Experimental Investigation of Wear Behavior of Polytetrafluoroethylene (PTFE) Composite to Enhance the Life of the Piston Rings

Pramod Ashok Bansode[1] Assistant Prof. D.U.Gopekar[2]
[1]PG Student [2]Assistant Professor
[1,2]Diems, Aurangabad, India

Abstract— Piston rings are the seals which are widely used in compressor for the prevention of leakage and increasing the efficiency of compressor. Due to the reciprocating motion of piston, these piston rings located in the grooves of the piston slides against cylinder wall surface, subjected to wear and gas pressure. The use of conventional materials like cast iron and steel subjected to high wear,noise and required lubrication. These materials were replace by materials which has extremely low coefficient of friction and high thermal stability and forms transfer films which reduced the further were and doesn't requires any lubrication. Currently used filler material in industry was bronze added base material. Many researchers has done to increase the life of piston rings with fillers carbon, graphite, bronze, glass etc. This paper presents a review of wear study of composites.

Keywords: Composites, Piston Rings, Wear Rate

I. INTRODUCTION

A reciprocating compressor or piston compressor is a positive-displacement compressor in which pistons is operated using a crankshaft to deliver high pressure output. It is used in various applications such as oil refineries, gas pipelines, natural gas processing plants and refrigeration plants as well as some specific application as manufacturing of plastic bottles of poly-ethylene-terephthalate (PET). In compressor piston and cylinder has clearance which is compensated using piston rings. Reciprocating action between piston and cylinder result in wear and tear of the contacting surface. This results in leakage of the medium and reduces the efficiency of the compressor. These can be reduced using piston and rider rings which provides sealing. Piston rings reduces the rubbing surface area hence reduces the possible wear between piston and cylinder and improves piston efficiency. These rings are generally made up materials such as steel and cast irons.

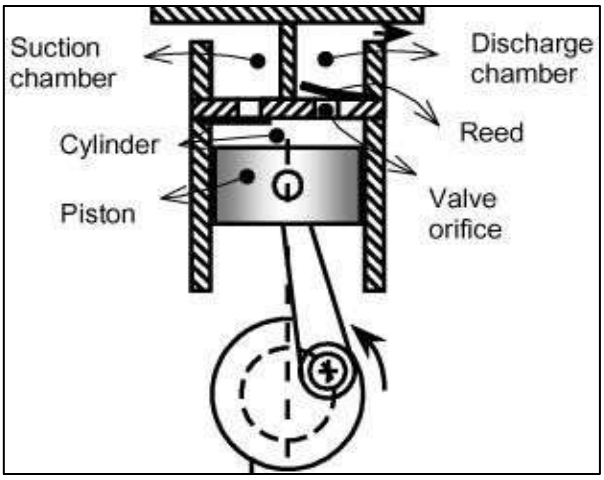


Fig. 1: Working of the reciprocating compressor

The disadvantages incurred in using these traditional materials:

- Lower Piston life because of high wear
- Excessive noise generation
- Assembly weight considerably high
- Piston rings being metallic, need for continuous lubrication
- Problem of leakage High maintenance

These drawbacks can be overcome by providing proper lubrication which increases the life of piston rings but also increases the weight hence decreases efficiency of the compressor. This problem is solved by the use of dry gas seals.

- Dry gas seals are an integral part of modern centrifugal and reciprocating compressors
- It doesn't require lubricating oil, chemical.
- Purpose of these seals is to prevent leakage of highly hazardous gas to atmosphere

Polytetrafluoroethylene (PTFE) is an engineering plastic generally known as Teflon with unique chemical, thermal, tribological and electrical properties. PTFE is composed of long, straight chains of fluorinated carbons. PTFE is a popular polymer solid lubricant due to its resistance to chemical attack in a wide variety of solvents and solutions, high melting point, low coefficient of friction, and biocompatibility. It is generally used in bearing and seals applications. Unfortunately, PTFE suffers from poor wear resistance due to its relative softness. Its load-carrying ability and its wear resistance might be improved by the addition of suitable fillers. Accordingly, several fillers are tried by researchers in combination with this plastic, such as graphite, molybdenum disulphide, fibre glass, carbon, bronze, dental silicate, silicon, titanium dioxide, silver, copper, tungsten and molybdenum.

