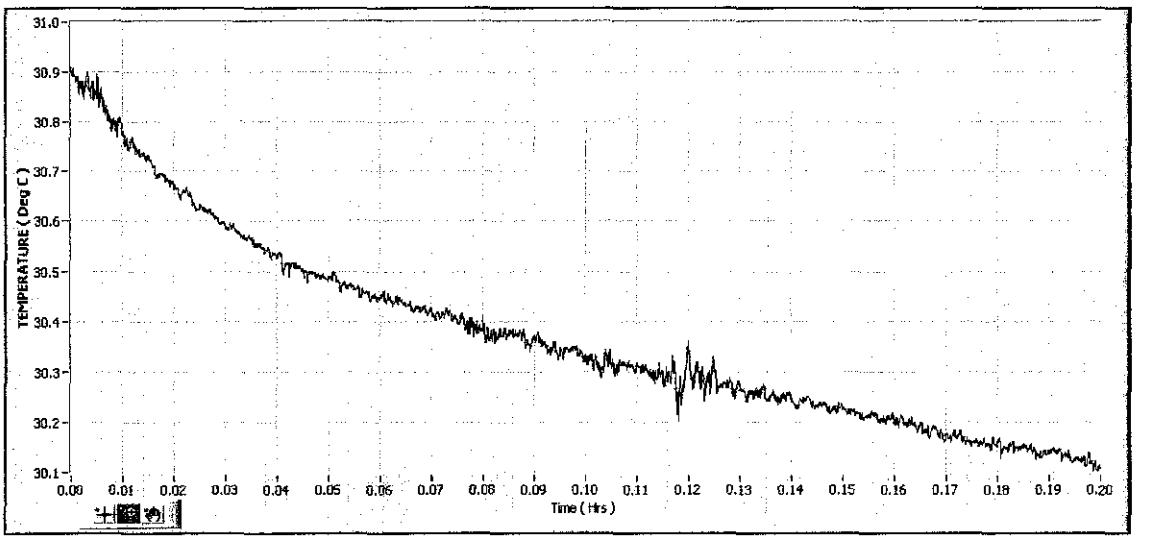


Figure 4

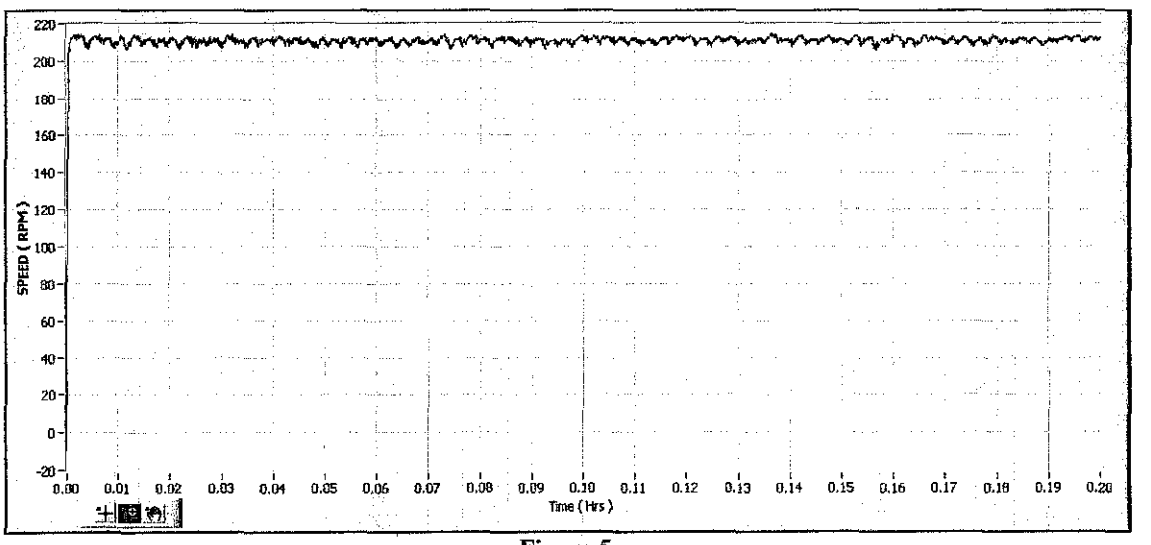


Figure 5

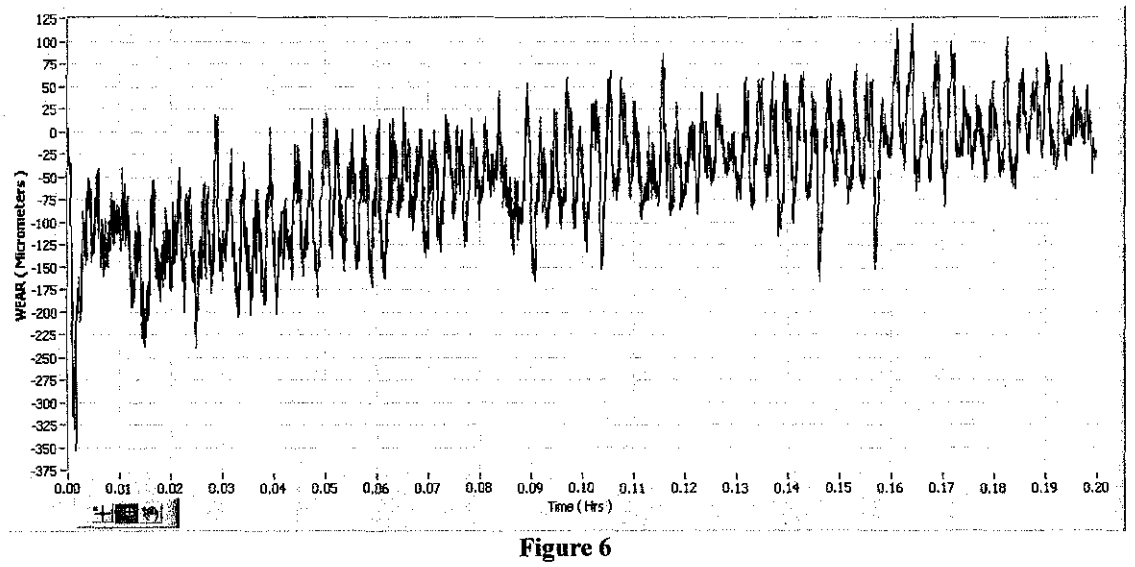

WEAR (Micrometers)
125
100
75
50
25
0
-25
-50
-75
-100
-125
-150
-175
-200
-225
-250
-275
-300
-325
-350
-375
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
Time (Hrs)

