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Effect of Temperature on Friction Behavior of Epoxy Resin Composite Coatings for Sliding Contact

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Abstract- **Epoxy composite coatings are used to reduce friction in mechanical components. The epoxy composites at high temperatures cause serious frictional effects due to poor surface characteristics. Hence, there is a need to find a substitute to improve their frictional behaviour in high-temperature conditions. Adding fillers and lubrication are key solutions to improve tribological properties. In this research work, diglycidyl ether of bisphenol A (DGEBA) epoxy resin was coated on steel, and silica powder (5% by weight) was used as filler. The experiments were conducted under dry and lubricated conditions with and without filler. The coefficient of friction (COF) was examined at different temperatures. The results show that the COF increases with an increase in temperature. In addition, the minimum average COF was observed in the case of epoxy coating with the filler under lubrication conditions. For that case, up to 94.4% decrease in COF was observed as compared to epoxy coating without filler under dry conditions, a 48.33% decrease in COF to epoxy coating without filler under lubricated conditions and a 17.98% decrease in COF than epoxy coating with the filler under dry condition was perceived. Scanning Electron Microscopy (SEM) and surface roughness analyses were also conducted to examine the surface of the specimen after the experiment. A worn and rougher surface was observed in the case of epoxy without filler under dry conditions. The more coefficient of friction at high temperatures is due to the thermal degradation of the epoxy matrix at high temperatures, which results in a rougher surface.**

Index Terms-- **Epoxy Composite, Coefficient of Friction, Filler, Temperature**

I. INTRODUCTION

Nowadays, tribology is one of the widely used domains in material and mechanical engineering all over the globe. The tribology of a material has a great potential to make sure the largest utilization of engineering material where friction is unavoidable. In addition, many polymers have been considered high-performance polymer and their composites amongst numerous material classes, which are being under observation by the material scientist having greater strength and density ratio and structural stability. Numerous applications of composite polymers, such as tool manufacturing, seals, and bearing, are absorbed by the tribological behaviour of the larger-performance composite polymers in dry and lubrication conditions [1].

Several polymers like thermoplastic and thermosets are widely used for various tribological applications. Moreover, epoxies are generally known as thermoset polymers that have one or more than one active epoxide groups. Epoxies are the one polymer that can withstand its thoughtful nature and is delicate toward the micro-fracture [2]. Epoxy polymers are widely used as coating components which may produce a good protective layer against friction. The friction force and coefficient of friction (COF) can be reduced using epoxy polymer coating. In addition, due to the Three-Dimensional structure network of polymer, poor surface characteristics, the impact of temperature, and other environmental conditions, an epoxy polymer cannot be directly contacted with the material surface to decrease the friction force between two material contacts. Fillers can be added to epoxy polymers to improve their anti-frictional behaviour and deal with other environmental effects [3]. The mechanical and tribological characteristics of epoxies can be modified or improved by using some filling fibres at massive volume contents. With the advancement in nanotechnologies, there was an increasing research interest in enhancing the high wear and friction-resistant epoxy nanocomposites by using filler materials [4].

Fillers are categorized into numerous subgroups: carbon-based fillers, metallic fillers, polymer-based fillers, ceramic-based fillers, mineral-based fillers, and lubricant-based fillers [5]. It has been studied that composite fillers are best for reducing the friction of the mating surfaces. Friction is one of the most important factors which may damage the surfaces if their value is increased above a certain value. Friction is generally a resistive force generated between two mating surfaces when they move in the opposite direction. Friction is mainly categorized into static friction, sliding friction, rolling friction, and fluid friction [6]. Frictional resistance and friction factor can also be controlled by composite coating. The coating technique is widely used in numerous industrial sectors such as oil and gas sectors, petrochemical, construction, medical and marine sectors in order to prevent the metal components from the corrosive or chemical environment [7].