It was observed that PTFE composites with metal counter face sliding system provides low friction and wear under dry sliding condition. It's self-lubricating ability deposits a thin layer of polymer on the counter face, this film is called as transfer film.

Properties of PTFE:

PTFE has different mechanical thermal chemical properties which are given below:

Sr.no	Property	value
1	Specific Gravity	2.15
2	Tensile Strength	21-34 MPa
3	Elongation	300-500%
4	Flexural Modulus	496 MPa
6	Impact Strength	18.9 KJ/m^2
7	Hardness	50-65 Shore D
8	Coefficient of Friction, Dynamic	0.05-0.10

Table 1: Mechanical properties

Property	Value
Melting Point	327 °C
Cure Temperature	379-429 °C
Heat of Combustion	5.1 MJ/kg
Coefficient of thermal conductivity	5.86*e-4 cm-sec degree celcius
Coefficient of thermal expansion	9.6*10^-5 mm/mm ^{0}C

Table 2: Thermal properties of PTFE

A. Factors affecting polymer composite wear and friction

There are many factors that affect material tribological properties. For polymer composites the most influential are:

1) Normal load:

In order for a polymer composite to function as a solid lubricant it must be able to support the load, as well as the tangential stresses induced by sliding. At high loads severe wear occur, characterized by brittle fracture or severe plastic deformation. On the other hand, at low loads usually mild wear occur, characterized by the local plastic flow of the thin transfer film and surface layers (decreasing friction), together with delaminating wear.

2) Contact area:

The contact area will determine the projected contact stresses. If the load cannot be reduced, one way of reducing stress is to increase the projected contact surface. Nevertheless, if the surface of contact becomes too large instead of the material flowing over the counterpart surface, it will have a tendency to build up, forming ridges, which can cause high localized stresses and higher adhesion, thus higher friction and wear. It is essential to engineer a part with correct match up of load and contact surface.

3) Sliding speed:

The high sliding speeds can generate high temperatures because of friction heating. This may cause the polymer or the polymer composite additives to degrade. However in some cases higher temperature might be beneficial to the lubricating process. In order to develop a surface shear film and/or a transfer film, the molecular chain must have time to reorient. If one slides too fast over these un- oriented chains, instead of reorienting, they will fracture, leading to the production of large wear particles and high wear. Thus it is important to choose sliding speed for each particular polymer to ensure the optimum performance.

II. IMPORTANCE OF PROBLEM

The present work "Experimental Investigation of Wear Behavior of Composite Material to Enhance the Life of the Piston Rings," has been undertaken keeping into consideration the following problem: During working of the reciprocating compressor there is the friction between the cylinder wall and the piston rings due to the reciprocating motion of the piston. At high working conditions the piston rings are subjected to reciprocating action at very high speed. Along with this mass of the piston ring is somewhat increases to bear this load. These will causes excessive wear of the piston rings causing earlier failure and decreases the life of the piston ring. Therefore, present study focuses on development of novel piston ring material in order to enhance its working life.

A. Objectives:

1) Identification of composite material.
2) Wear study of proposed composite material under different condition such as load, sliding velocity (RPM), pin temperature over fixed time.
3) Find out the empirical relationship between the input parameters (Pressure, RPM, and temperature) and output (Specific wear rate) by preparing mathematical model for the prediction of pin wear.

III. LITERATURE SURVEY

Polytetrafluoroethylene (PTFE) is a fluorocarbon commercially known as Teflon which is a DuPont company registered trademark. It is white or grey waxy solid, tough, strong, non-flammable. It is used for wiring in aerospace and computer applications, insulator, handling and storing corrosive chemicals, non-stick coatings etc. PTFE can be widely used as a non-metallic material in various applications due to the reasons like extremely low coefficient of Friction, chemical inertness and thermal stability. It can be used in the friction and wear application. PTFE when rubbed against surface forms transfer film on that surface which plays vital role for the reduction in wear. Although, the use of PTFE is limited by the poor mechanical properties like the low load carrying capacity, high wear rate and high percentage elongation. This is overcome by adding various filler materials as reinforcements in pure PTFE. The most commonly used fillers are carbon, glass, graphite, bronze, MoS_2, alumina, PEEK (polyetheretherketone), potassium titaniate whisker (PTW). Along with this other fillers used ekanol, polyethersulphone, poly-p-phenyleneterephthalamide (PPDT) fibres etc.