Figure 6

LOAD : 40N
REINFORCEMENT: CARBON UD
SPEED : 200rpm
CoF : **0.24314**

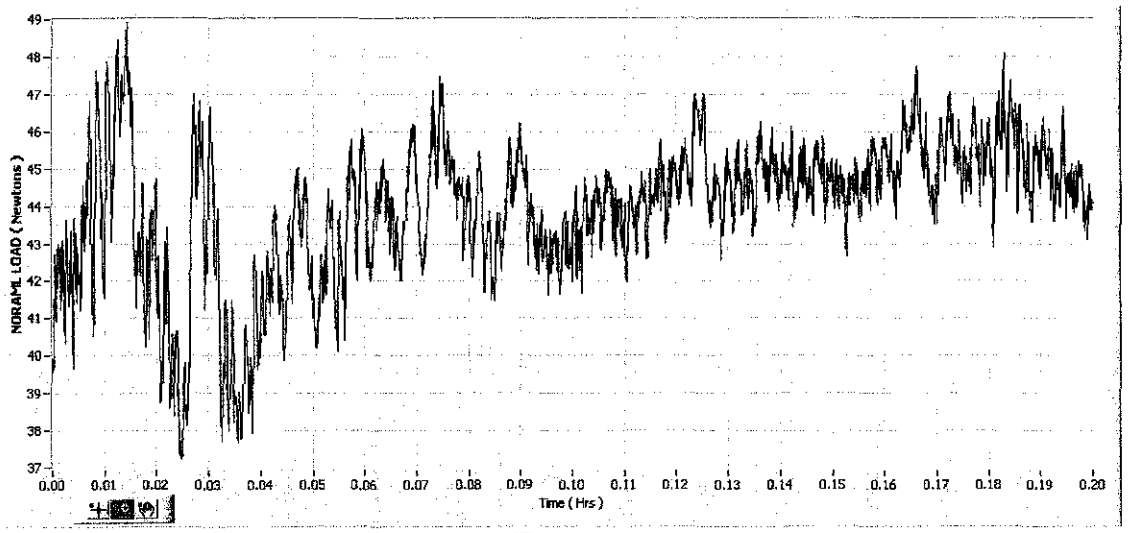


Figure 7

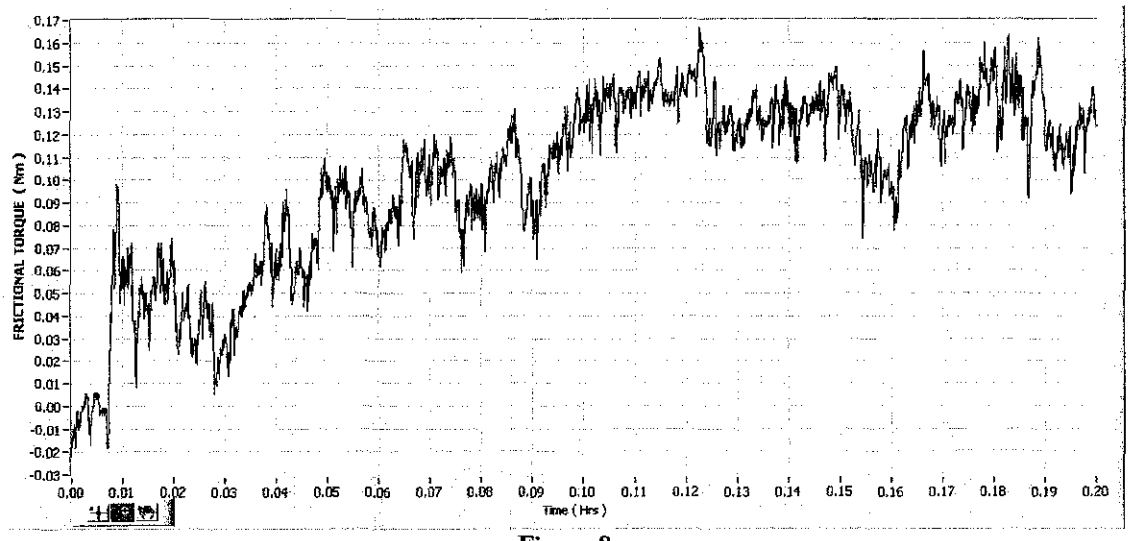


Figure 8

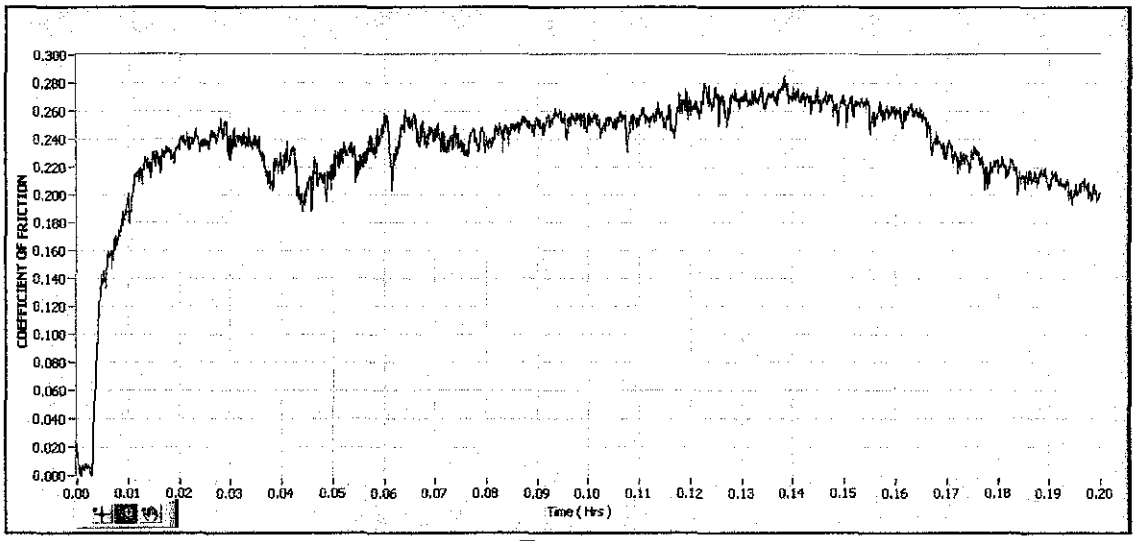


Figure 9

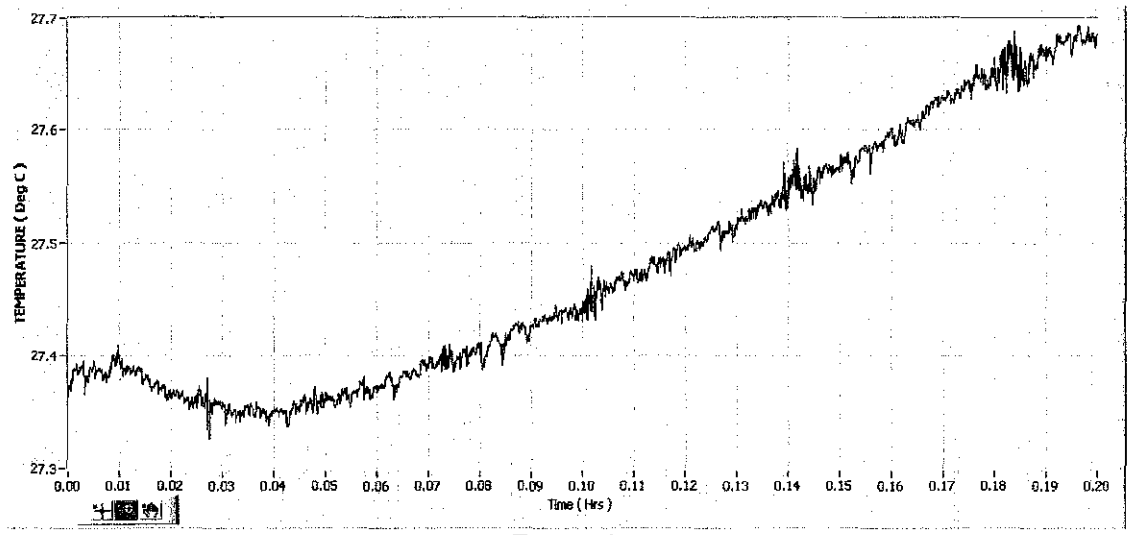


Figure 10

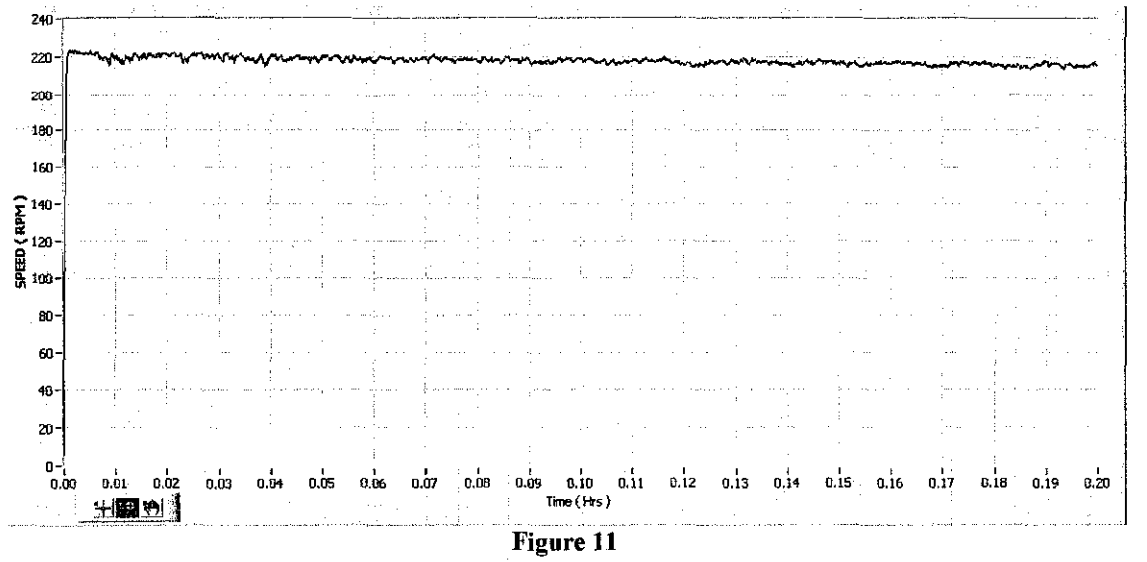


Figure 11

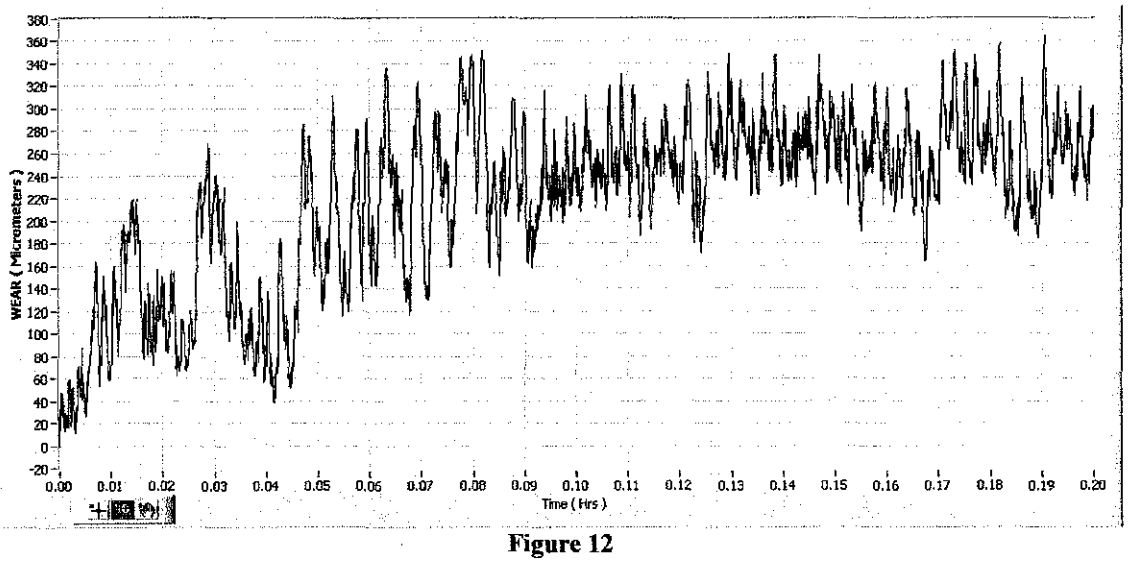


Figure 12

LOAD : 60N
REINFORCEMENT: CARBON UD
SPEED : 200rpm
CoF : **0.23444**

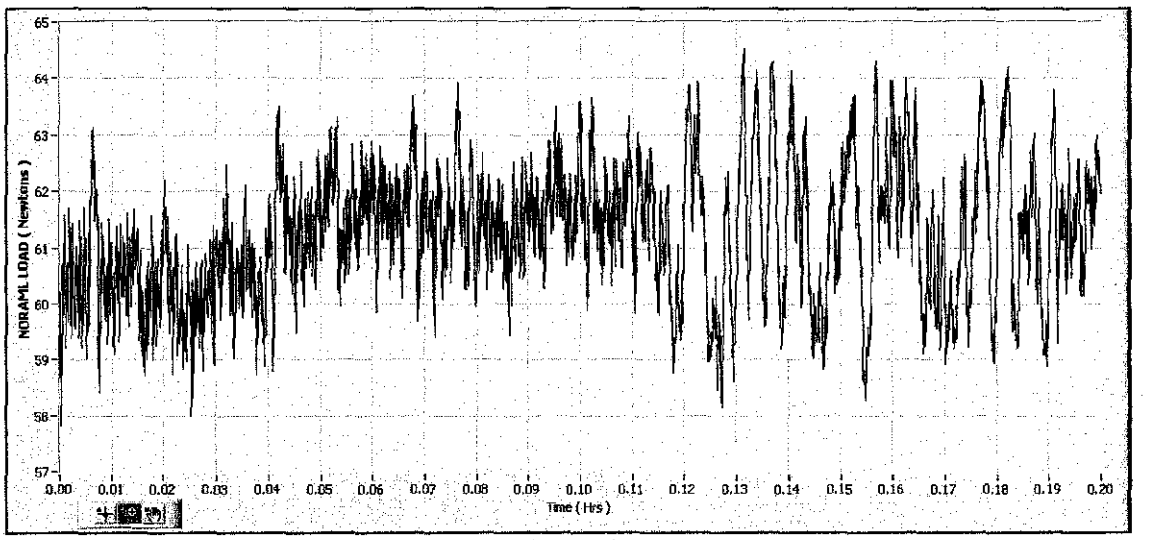


Figure 13

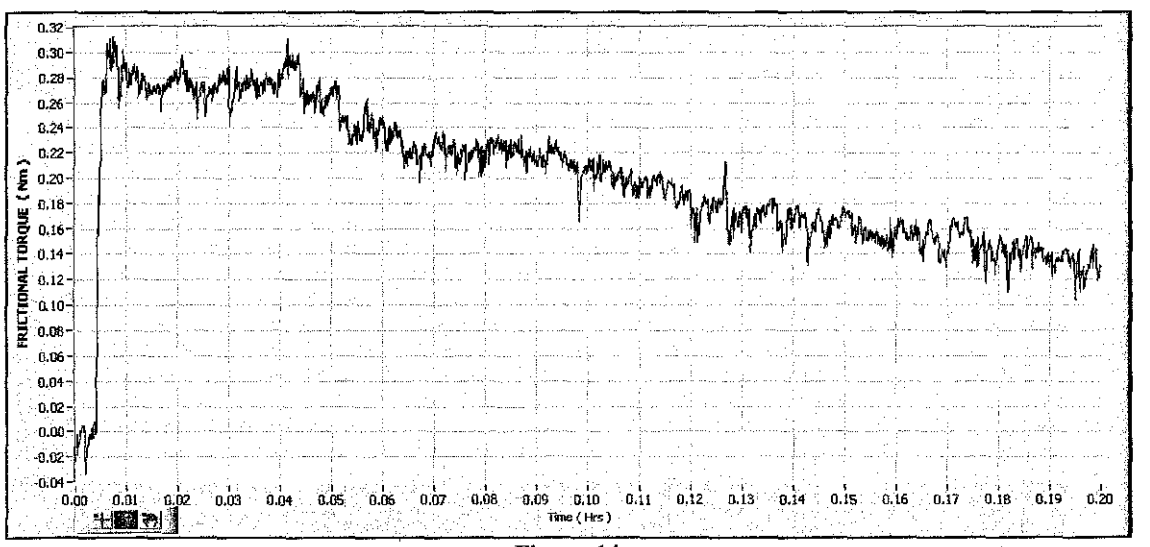