The epoxy composite coating is a widely used polymer coating method to improve frictional behavior. The mechanical and thermal properties of epoxy composite, such as shear strength, are also excellent [8]. Thermoset polymers such as polyamide, epoxy, vinyl ester, phenol, polyurethane, polyester, and others can be used as a coating material for tribological applications. Nowadays, Polyester composites with layered textile structures of 3-ply woven nylon fibres are used for tribological applications. Fabric orientations parallel to the sliding plane have low coefficients of friction and wear rates, whereas perpendicular orientations have high friction [9]. The pin-on-disk method generally provides a technique for characterizing friction and wear between two different material surfaces. Pin-on-disk method is generally used to characterize the performance of various materials against a standard surface [10]. Yan Hao et al. [11] generated an epoxy composite coating by adding diamond, silicon carbide, molybdenum silicate, and graphite. They also investigated the impact of fillers on the wear and friction behaviour of the epoxy composite.

Ashutosh Pattanaik et al. [12] studied the ultrasonic stirring method to prepare an epoxy resin matrix composite containing fried ash particles. The experiment utilized Pin-On-Disk equipment to analyze the material specimen's frictional and wear behaviour. According to the findings, signal-to-noise ratio analysis optimizes the parametric condition that provides the lowest value of friction coefficient. C. Cwin et al. [13] studied the friction and wear behavior of kernel fibers reinforced epoxy (KFRE) composites using Block on Disc apparatus. The results revealed that the composite gave lower coefficient of friction in normal orientation (N-O) as compared to parallel (P-O) and anti-parallel (AP-O) orientations.

Tianjiao Bao et al. [5] made epoxy composites by using polyether amine-functionalized graphene oxide. They also deliberated the mechanical and thermal properties of composites with frequent kinds and filler contents. They inspected from the results that the 0.2 wt.% polyether amine functionalized graphene oxide composite showed well tribological efficiency. Stefan Hofmann et al. [14] investigated the impact of friction and temperature on the surface coating in the rolling-sliding contacts for application in dry lubricated gears. N. Nemati et al. [15] researched a composite covering made of Polytetrafluoro Ethylene (PTFE) and graphene oxide to improve frictional behaviour in ambient and increased temperature environments considerably. The results revealed that adding 15% graphene to the PTFE matrix significantly reduced the coefficient of friction to 0.1. V. B. GUPTA et al. [16] conducted tensile mechanical characteristics and fracture toughness of a Bisphenol-A type epoxy resin cured with varying quantities of meta phenylene diamine using two separate cure cycles at different temperatures.

They also determined that the use of filler materials improves tribological capabilities while decreasing the coefficient of friction. H.A. Deore et al. [17] manufactured and examined the three different filler materials: multiwall carbon nanotubes, copper, and silicon carbide via friction stir processing route with homogenous dispersion of all filler material components. They also conducted a comparative study of the impact of different filler materials. They examined from the results that SiC filler gave the lowest COF among the three filler materials in these experiments. Yuefeng DU et al. [18] manufactured a highly associated graphene epoxy composites. They examined from the gotten results that COF was 87.5% lower in case of graphene epoxy coating as compared to net epoxy. Ronaldo Câmara Cozza et al. [19] studied the frictional and wear behavior of titanium nitride (TiN) and titanium carbide (TiC) coatings. The COF was calculated as the ratio of tangential and normal forces acting on the material surface. The COF values recorded ranged from 0.4 to 0.9. Pieter Samyn *et al*. [20] examined the friction and wear behavior of unsaturated polyester with a plain weave polyester fabric and PTFE fillers in reciprocating sliding at temperatures ranging from 23°C to 220°C. According to the observed results, pure polyester composites represented a regime of continually increasing friction and overload over 120°C, whereas PTFE filler composite materials represented a regime of increasing friction up to 100°C and reducing friction from 100°C to 160°C. N. Ayuma et al. [21] evaluated the influence of temperature and sliding distance on the tribological properties of Palm Kernel Activated Carbon-Epoxy (PKAC-E) composites using a Pin-on-Disc tribometer. They concluded that the sliding distance had no effect on the coefficient of friction. However, the COF increases with rise of temperature due to the thermal degradation of epoxy matrix at higher temperatures.

In this research work, the effect of temperature on COF was investigated using epoxy composite coating on steel under different dry and lubrication conditions. For this purpose, Pin-on-disk apparatus was used.

II. EXPERIMENTAL METHODOLOGY

A. MATERIALS

Epoxy resin diglycidyl ether of bisphenol A (Araldite 506) and Hardener HY 951 were used for coating. Silica particles of size 7µm to 10µm purchased from UNI-CHEM were used as filler. The coating was performed on stainless steel (SS304) pin with a diameter of 9mm and a length of 25mm. A steel disk with a hardness of 65 HRC was used for all tribological tests. For lubrication, engine oil (SAE 5w-30) having a viscosity index of 150 was used. The mechanical properties of SS304 are given in Table I.