Carbon is widely used as compared to other fillers as it increases the wear resistance of the base material, tensile strength, impact strength and hardness. Moreover, with small addition of Carbon, mechanical properties improve considerably when compared with other fillers [1], which need to be added in large proportions. Appropriate percentage of carbon found to be 15% [5].

Treatment of carbon with rare earth also improves the mechanical properties and reduce the wear rate. [6].

Glass when used as filler in PTFE improves the hardness, tensile strength. It also reduces wear rate and improves the load carrying capacity of the composite and capable of making the transfer film on the counter surface. Glass fibres are abrasive in nature and possess less wear resistance than carbon [1, 25]. Optimum percentage of glass varied from 15 to 25.

Bronze is ductile metal. It forms highly smooth, uniform, thin film on counter surface than most of the fillers which is vital cause in reducing the wear rate. But when used in low percentage cannot contribute to the wear performance due to its ductile nature. So it is used in between 40 to 60 % in PTFE composite. Bronze in combination with PTFE possess highest tensile strength and moderate hardness. It is generally used in combination with MoS_2 which is solid lubricant in filler percentage of (55 bronze+ 5 MoS_2) %. [1]. MoS_2 is scratch resistant solid lubricant used in combination with the other fillers in PTFE composite (glass, bronze) [1].

PEEK has high hardness, noncorrosive, nonreactive and hydrophobic with very strong bonding with PTFE, hence increases the hardness when used with PTFE as filler Optimum percentage of PEEK in PTFE was observed to be 20%. [3]

Ekanol as filler in PTFE decrease tensile strength, elongation at break but increase the modulus and wear rate. Optimum filler content is 20% (10^-6 mm^3/Nm). Ekanol when use in combination with slight percentage carbon nano tube PTFE improved the tensile strength. modulus and elongation at break, creep resistance. Optimum filler percentage of ekanol and c in PTFE composite is 20 % Ekanol, 1% carbon nano tube at which wear rate is in the range 10^-7 mm^3/Nm. [4]

Potassium titaniate whisker (PTW) as filler on PTFE improves the tensile strength, hardness and impact strength. It can be used for high load high temperature applications. Optimum filler percentage is 15%. Friction coefficients (μ) and wear rates for PTW/PTFE composite follows the order $\mu_{dry} > \mu_{water} > \mu_{alkali}$ and $W_{water} > W_{dry}$ $W_{alkali.}$ It is favorable for alkaline condition but unfavorable for water lubrication. Wear rate in the order of 10^-6 mm^3/Nm. [5]

Addition of nano ZnO in PTFE improve the wear resistance. PTFE/nano ZnO forms thin and tiny transfer film on the counter face. PTFE/nano ZnO has high friction coefficient as compared to other PTFE composite. 15 % nano ZnO filler gives best wear performance and wear rate in the order of 10^-5 mm^3/Nm. [8]

Alumina as filler in PTFE improves the mechanical properties and reduce the wear. It is favourable for N_2+O_2 but unfavourable for the lubricated conditions [9]. Least wear rate is in the order of 10^-6 mm^3/Nm. PTFE alumina composite forms transfer film on the counter surface. Appropriate percentage varies from 12 to 20 %. Nano alumina particles requires less percentage (5%) and performance equivalent to 20% micro alumina particles. [9,10]. Wear has greater impact of material (40 to 60%), load (10 to 20%), sliding distance, sliding velocity , interaction of load and material . Polyethersulphone filler in PTFE reduces friction coefficient. It is suitable for high load low velocity application. 1200 N is the critical load and 150-200 ^{0}C are the critical temperature. 20% is the optimum filler percentage.

IV. Methodology

1) Detailed literature survey on the specific wear rate of the polymer composites to get the idea about the suitable material.
2) Selection of the suitable composite material and the input parameters from the actual working conditions.
3) Fabrication of Composite
4) Cutting the specimen for wear test as per ASTM G99 Standard.
5) Experimental testing on Pin-on-Disk wear test rig.
6) To carry out DOE and experimentations using CCRD
7) Developing mathematical model using DATA FIT software giving imperial relationship between input and output parameter.
8) Comparing of the experimental and model results.
9) Drawing the conclusions using the obtained results
10) rom obtained results conclusions are made.