Figure 14

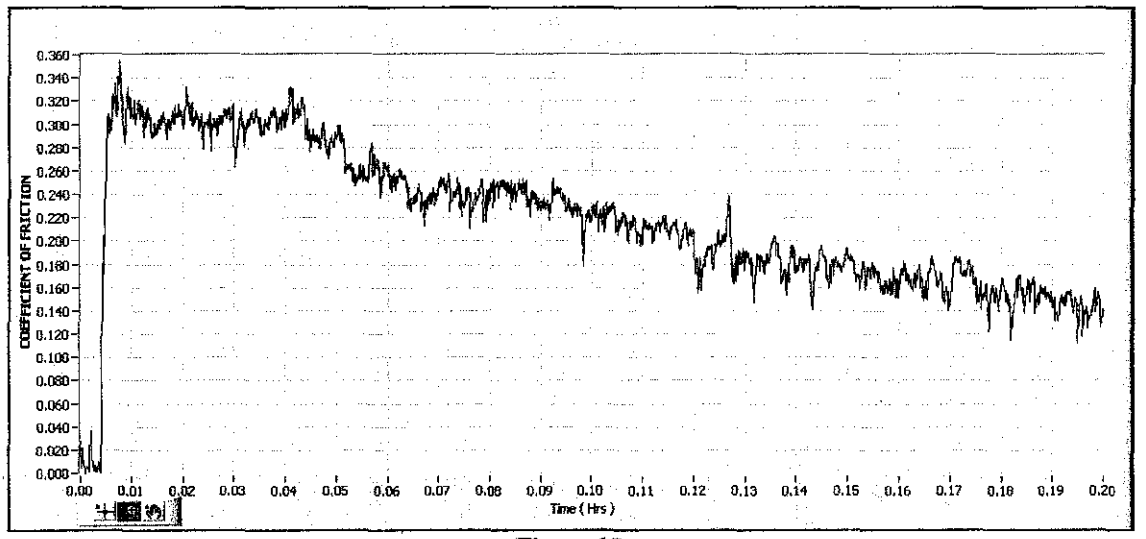


Figure 15

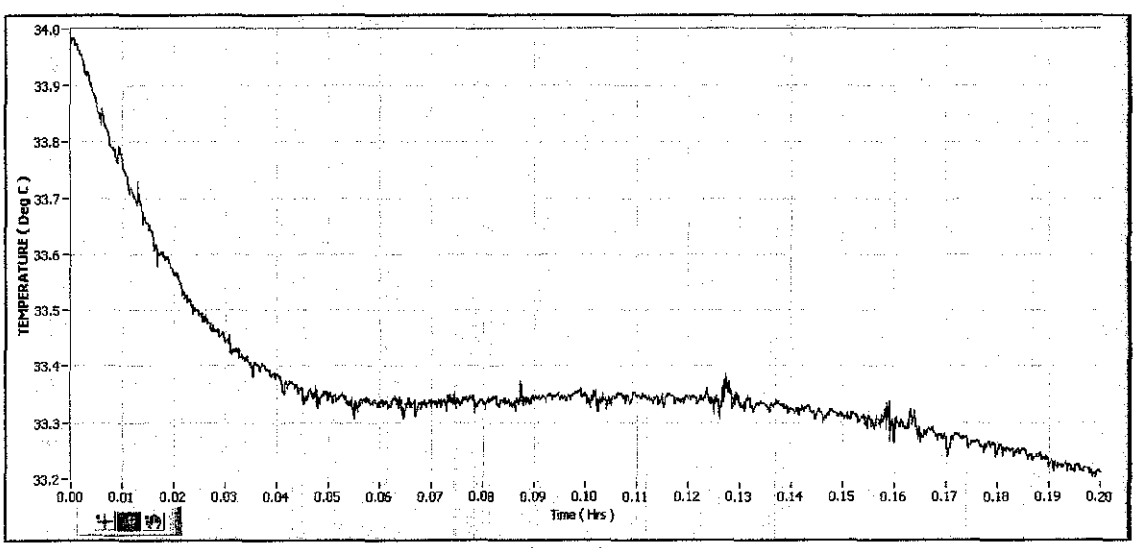


Figure 16

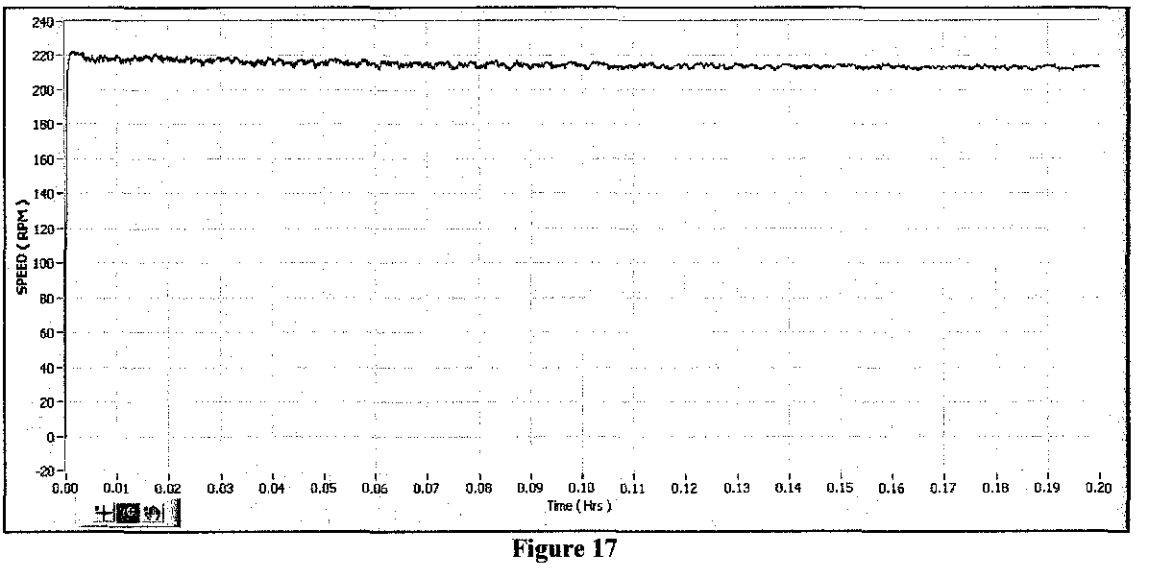


Figure 17

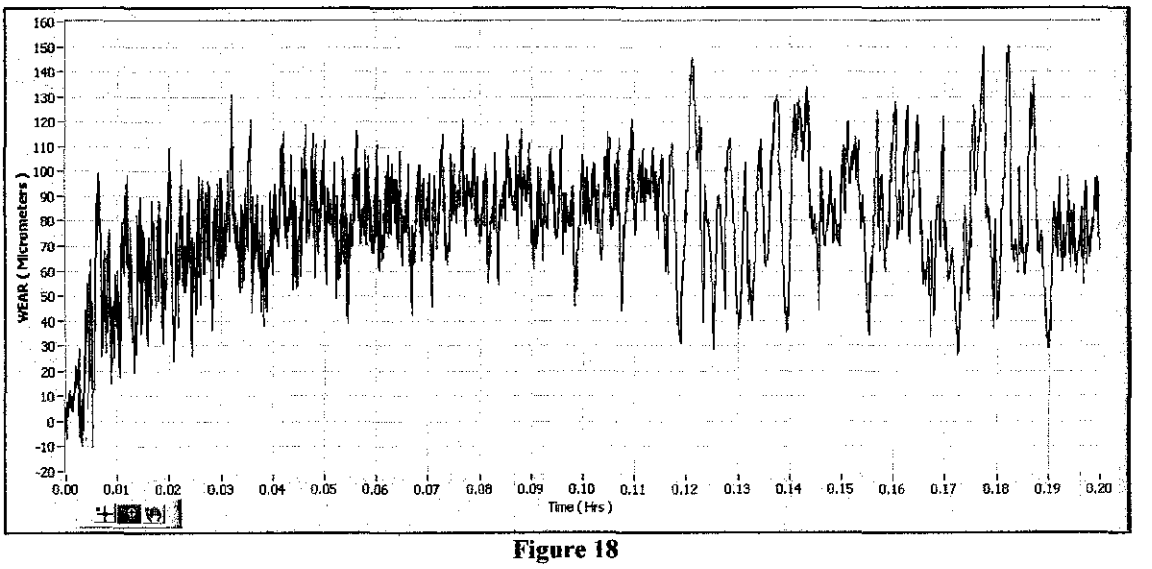


Figure 18

LOAD : 80N
REINFORCEMENT : CARBON UD
SPEED : 200rpm
CoF : **0.22059**

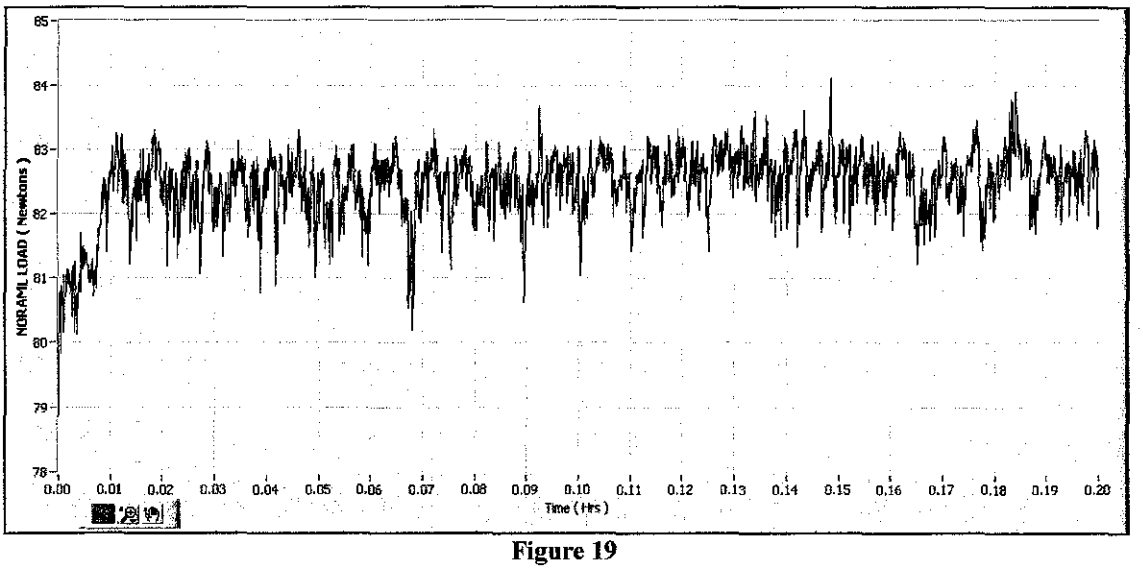


Figure 19

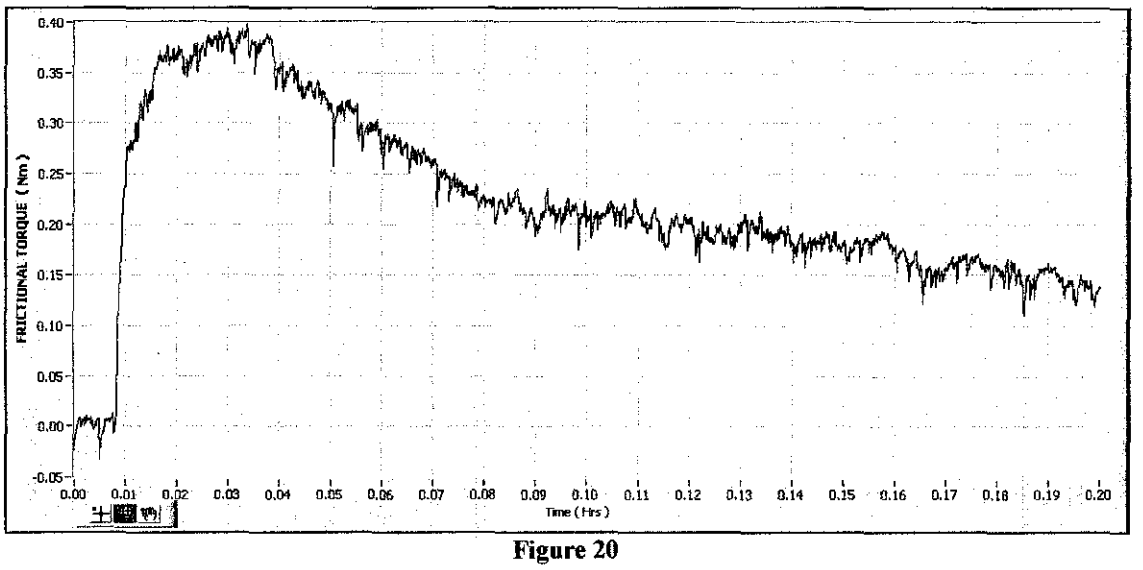


Figure 20

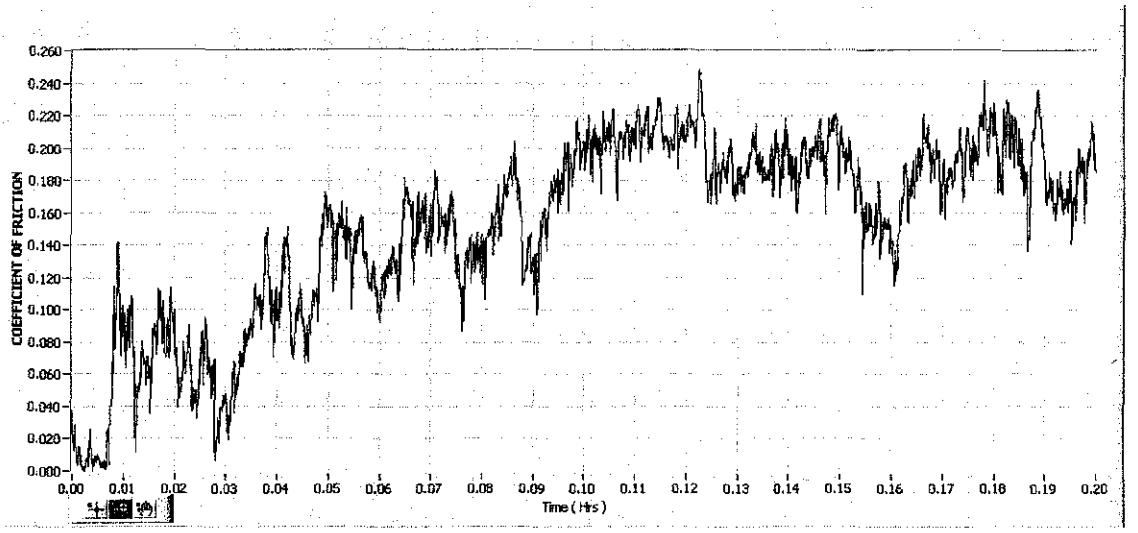


Figure 21

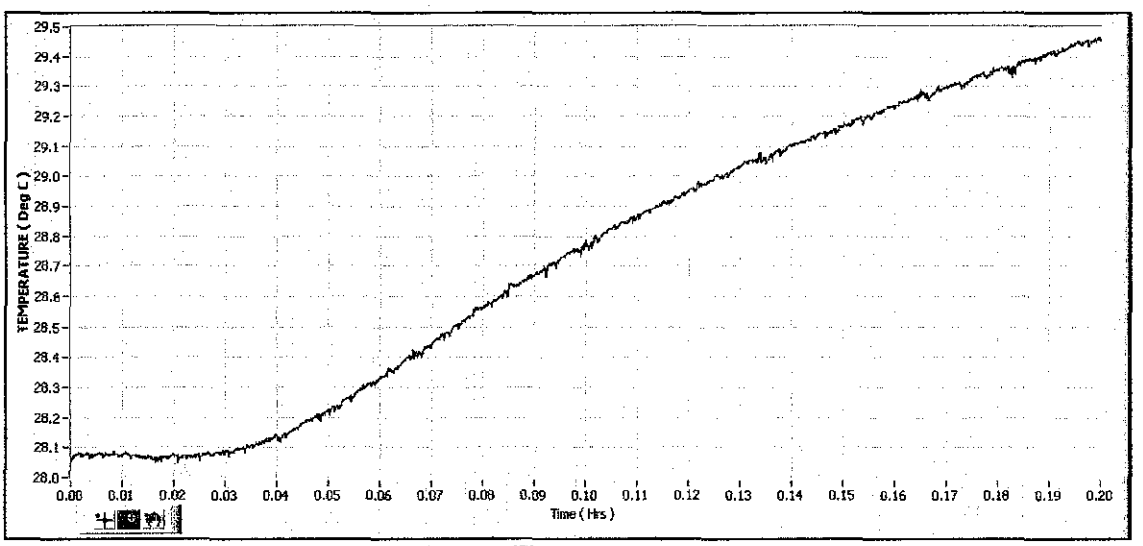


Figure 22

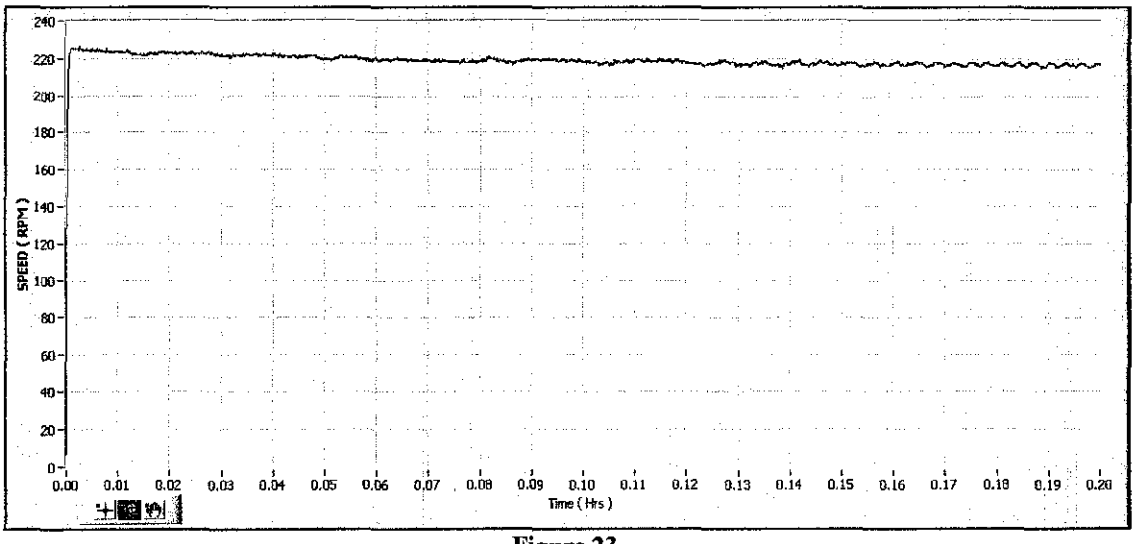