TABLE I
Mechanical properties of SS304

Parameter	Value
Young's Modulus (GPa)	193
Shear Modulus (GPa)	79
Poisson's Ratio	0.27
Density (Kg/m3)	7900
Yield Strength (MPa)	350
Shear Strength (MPa)	350

B. COMPOSITE PREPARATION

The steel pins (SS304) of 9mm diameter and 25 mm length were prepared by turning operation using a lathe machine. The samples were ground with medium fine silicon carbide abrasive paper for the polished surface. After polishing samples were cleaned with Acetone. The epoxy composite coating was prepared by mixing epoxy and hardener HY951 with uniform stirring for about 10 minutes at ambient temperature. The hardener was added with a ratio of 2:1. The silica powder as filler material was added in the composite 5% by weight of the epoxy resin.

FIGURE 1: Coated Samples

After that, Ultrasonic cleaning of the steel specimen was performed in distilled water for 10 minutes and Drying with hot air for 5 minutes. The coating for composite preparation was carried out using the Dip Coating technique. Then, the composite sample was cured at ambient room temperature for 20 hours and 4 hours cured at 80°C in the oven. The prepared material samples are shown in Fig. 1.

C. Tribological Test Apparatus

Pin-on-disk apparatus was used, available in the Fracture mechanics lab UET Taxila. In a pin-on-disk mechanism, either pin or disk remains stationary during the test and slides against the counter face. A pin heater with a thermocouple is also provided to heat the specimen. The load was applied to the pin using a load pan. The pin-on-disk mechanism is represented in Fig. 2.

FIGURE 2: Pi-on-Disc Tribotester

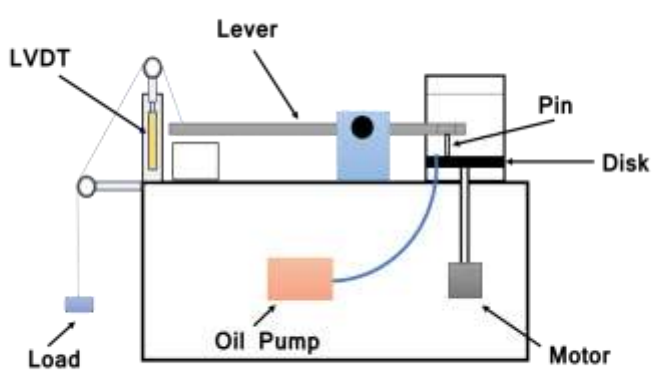

FIGURE 3: Pin-on-Disc Schematic Diagram

D. TRIBOLOGICAL TEST PERAMETERS

The description of test parameters is given in Table II.

TABLE II
Test Parameters

Parameter	Value
Applied Load	49.05 N
Test RPM	400
Track Radius	35 mm
Pin Diameter	9 mm
Temperature	25^0C-150^0C

III. RESULTS AND DISCUSSIONS

A. FRICTION ANALYSIS

The experimental approach examines the frictional behaviour on the material surface for different samples. There are four experimental cases: epoxy fillers under dry and lubricated conditions and epoxy composites without fillers under dry and lubrication conditions. In this experimental study, the material samples were heated, and friction behaviour was noted at six different temperatures such as 25°C, 50°C, 75°C, 100°C, 125°C, and 150°C. The applied load on the Pin-On-Disk apparatus was kept constant at 49.05N. In addition, a comparison study was also carried out to evaluate the friction behaviour on the epoxy test sample surfaces for four different conditions and different temperatures.