V. Experimental details

A. Fabrication of PTFE materials

Manufacturers mostly use three different methods to produce PTFE materials. These methods are:

1) Suspension polymerization

End product obtained from this method is either fine powder or granular of PTFE. To become polymerized, liquid form of tetrafluoroethylene monomer (TFE) is pumped inside vigorously shaken reaction chamber. The compartment is under pressure and is poured with purified water and a free-radical catalyst as the initiator.

2) Dispersion polymerization

An aqueous dispersion form of PTFE is synthesized by polymerization of TFE in a gently agitated reaction chamber in the presence of reaction agent and purified water.

3) Direct fluorination

In this method PTFE is prepared at 20°C when hydrogen atoms get displayed by fluorine

Pin on disk wear machine:

The fig. of pin on disk machine for wear testing of composite Material is as shown above. It consists of wear disk of outer diameter 165 mm 8 mm thick hardened to 60 HRC, 1.6 Ra surface roughness the disk is rotated with the help of electric motor through shaft and gear arrangement. Disk speed ranges from 200 to 2000 RPM). Cylindrical pin s can be used in varying sizes ranging from diameter 3, 6, 8 and 10. For different sizes of pin there are different type of pin holders. This holder is mounted on rod at one end and other end weights are placed on pan and is connected to rod with the help of steel wire. The weight is transferred through pin to disk due to sea saw arrangement of the rod. There is separate arrangement for the lubrication purpose. Oil can be filled in the tank seen on the left side of the apparatus. Near the rear end of the rod two sensors are placed one is to measure friction force (measured with the help of beam type load cell having least count of 0.1 N and 0.1 % accuracy) and other measure the linear wear in micrometre [measured by the LVDT (Linear Variable Differential Transducer) range up to 2000 and least count of 1 Force applied ranging from 20 N to 200 N.

B. Materials for wear testing

In present study, to improve the life of the piston rings reinforcement materials are used in the composite with appropriate percentage. Considering literature review and all the design factors including the wear 3 materials had been finalized for the wear testing. The materials are supplied by the POLYMASTERS, Pune. Initially three materials are in the form of rods, the dimensions of the rods are 400 20 mm. These specimen cut in dimensions of 40 mm of equal length and then machined to diameter of 10 mm on lathe machine. These specimen further machined to length of approximately 31mm considering the space restriction of the pin heater holder in which pin is going to be fit. Eight cylindrical specimen (pin) are there for each composite material. Each specimen has two circular surface which are subjected to the wear. Surface 1 of specimen A is written as A1 and surface 2 of material A as A2. Similar process is done for the other specimens.

Test specimen a) Material 1

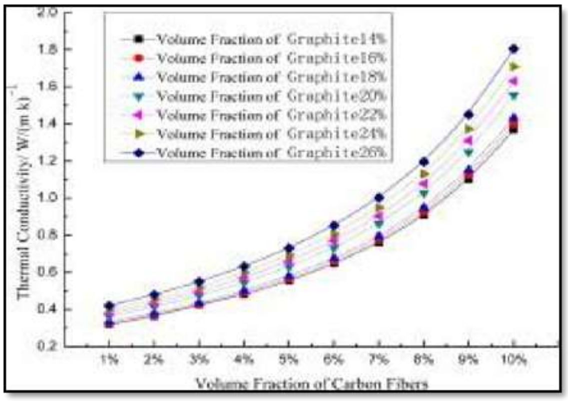
Test specimen a) Material 2

Test specimen a) Material 3

C. Experimental procedure

1) Effect of Thermal Conductivity on the piston and rider rings:

The thermal conductance of the Material 1s also important as there is a considerable amount of heat that is developed inside the compressor, which needs to be dissipated with priority for the proper functioning of the compressor. The Thermal conductivity of the Material 1ncreases with carbon content. But it is equally important that the carbon content be optimum.