Figure 23

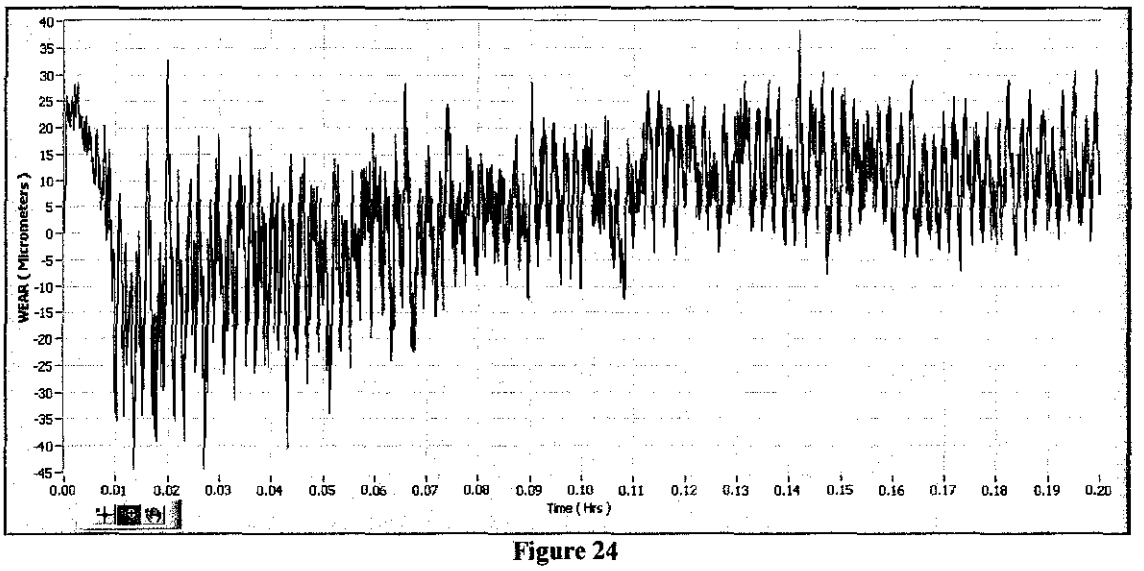


Figure 24

LOAD : 100N
REINFORCEMENT: CARBON UD
SPEED : 200rpm
CoF : **0.20943**

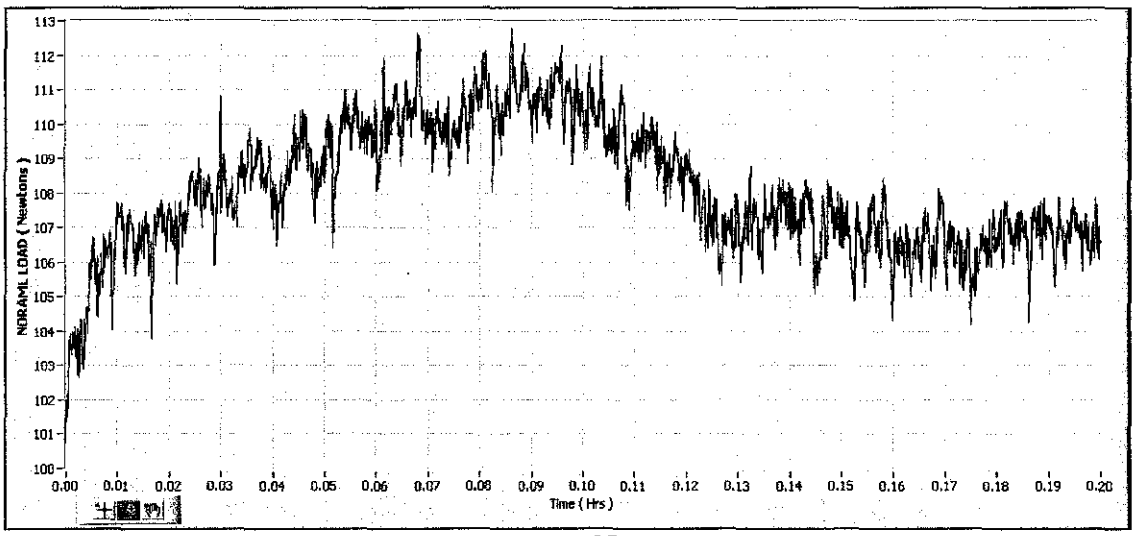


Figure 25

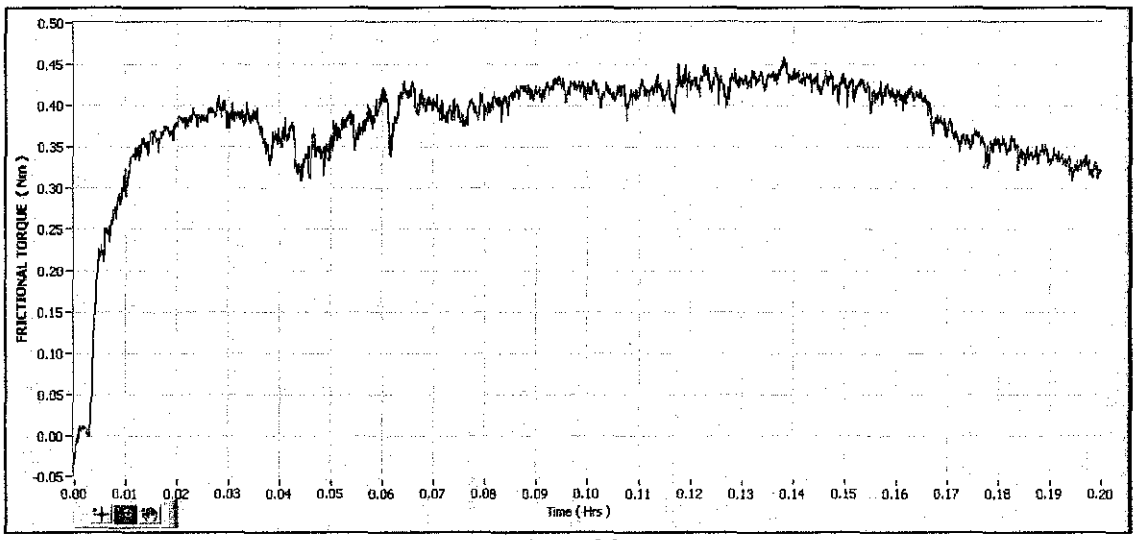


Figure 26

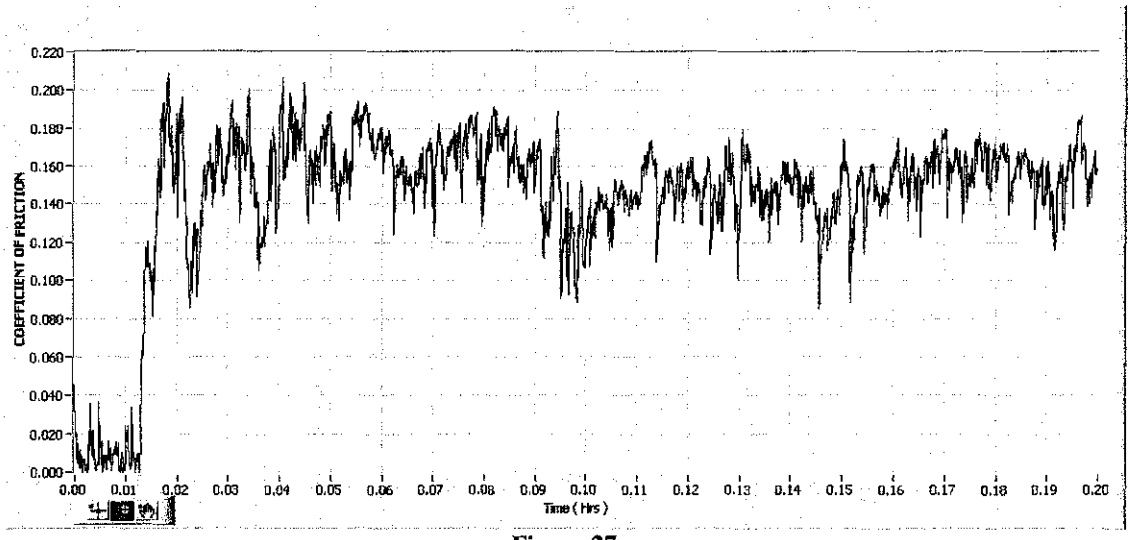


Figure 27

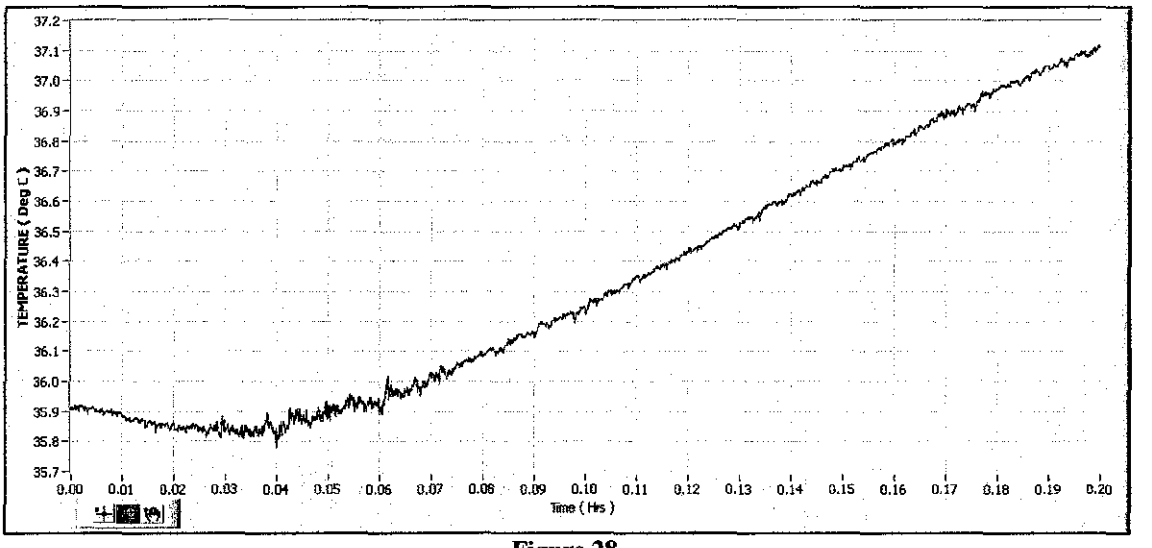


Figure 28

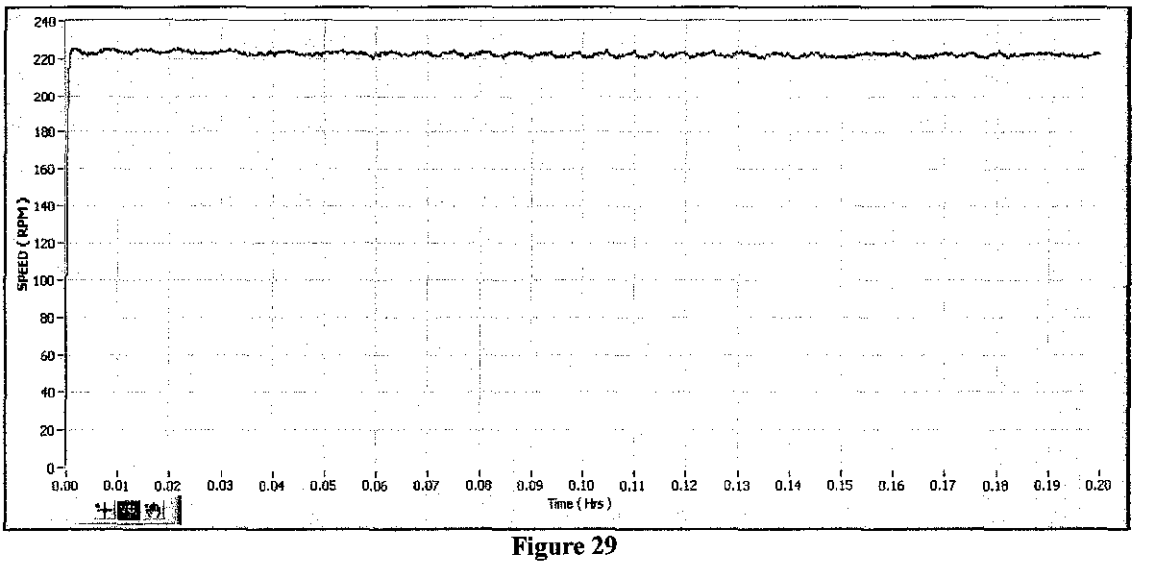


Figure 29

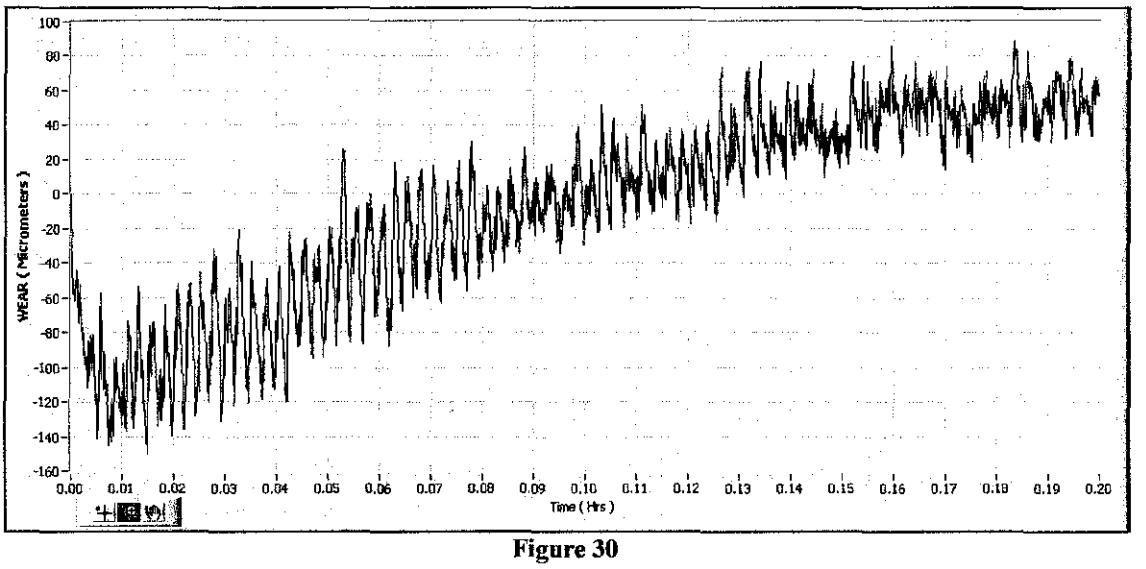

WEAR (Micrometers)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
Time (Hrs)