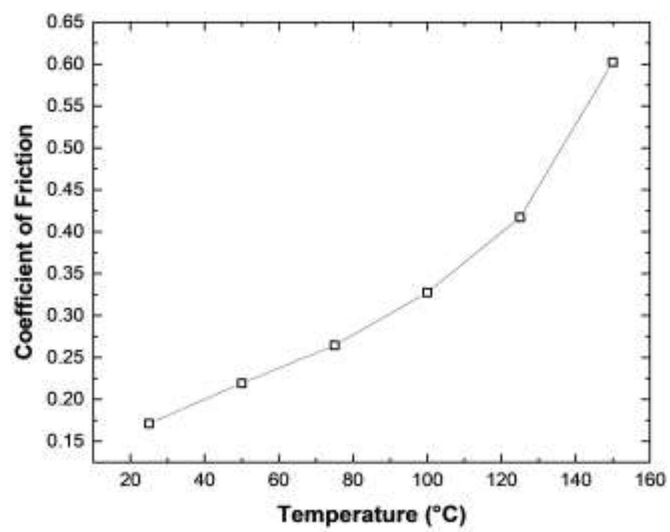

FIGURE 4: Coefficient of friction at different temperatures without filler under dry condition

Fig. 4 shows the friction coefficient variation at different temperatures of the epoxy composite without filler under dry conditions. The graphical trend in Fig. 4 increases with the increase in temperature. The maximum and minimum values of COF of 0.60231 and 0.17112 were recorded at temperatures of 150°C and 25°C, respectively. The reason behind this increment in COF is due to the thermal characteristics of the epoxy composites. The more heated material generates more friction force, making the material surface rougher. Thus, the value of the coefficient of friction was also increased.

Similarly, Fig. 5 represents the variation of COF for the net epoxy coating under lubrication conditions. In this case, a comparatively low coefficient of friction was observed. The lower friction coefficient values in the lubricated condition are due to the addition of lubricant layers between the sample and disc, producing a less rough surface and a low coefficient of friction [11].

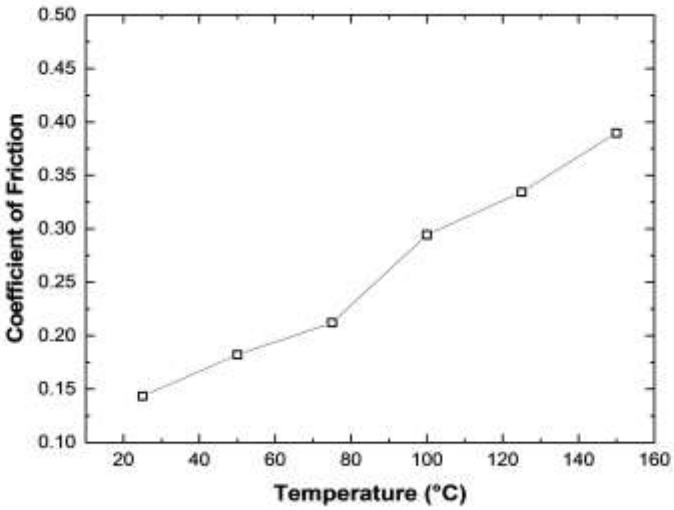

FIGURE 5: Coefficient of Friction at different temperatures without filler under lubrication condition

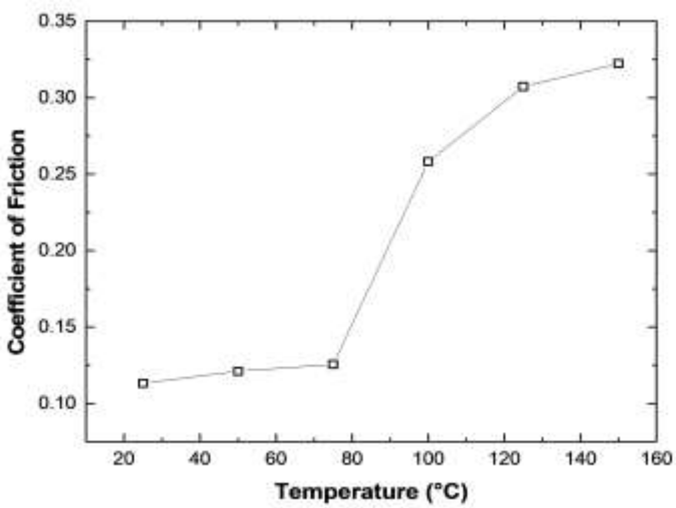

FIGURE 6: Coefficient of Friction at different temperatures with epoxy filler under dry condition

Fig. 6 represents the variation of the Coefficient of Friction (COF) at different temperatures with the epoxy filler under dry conditions. It can be seen from Fig. 6 that the increment behaviour of the graph is shown linear at a certain temperature and then exceeds exponentially. The value of the coefficient of friction of 0.12558 was noted at a temperature of 75°C; after that, the COF increased exponentially. This is due to the thermal degradation of the epoxy matrix at high temperatures. At the temperature of 80^{0}C the thermal degradation of epoxy started, and the epoxy matrix started to damage. Hence, the surface becomes rougher and irregular. The maximum and minimum values of COF for the case of epoxy with the filler under dry conditions were 0.32231 and 0.11324 at 150°C and 25°C, respectively.