As it is known that, the thermal expansion is more in ductile materials than that in brittle, the reason being, crack propagation is easier in ductile materials. In brittle materials, the failure is catastrophic. Hence the amount of Carbon added should be optimum so that the material does not tend towards brittleness.

– Summary

1) The hardness of the former Material increases up to a certain carbon content after which the material starts to tend towards a brittle nature.
2) To sum up, it is quite evident from the two tables above that, the tensile strength increases with increase in the carbon content up to a particular limit (about 15- 20%) where after it reduces.
3) Also, the fatigue resistance increases with increase in Carbon content (up to 15- 20%) and then starts to decrease thereafter due to the material transition towards brittle behaviour.
4) Thermal conductivity of the Material 1ncreases with increase in Carbon content.
5) The thermal expansion should be very less. Thus the carbon content must be as much to give a small expansion, but not as much to cause a catastrophic failure on brittleness.

2) Design Calculations of Piston Ring

a) Design for Maximum Permissible Elongation:

During the installation of piston ring in between the groove of the piston, ring get stretched. Maximum elongation allowed (maximum permissible radius of curvature) (ρ_2) in piston ring before permanent deformation initiates can be given by the equation

$$\frac{\sigma_{yeild}}{FOS} = \frac{TE}{2}\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)$$

Where σ_{yeild} = Yield strength of the composite material (MPa)

FOS = Factor of safety

T = Radial wall thickness (mm)

ρ_1 = Radius of curvature (unstretched condition) (mm)

b) Design for Hoop Stress Acting on The Piston Ring:

Hoop stresses are developed due to internal gas pressure acting on the piston ring.

$$\sigma_{hoop} = \frac{P * r_i}{a}$$

c) Design for Bending Stress on the Ring

$$F = P \times A = P \times \frac{\pi d_c^2}{4}$$

M_{max} is the maximum bending moment

$$M = F.t.\frac{t}{2} = \frac{Ft^2}{2}$$

From the flexure formula,

$$\frac{M}{I} = \frac{\sigma_b}{y}$$

$$\sigma_b = \frac{\frac{Ft^2}{2}}{\frac{a^3 * 2\pi r_i}{12}} * \frac{a}{2}$$

$$\sigma_b = \frac{3Ft^2}{2\pi a^2 r_i}$$

Now for the failure free performance of the ring,

If $\sigma_b \leq \frac{\sigma_{yeild}}{FOS}$ Design is safe.

If $\sigma_b > \frac{\sigma_{yeild}}{FOS}$ then design is unsafe.

A. *RSM (Response Surface Methodology)*

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables). An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response.

B. *Central composite rotatable design (CCRD):*

Wear testing experiments were planned using central composite rotatable design (CCRD) matrix varying the pressure, RPM and temperature. CCRD is useful in response surface methodology. It is applied for analyzing and optimizing the effect of pressure, RPM and temperature. CCRD method to design experiments is illustrated in following section.

According to CCRD, number of experiments to be performed is given by:

$$2^K + 2 * K + \text{Central runs}$$

K stands for the number of input variables.

VI. RESULTS AND DISCUSSION

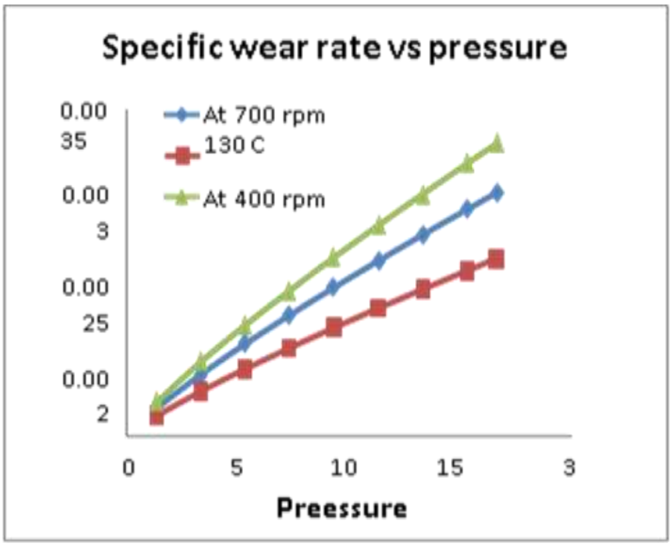
Experimental and model results obtained for given three materials are as follows: Model equation for all three materials assumed to be

$$\text{Specific wear rate} = a.P^b.R^c.T^d$$

Where a, b, c and d are constants. P , R and T are the pressure, RPM and temperature respectively. Theoretically, Specific wear rate is calculated by the formula :