Figure 30

LOAD : 20N
REINFORCEMENT: CARBON WOVEN
SPEED : 200rpm
CoF : **0.26861**

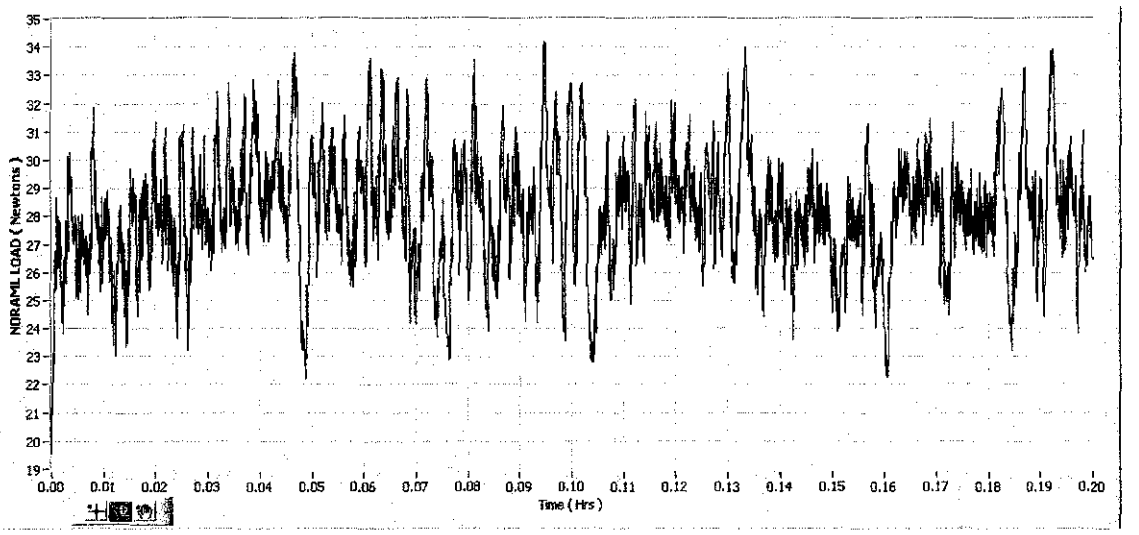


Figure 1

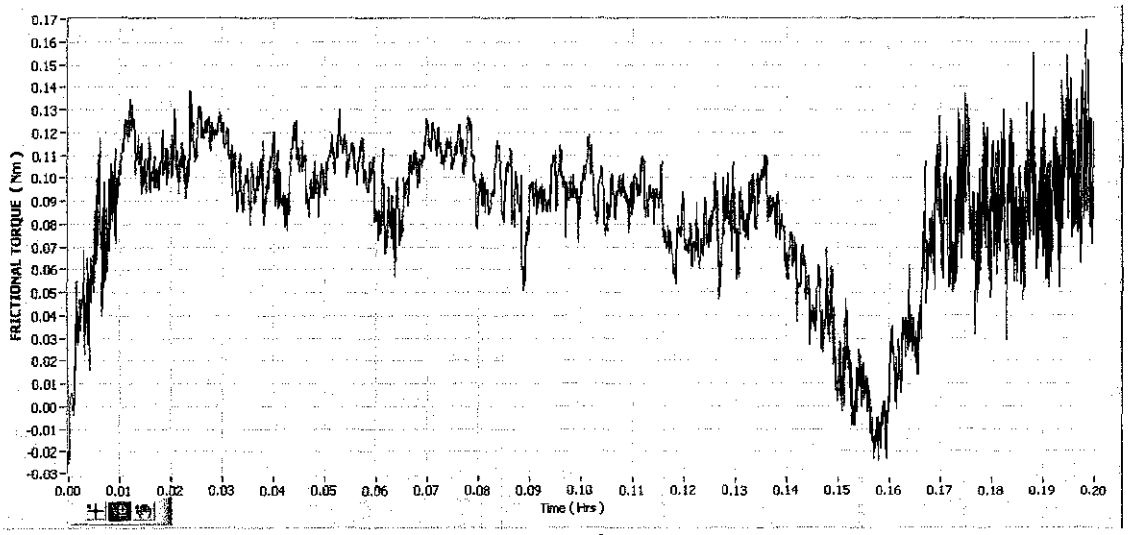


Figure 2

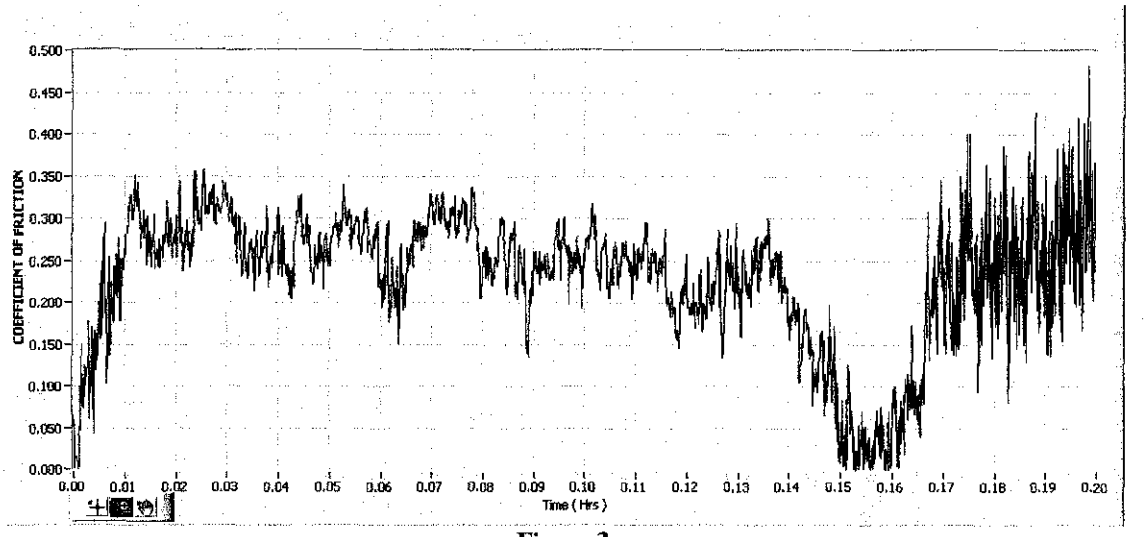


Figure 3

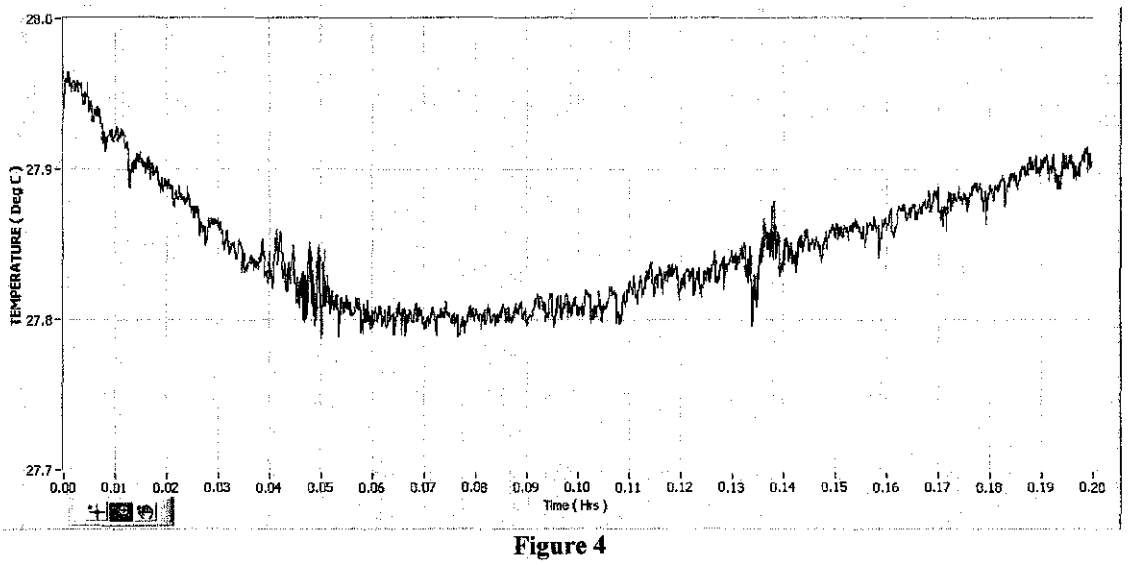


Figure 4

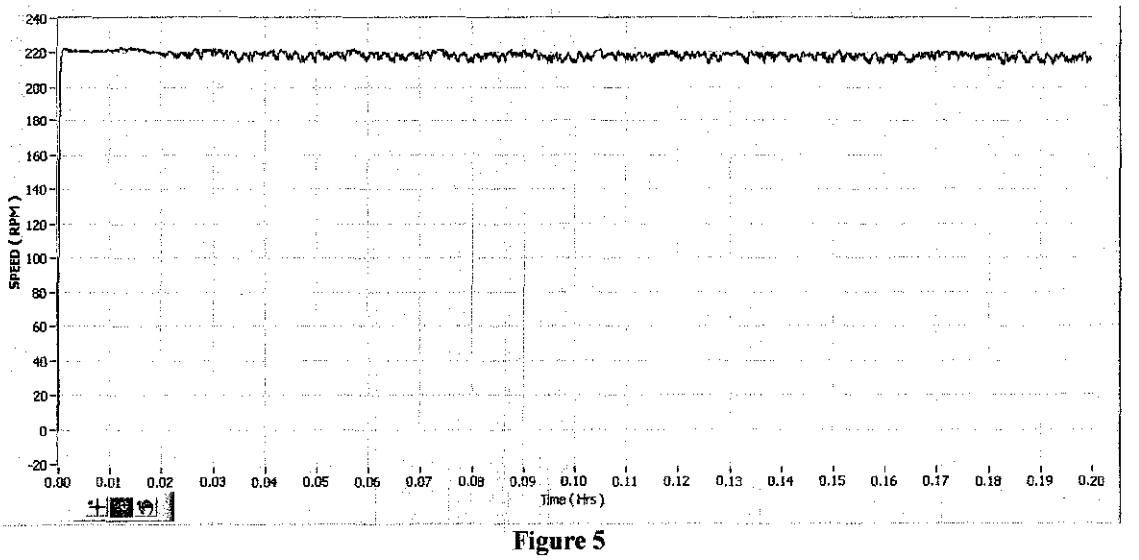


Figure 5

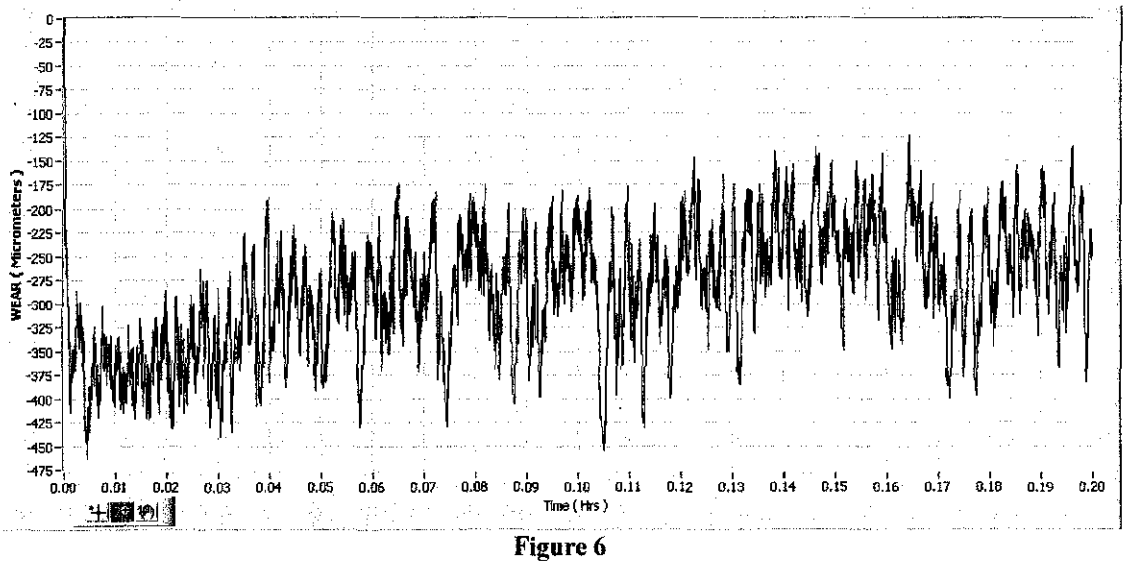

WEAR (Micrometers)
0
-25
-50
-75
-100
-125
-150
-175
-200
-225
-250
-275
-300
-325
-350
-375
-400
-425
-450
-475
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
Time (Hrs)