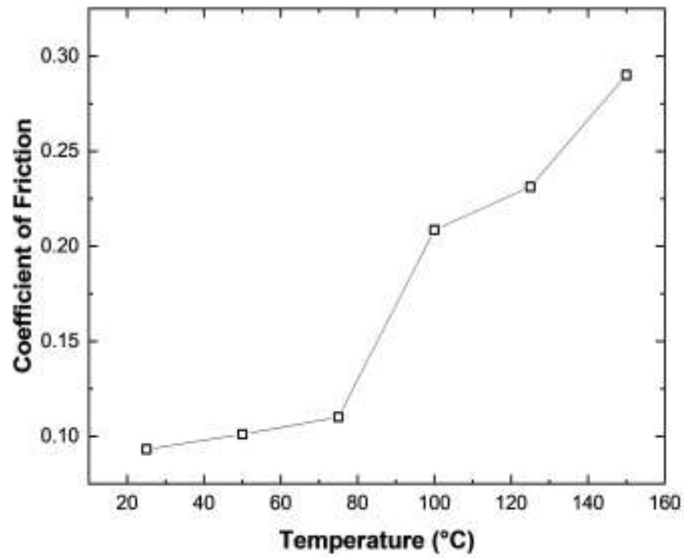

FIGURE 7: Coefficient of friction at different temperatures with epoxy filler under lubrication condition

Similarly, the variation of COF with temperature for the case of epoxy filler under lubrication conditions was also investigated and shown in Fig. 7. In this case, firstly, COF increases up to a 75°C temperature and then rises exponentially up to 150°C. The maximum and minimum values of COF of 0.29013 and 0.09318 at the temperature of 150°C and 20°C, respectively. The reason behind this increment in both cases is due to the thermal properties of material samples. The epoxy binding may affect the increasing temperature because of the thermal degradation of epoxy binder after 80^{0}C, which causes the plowing on the surface of the specimen, which may lead to high surface roughness and higher COF values [21].

Furthermore, the comparative study of all cases was presented in graphical form to examine the friction behaviour of material samples with and without epoxy fillers under dry and lubricated conditions. The graphical representation of the comparison graph is shown in Fig. 8. The average value of COF for each case was also calculated and shown in Fig. 9. The value of the coefficient of friction was lowest for the case of epoxy with the filler under lubrication condition as compared to all other cases. Because the lubricated oil and filler materials help to reduce the material removal from the material surface, therefore, it may observe from the obtained results that the epoxy composite with and without filler materials may affect the frictional behaviour of the material surface.

SEM analysis of material specimens was conducted after the tribological test of epoxy composite coatings. The experimental results noted that the friction coefficient was highest in the case of epoxy composite coating without filler under dry conditions.

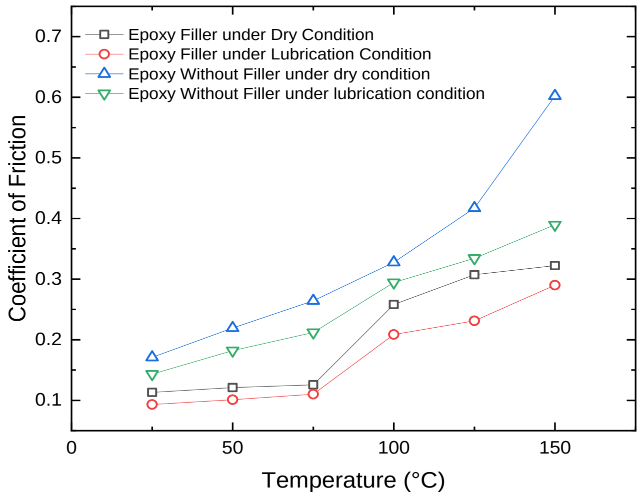

FIGURE 8: Comparison of variation of coefficient of friction at different temperatures for four different cases