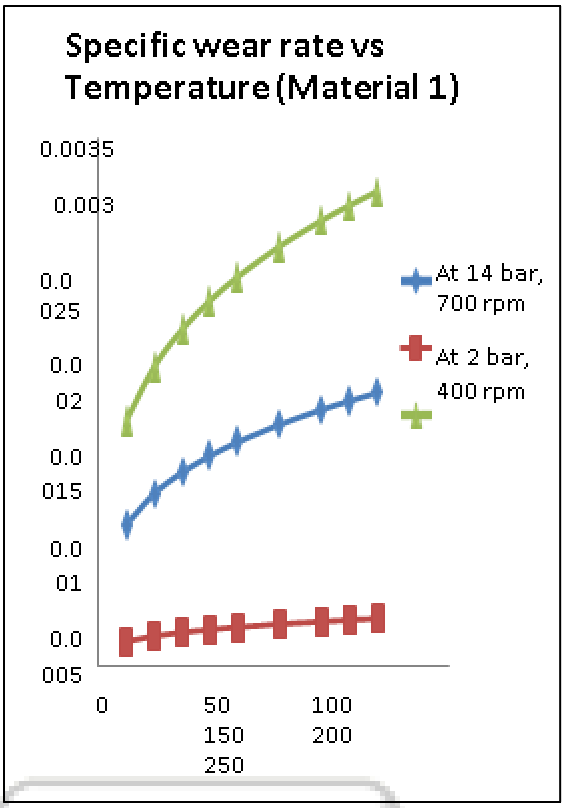
Volume loss obtained with the help mass loss and density.

$$\text{Volume loss} = \frac{\text{Mass loss } (m)}{\text{Density } (\rho)}$$

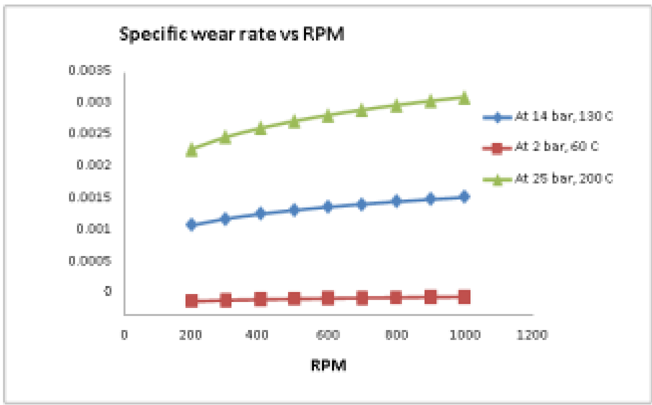


Graph of effect of pressure on specific wear rate at low, moderate and high level for Material 1

Graph shown above represents the variation of specific wear rate with pressure at low level (400 RPM, 60 ^{0}C), moderate level (700 RPM, 130 ^{0}C) and high level (1000 RPM, 200 ^{0}C) conditions for Material 1. The graph obtained for all three conditions is linear that is specific wear rate increases with the increase in pressure. At low load transfer film formed is thin hence the wear increases rapidly. As the load on increases thick and uniform transfer film is formed. But this formation interrupted by the effect of temperature and revolutions in short time. On increase of temperature ductility of the Material 1 increases and transfer films become unstable. On the other hand increased revolutions per minute (velocity) destroyed the transfer film because of the high ductile nature of the material. Due to which high level subject to severe destruction and increased slope. On the increase of load deformation keep on increasing due to the highly ductile nature of the material. This may be the reason that intensity of wear remains same even after increase in pressure. Similarly graph can be plotted to see the effect for RPM and temperature at low, moderate and high level.