Figure 6

LOAD : 40N
REINFORCEMENT: CARBON WOVEN
SPEED : 200rpm
CoF : **0.2544**

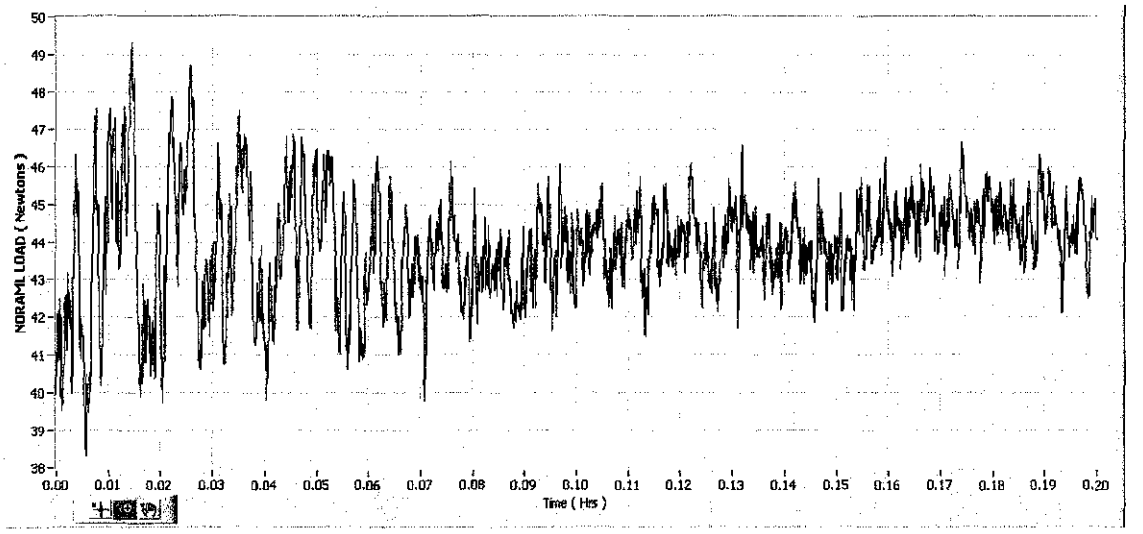


Figure 7

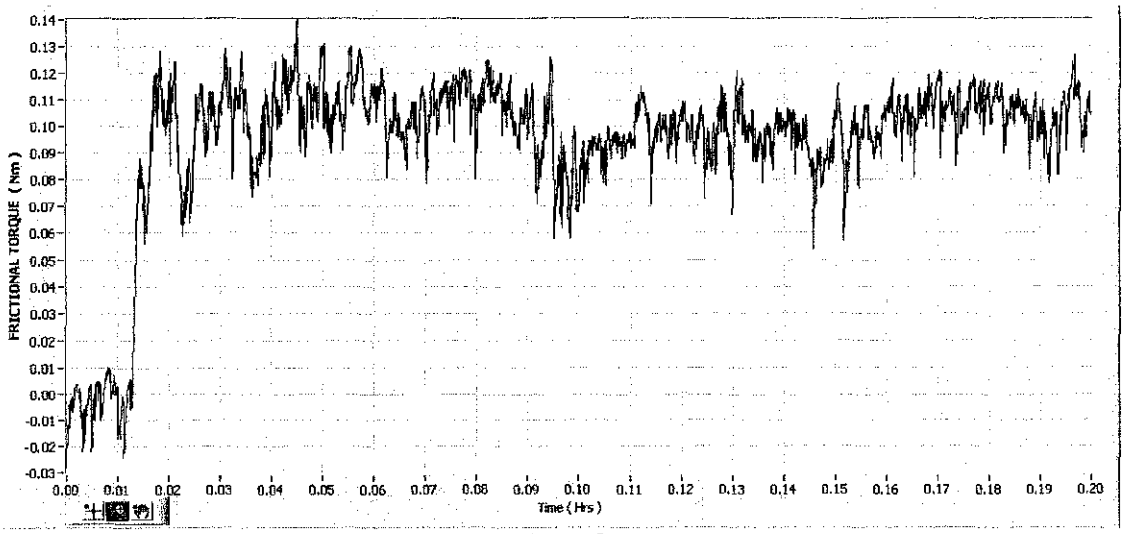


Figure 8

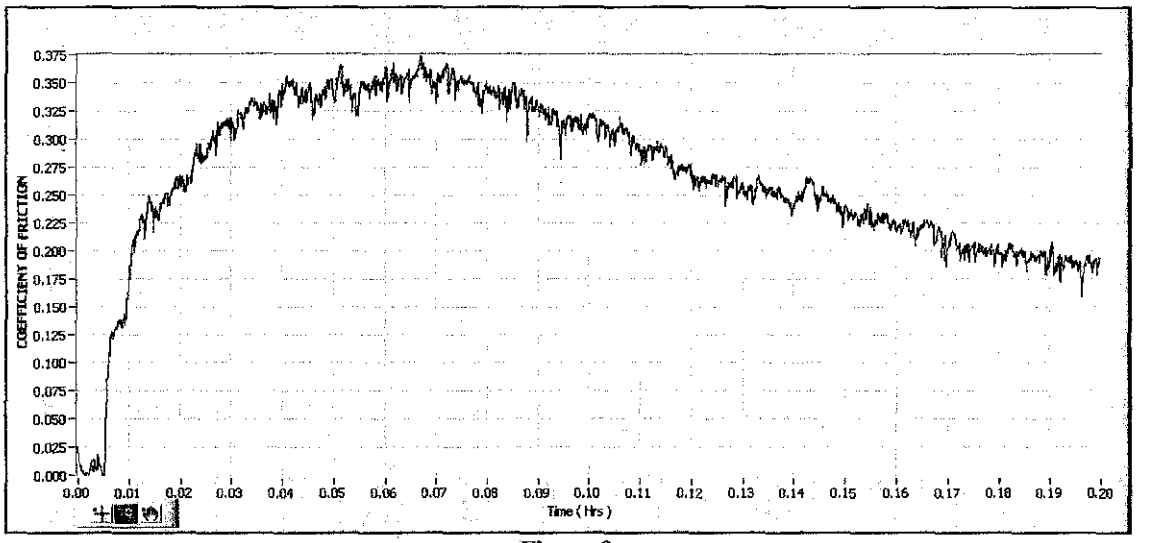


Figure 9

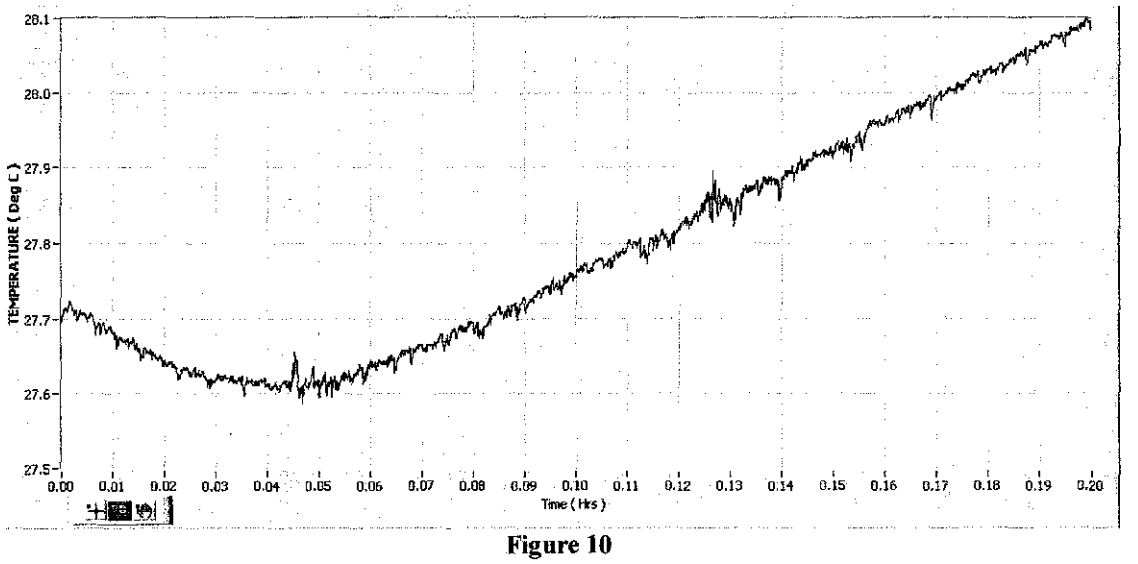


Figure 10

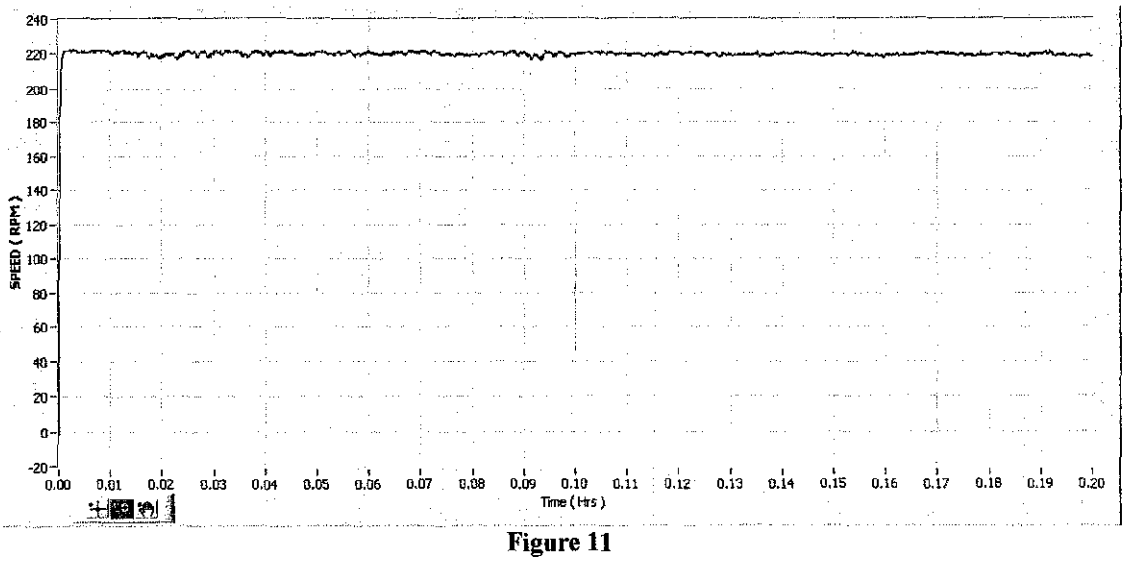


Figure 11

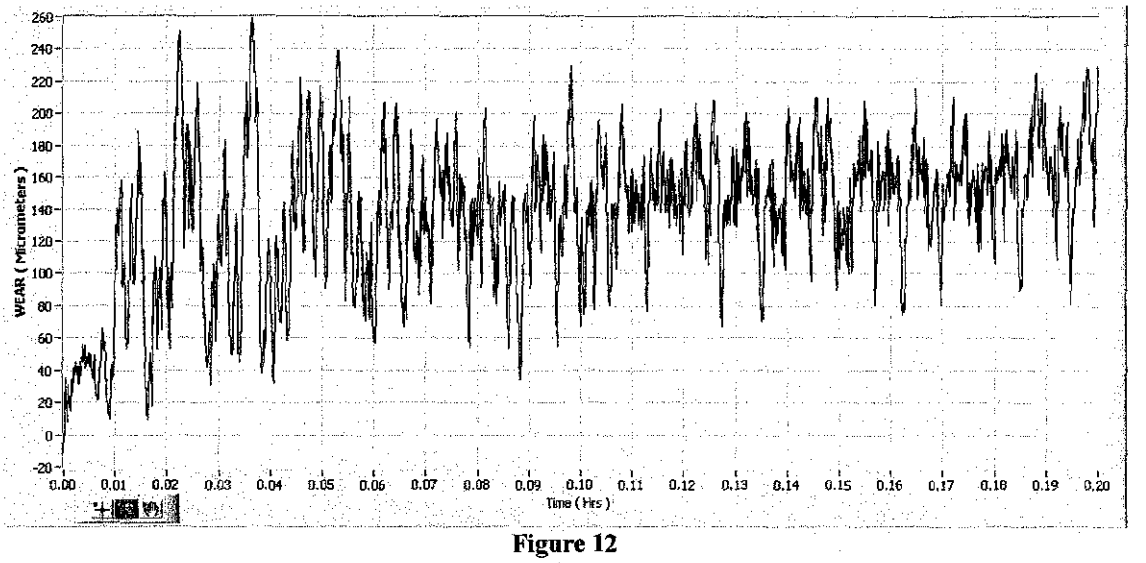

WEAR (Micrometers)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
-20
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
Time (Hrs)