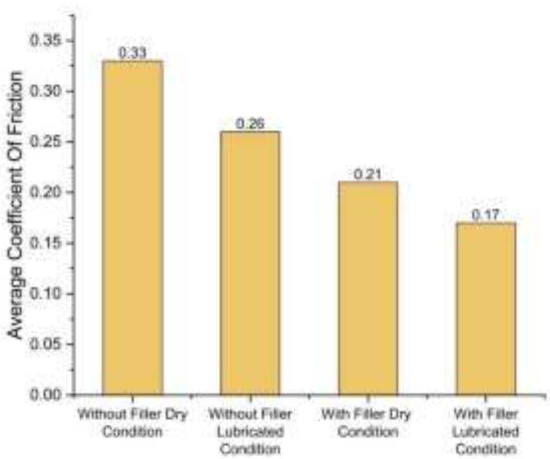

FIGURE 9: Comparison of average value of Coefficient of Friction for different cases

B. SCANNING ELECTRON MICROSCOP (SEM) ANALYSIS

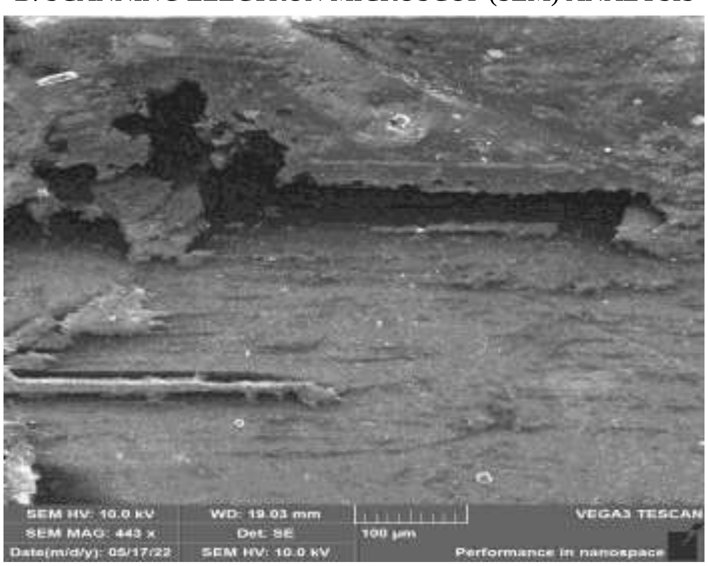

FIGURE 10: Scanning Electron Microscopy Analysis of epoxy composite without filler under dry condition

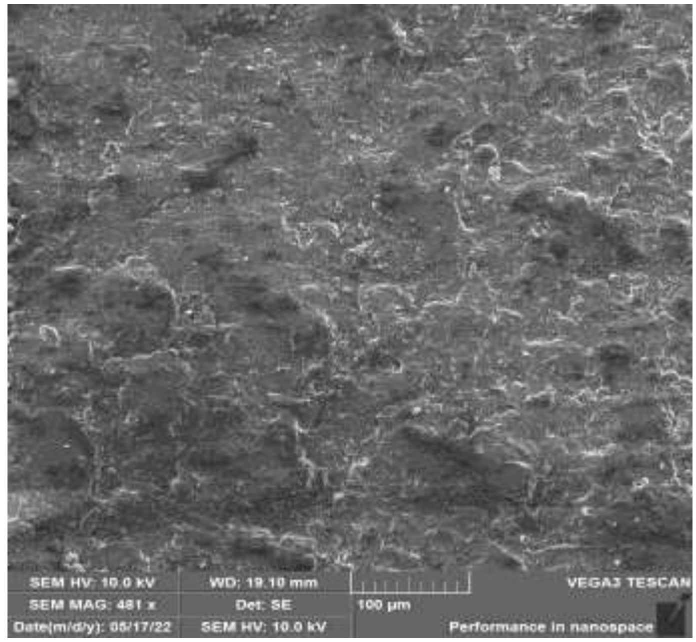

FIGURE 11: Scanning Electron Microscopy Analysis of epoxy composite without filler under lubricated condition

It can be seen from Fig. 10 that a larger worn and rough surface was observed in the case of epoxy without filler under dry conditions as compared to lubricated conditions Fig. 11. There are more scratches and debris on the surface observed, which indicates the rough surface of the specimen after experimentation. In this case, no filler material was present in the coated epoxy composite. But the lubrication made the surface less rough and less damaged compared to dry conditions.