Graph shown above represents the variation of specific wear rate with temperature at low level (2 bar, 400 RPM), moderate level (14 bar, 700 RPM) and high level (25 bar, 1000 RPM) conditions bar for Material 1. The graph obtained for all three conditions is curve. Specific wear rate increases with the increase in temperature and with the severity of the level. Hence high level has the high specific wear rate followed by the moderate and low level i.e. High level > Moderate level > Low level. From the graph it seem that in the initial stage there is high wear for the small temperature differenceand later it declines down slowly with the increase in the temperature. May be with increase of temperature increase in thickness more and transfer film stability slightly more so there is declination in graph. The declination is more at low level than the other two levels due to the less revolution per minute due to which less destruction of transfer film.



Graph shown above represents the variation of specific wear rate with temperature at low level (2 bar , 60 ^{0}C), moderate level (14 bar, 130 ^{0}C) and high level (25 bar, 200 ^{0}C) conditions bar for Material 1. The graph obtained for all three conditions is curve. Specific wear rate increases with the increase in revolutions per minute and with the severity of the level. Hence high level has the high specific wear rate followed by the moderate and low level i.e. High level > Moderate level > Low level. Graph obtained is curve line. With the increase in the RPM increase in the thickness of the transfer film. This thick films adheres for some time to counter surface resists. So the graph declines. Also at low temperature ductility is less so deformation of transfer film is less and life of transfer film is more. So the graph declined and became curve and declination found to be more at low level due to low temperature.

A. Mass loss

Mass loss is obtained for 20 conditions (6 are repeated). It is obtained by measuring the mass of the pin before and after the wear of the pin. It seems that it increases with increased load and sliding distance. Mass loss is more in material 1 followed by material 3 and material 2. Least mass loss is obtained for material 2.
Material 1 > Material 3 > Material 2

B. Friction coefficient:

Specific wear rate is obtained for 15 different conditions. Specific wear rate more in material 1 followed by material 3 and material 2. Least specific wear rate is obtained for material 2 due to the formation of uniform and thin transfer film on the counter surface.
Material 1 >Material 3 > Material 2

It can seen Material 3 has stable friction coefficient and less than that of Material 1 and Material 2. Friction coefficient is unstable for Material 2 and Material 1 and increased drastically in some conditions

C. Specific wear rate:

Specific wear rate is obtained for 20 different conditions. Specific wear rate more in material 1 followed by material 3 and material 2. Least specific wear rate is obtained for material 2 due to the formation of uniform and thin transfer film on the counter surface.
Material 1 > Material 3 > Material 2

Comparison of specific wear rate between three materials for the moderate level has established and effect of individual parameter on wear rate is studied.

D. Wear surface analysis and transfer film formation

1) Wear surface analysis:

Wear surface analysis has done to know the possible wear mechanisms and severity of the effect by observing microstructure of the wear surface after the test. For this purpose Dino-Lite digital microscope used.

2) Transfer film formation:

During the sliding of the pin on the counter surface due the rubbing action some material get transferred to counter surface which reduces the coefficient of friction and wear. This film formed may be thin or thick, uniform or no uniform, continuous or discontinuous depending upon the nature of material surface, load applied, sliding velocity and temperature. This observation is very useful to find out specific conditions at which material can be subjected to the minimum wear so as to get the maximum life of the piston rings.

VII. CONCLUSION

Polymers composites makes ideal materials that can be processed easily, lightweight and desirable mechanical properties. They also have unique chemical, thermal, tribological and electrical properties. Composite materials are finding increased applications in many industrial applications. Hence of exploring tribological behaviour of these polymers and its composites have recently increased. It was observed that several factors control the wear and frictional characteristics of such materials. Therefore in present study three polymer composites were studied for their tribological behaviour based on controlling parameters as normal load, RPM and temperature. These polymers were tested under different conditions of controlling parameters on pin-on-disc wear testing machine. The effect of these parameters on specific wear rate and coefficient of friction was investigated. Following conclusions are derived from the obtained results

- Normal load imparts maximum influence on specific wear rate. It was observed that material 2 has greatest impact on wear rate due to variation in normal load whereas material 3 shows least influence when compared with other two parameters i.e. RPM and temperature.
- Material 1 has much softer surface which leads in forming highly unstable transfer film resulting in higher mass loss.
- Material 2 forms stable and uniform transfer film on its counter surface resulting in least mass loss and lowest coefficient of friction.
- It is concluded that material 2 possesses superior tribological properties.

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