Figure 12

LOAD : 60N
REINFORCEMENT: CARBON WOVEN
SPEED : 200rpm
CoF : **0.24349**

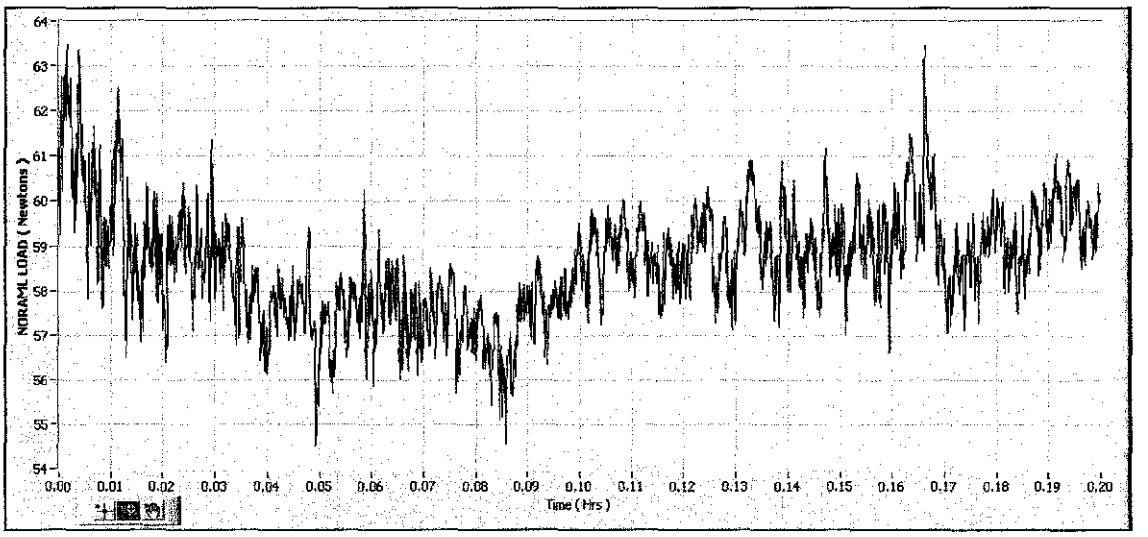


Figure 13

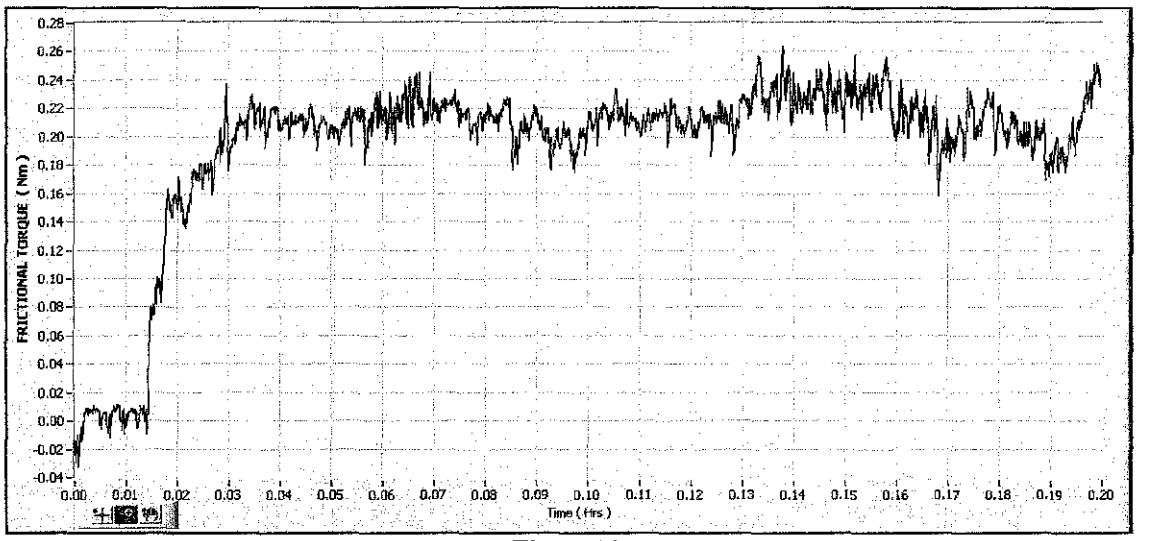


Figure 14

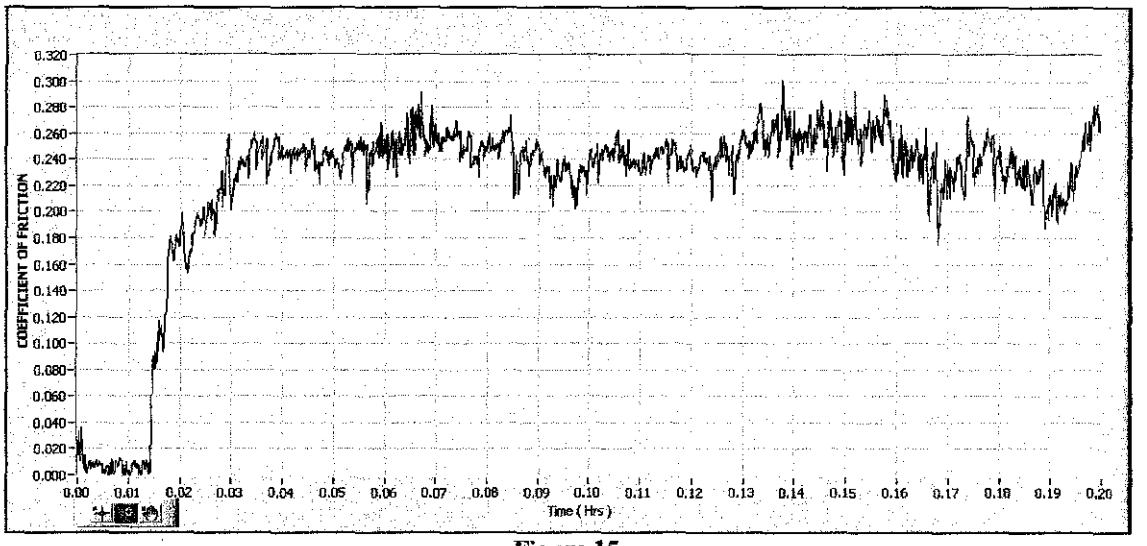


Figure 15

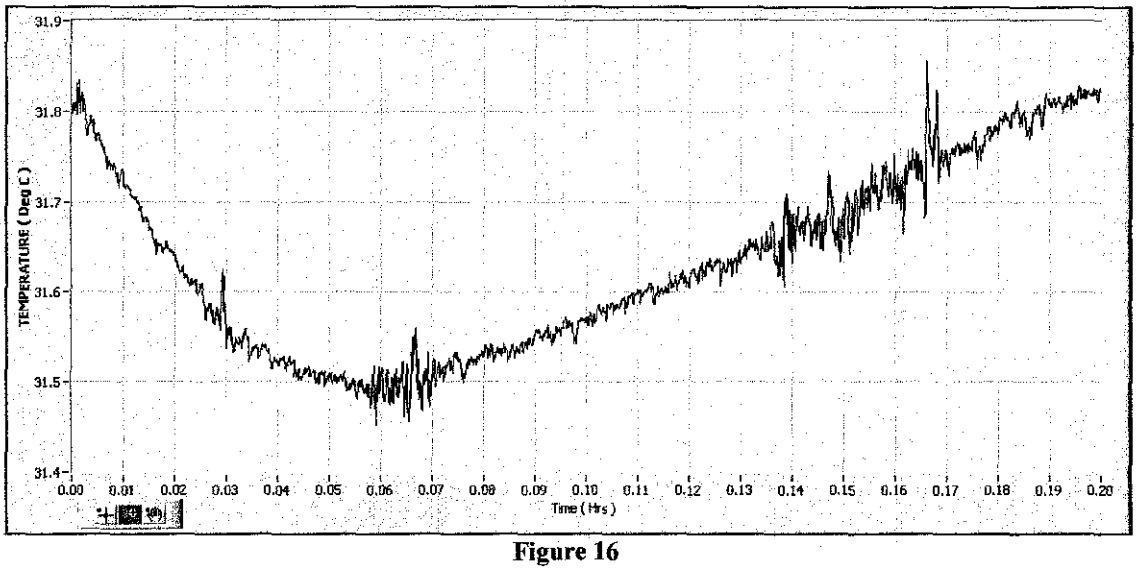


Figure 16

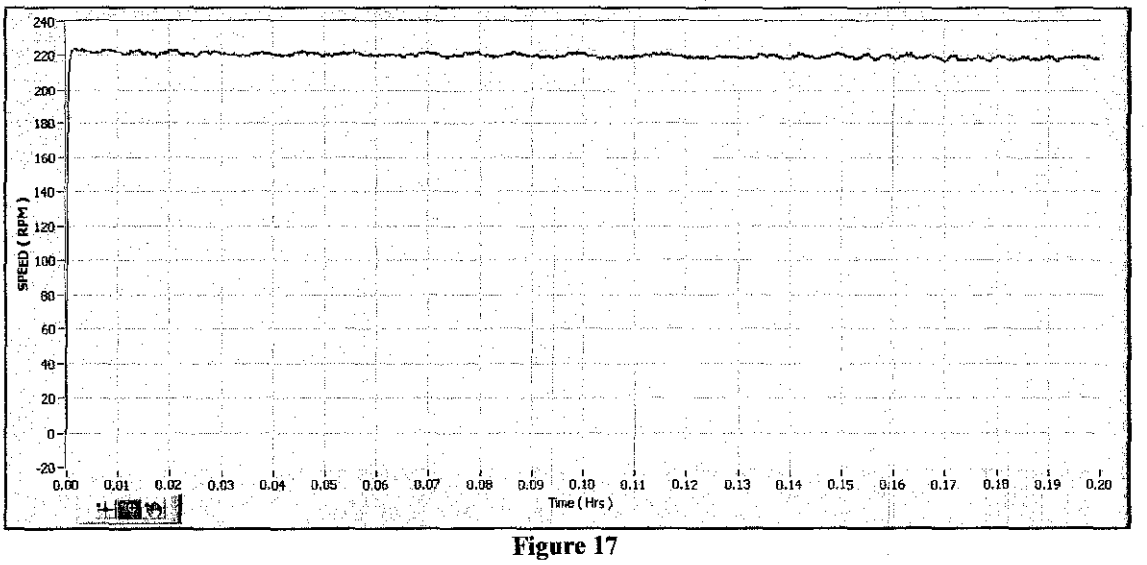


Figure 17

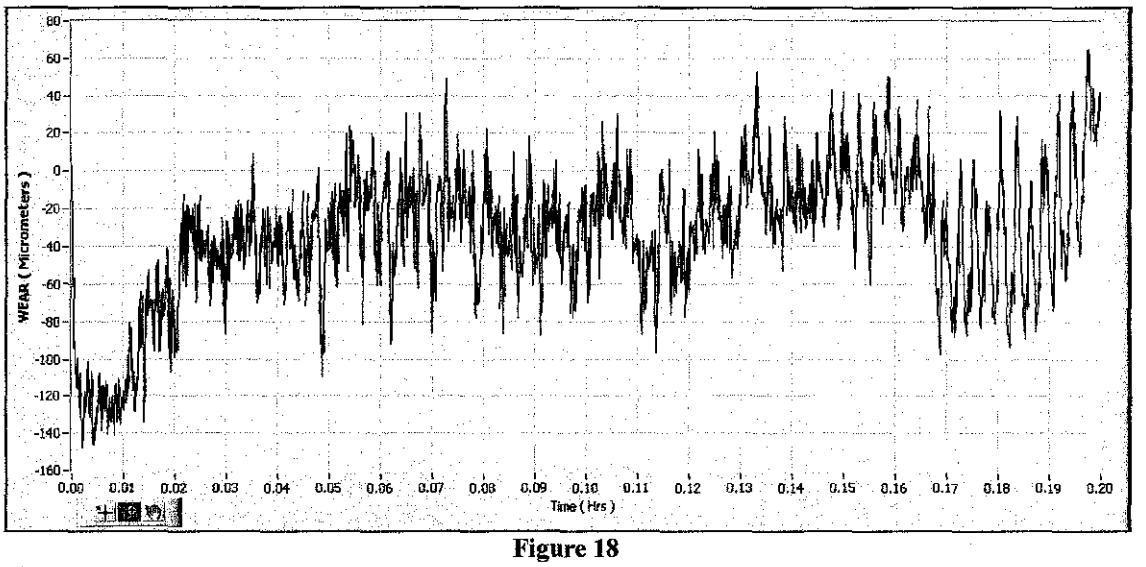

WEAR (Micrometers)
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
Time (Hrs)