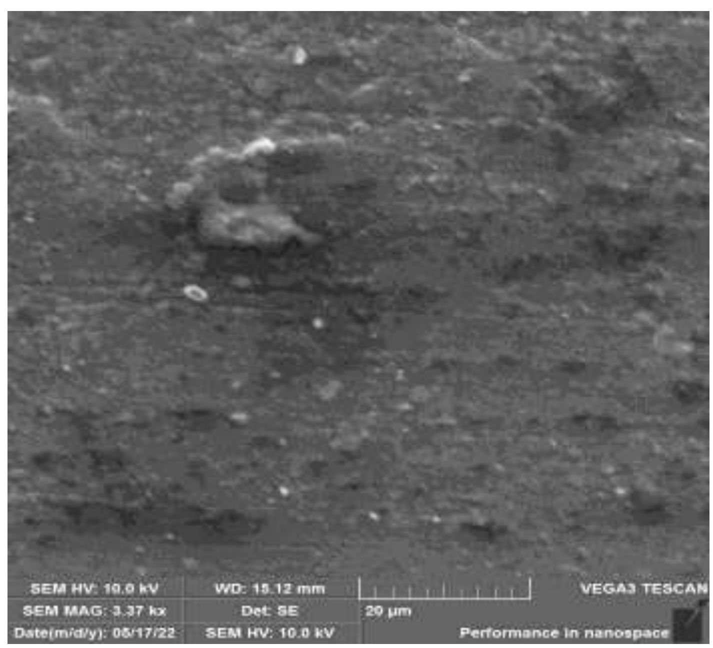

FIGURE 12: Scanning Electron Microscopy Analysis of epoxy composite with filler under dry condition

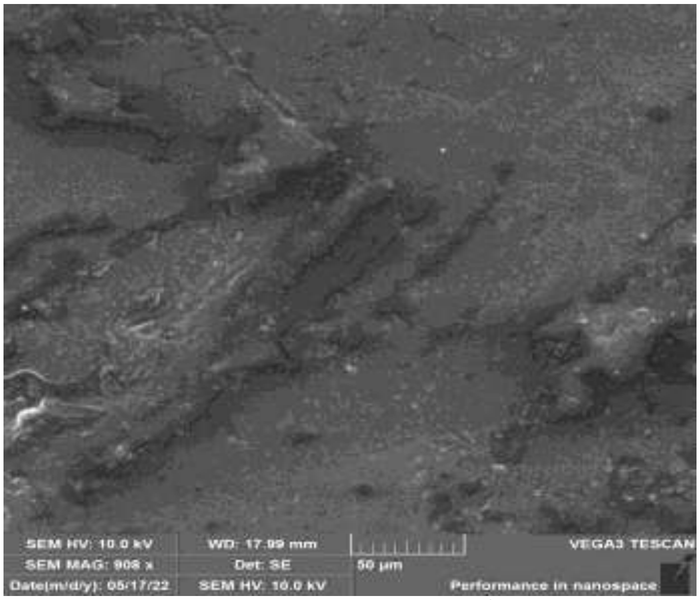

FIGURE 13: Scanning Electron Microscopy Analysis of epoxy composite with the filler under lubricated condition

SEM images of the material specimens with the epoxy filler are shown in Fig. 12 and Fig. 13. According to Fig. 12, the friction layer was exposed to stark damage for epoxy composite with the filler under dry conditions. It was also believed that the tribofilm starts to make a counter surface on the surface of the material sample. A similar situation has been indicated by N. Nemati et al. [15] in the case of epoxy filler under dry conditions. SEM images indicate more cracks and worn surfaces in the case of epoxy with the filler under dry conditions. It is because at high-temperature epoxy matrix shows thermal degradation, which causes the plowing on the sample's surface. Obviously, with an increase in temperature, the epoxy becomes softer, and COF increases. Higher frictional behaviour has been observed in dry conditions epoxy coating with filler material. Fig. 13 represents the SEM image of the material sample of epoxy composites under lubricated conditions. The experimental results showed that the COF was lower in lubrication conditions with filler than in dry conditions. Fig. 13 indicates fewer scratches and a comparatively smooth surface compared to dry conditions. The reason behind this is the addition of a lubricant particles layer on the material surface which reduces the material removal from the material sample and results in a relatively smooth surface. Thus, less frictional force is generated between two rubbing surfaces in the case of lubrication conditions. Similar behaviour of composite-coated steel specimens under lubrication conditions can be seen by Y. Hao et al. [11].