Figure 18

LOAD : 80N
REINFORCEMENT: CARBON WOVEN
SPEED : 200rpm
CoF : **0.22536**

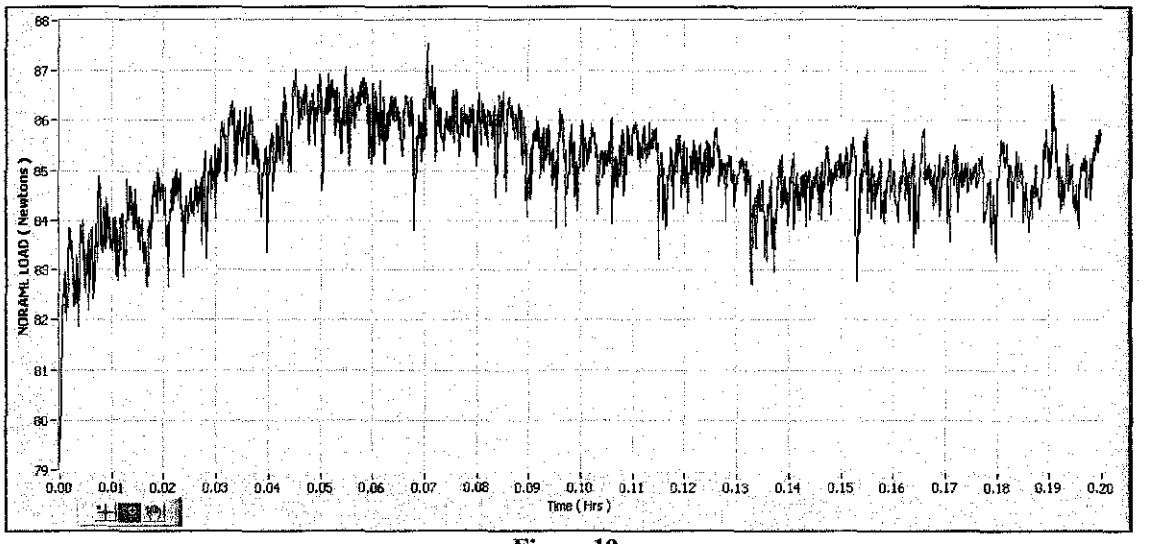


Figure 19

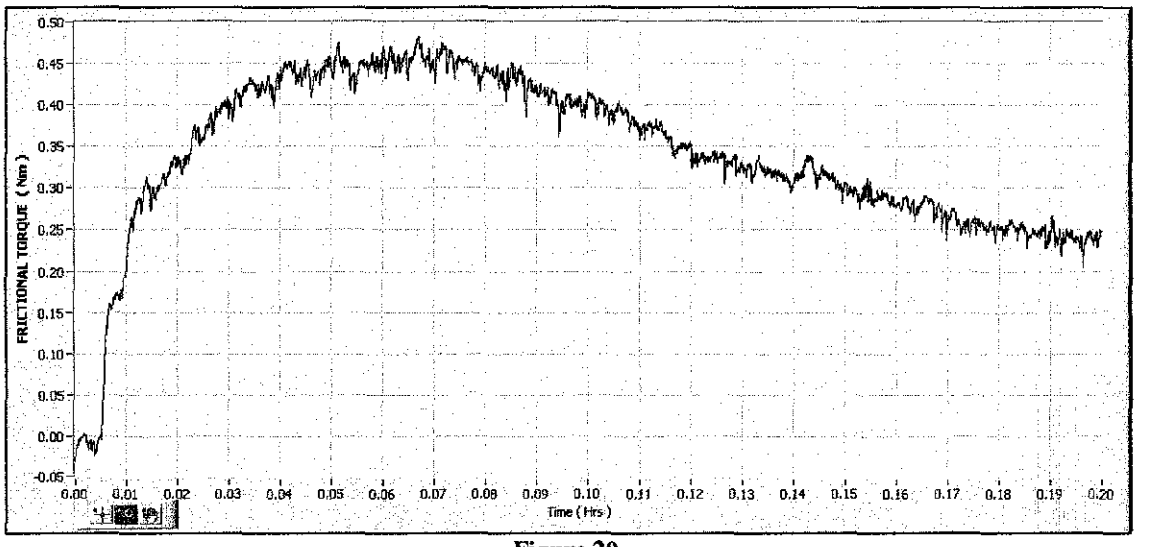


Figure 20

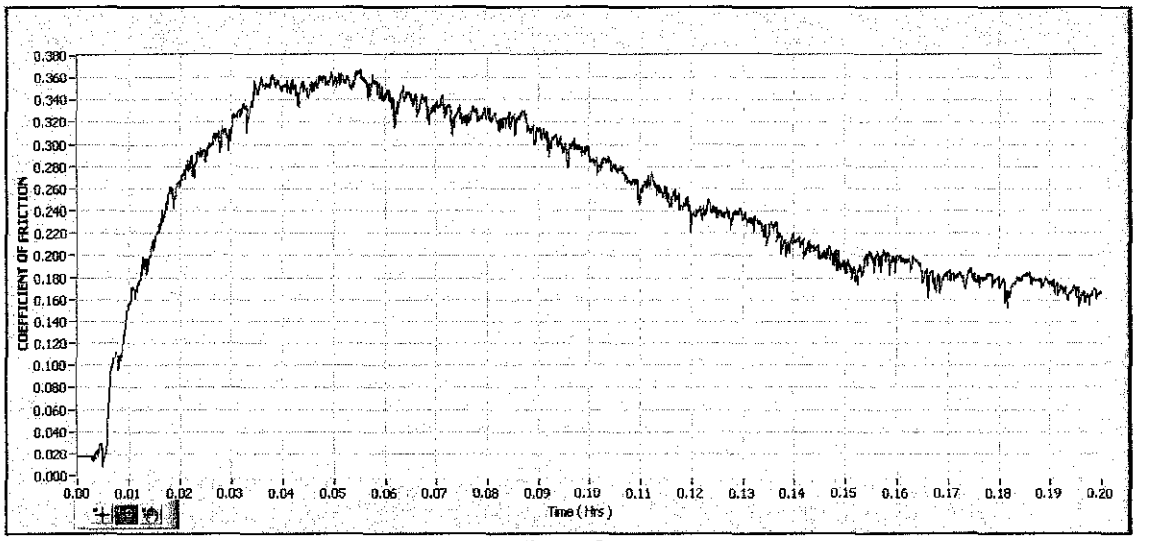


Figure 21

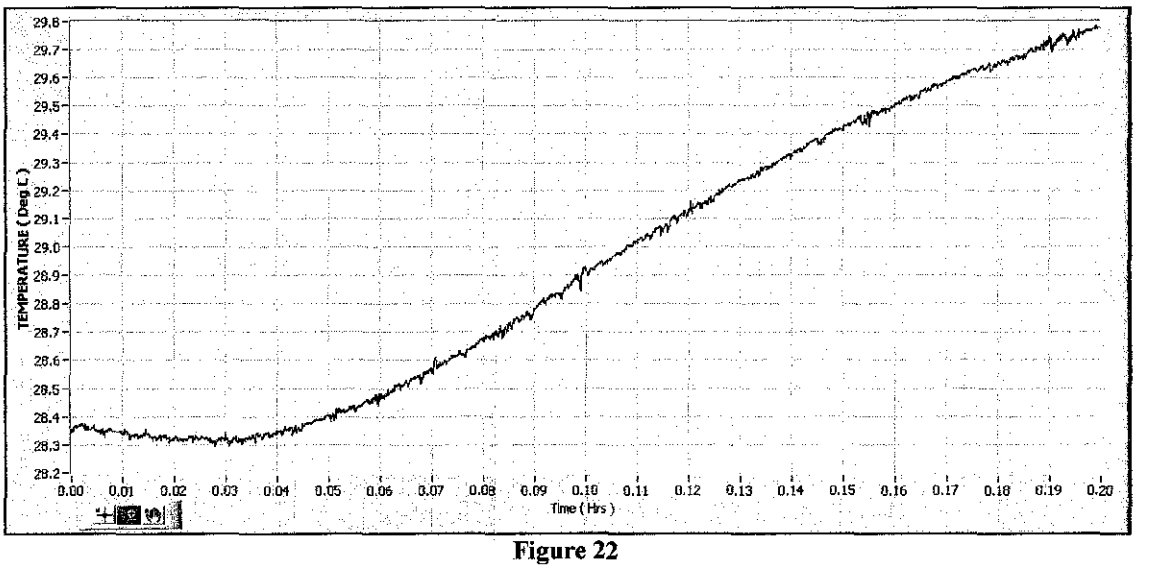


Figure 22

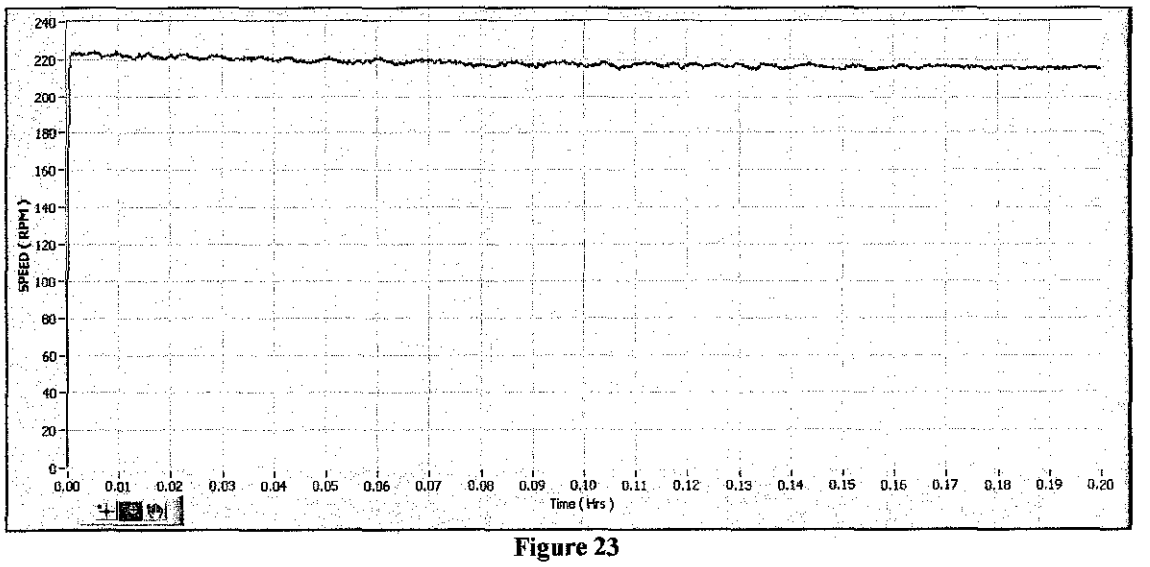


Figure 23

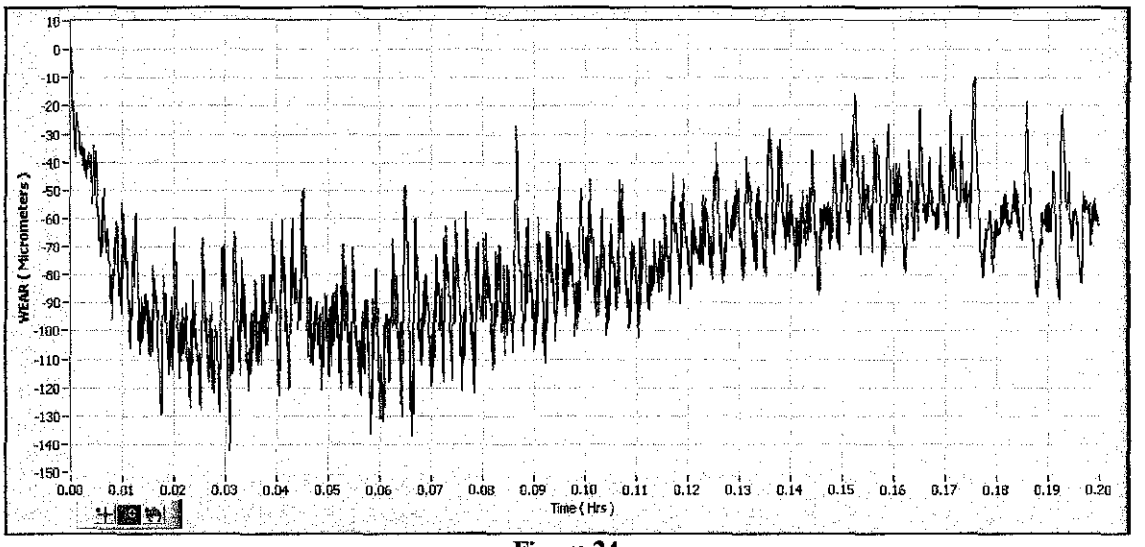

WEAR (Micrometers)
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
Time (Hrs)

Figure 24

LOAD : 100N
REINFORCEMENT: CARBON WOVEN
SPEED : 200rpm
CoF : **0.22113**

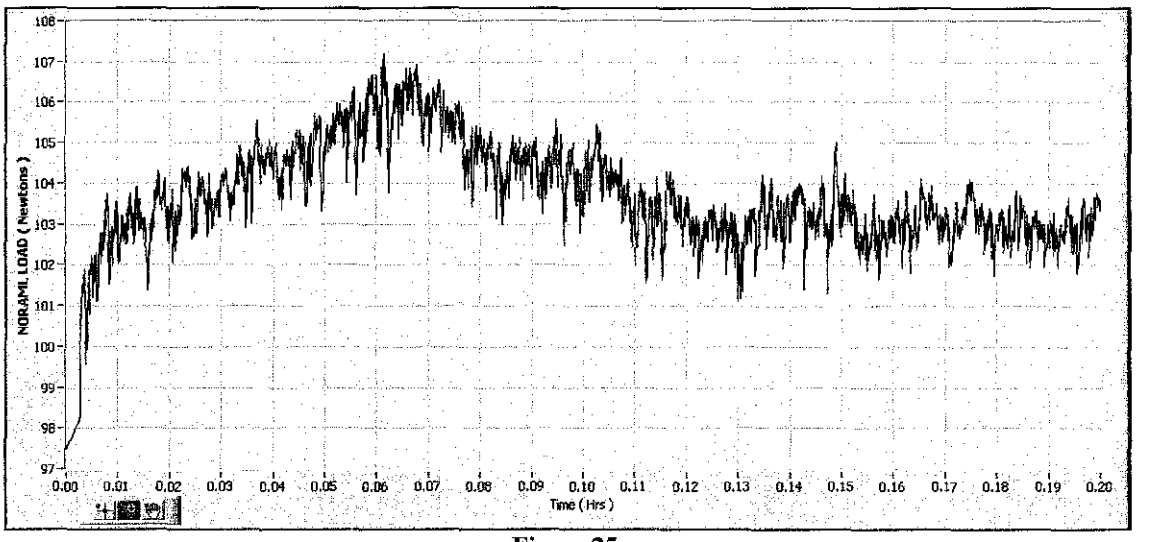


Figure 25

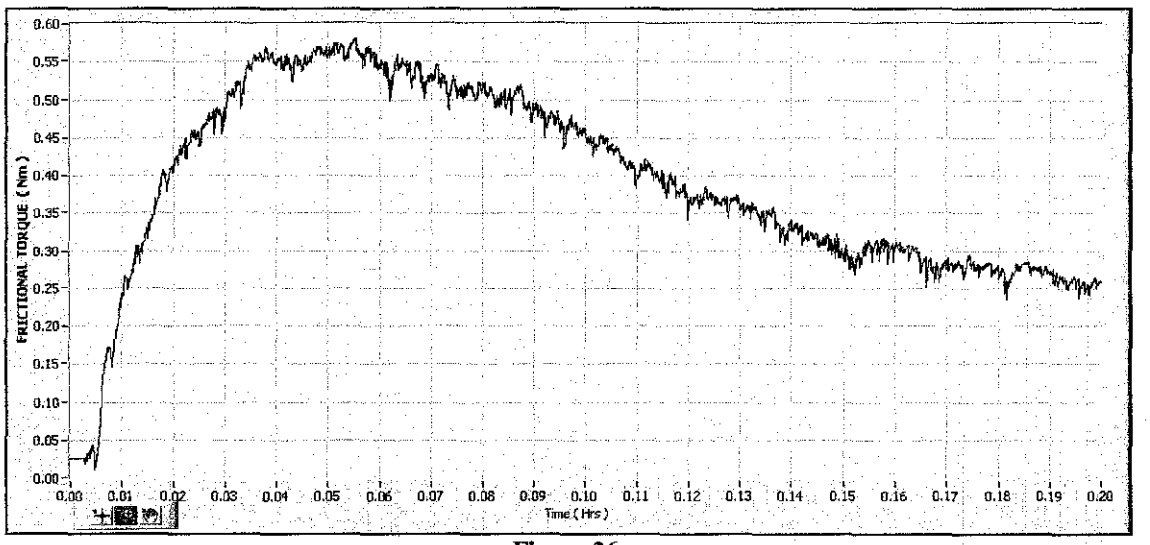


Figure 26

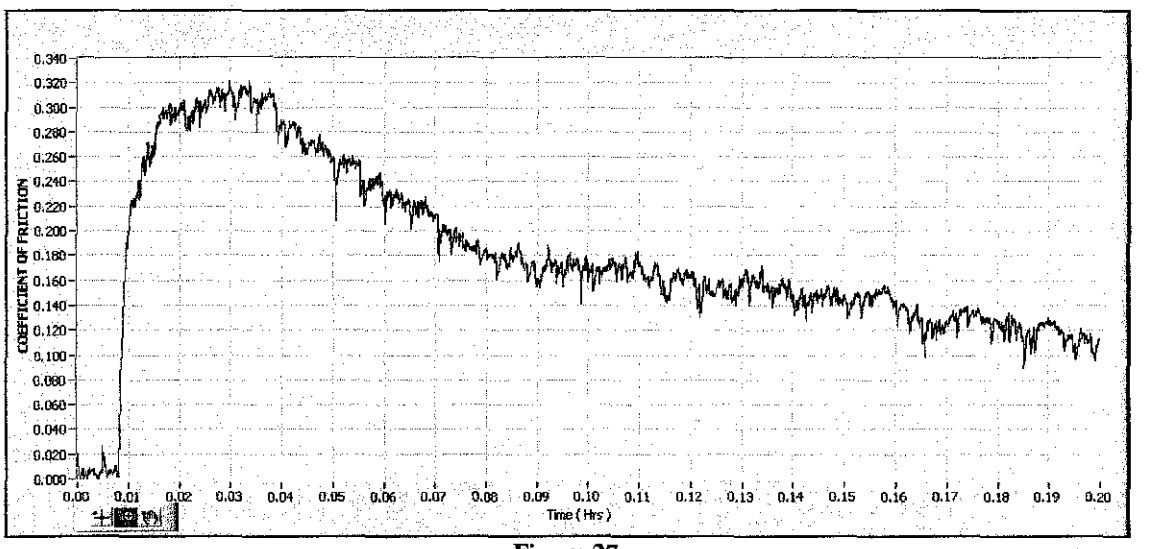


Figure 27

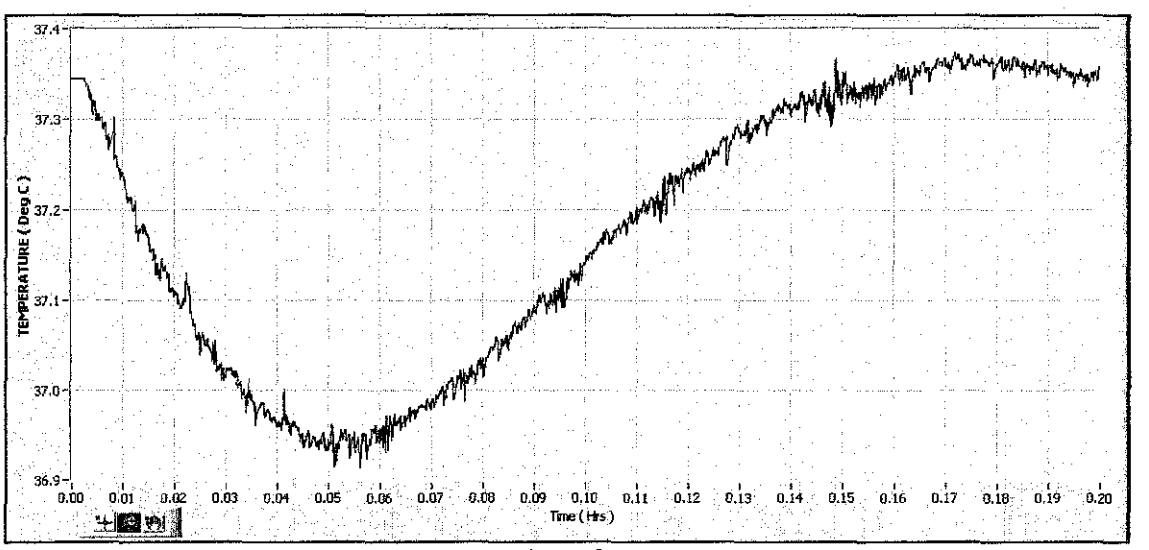


Figure 28

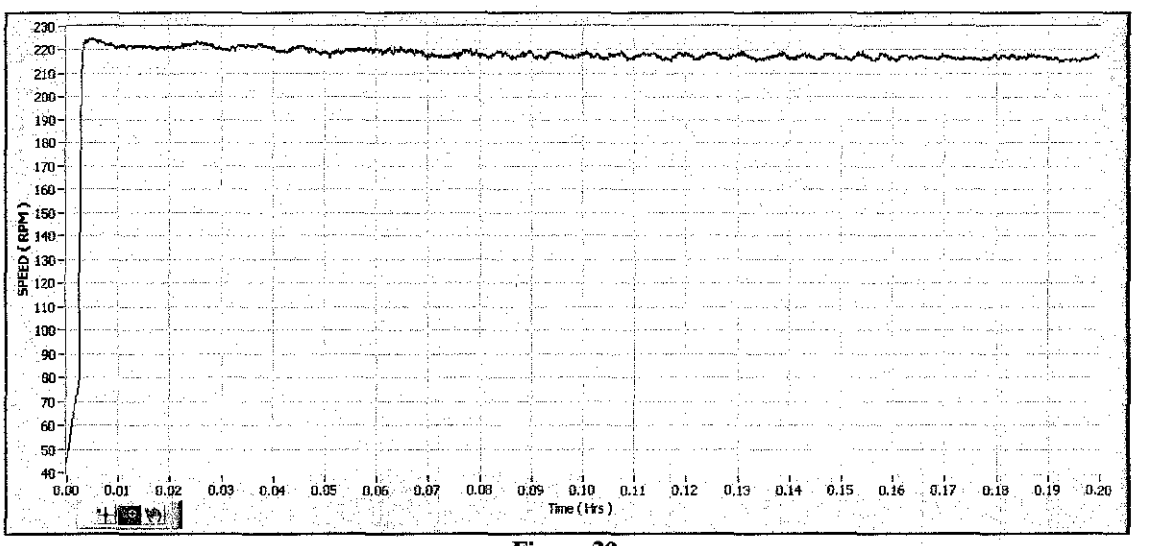


Figure 29

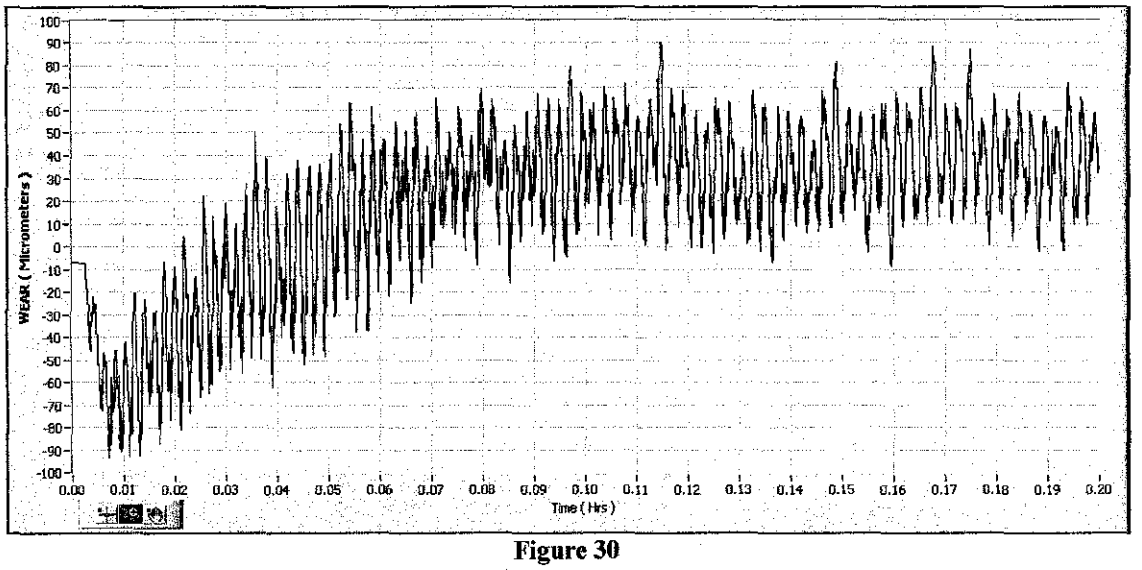

WEAR (Micrometers)
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
Time (Hrs)

Figure 30