C. SURFACE ROUGHNESS ANALYSIS

Surface roughness analysis was also performed after each experiment. For this purpose, the portable surface roughness tester Mitutoyo SJ-410 was used. The surface roughness factor Ra of the wear tracks was obtained for all cases. Three readings of Ra were obtained for each case, and the average of these was used. The influence of the specimen sliding on the roughness of the counter surface (steel disc) is presented in Fig. 14.

In the case of the epoxy composite without filler under the dry condition, the value of Ra was highest, i.e., 1.425, which indicates that some of the debris or film transfer was generated on the wear track of the sliding specimen, which hinders the sliding of mating surfaces. And highest average COF was observed for this case from experimental results. But in the case of epoxy composite without filler under lubrication, Ra is slightly lower than neat epoxy under dry conditions. The reason is the addition of a layer of lubricant between the mating surfaces, which also lowers the surface roughness and the COF [13].

Similarly, in the case of filler addition, a lower value of Ra was observed for dry and lubricated conditions. The reason is that the addition of silica filler makes the epoxy bonding stronger and helps to reduce surface damage. So, less debris or film transfer was generated in this case compared to the neat epoxy. So, the roughness value was also low, and hence lowest COF was observed in the experimental results.

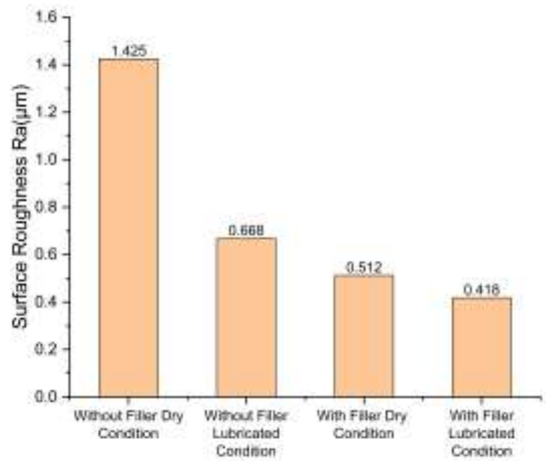

FIGURE 14: Comparison of surface roughness for different cases

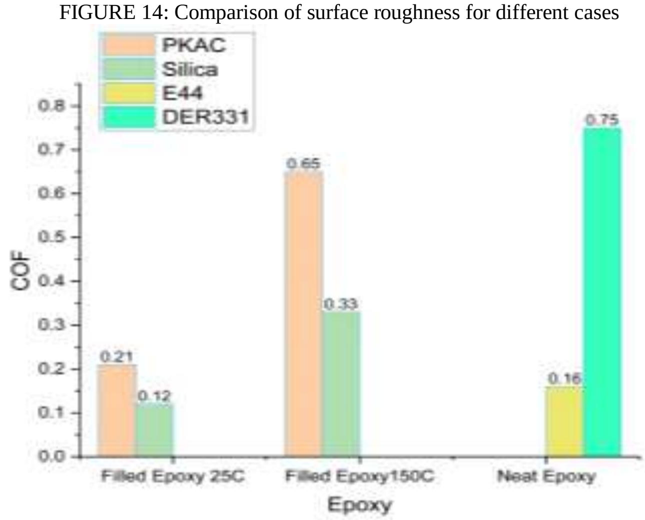

FIGURE 15: Comparison of COF results with existing literature for filled epoxy at $25^{0}C$ and $150^{0}C$ and neat epoxy at room temperature [21] [13]

IV. CONCLUSION

The influence of temperature on frictional behaviour was investigated under various scenarios, such as epoxy coatings with the filler under dry and lubrication conditions and epoxy coatings without fillers under dry and lubrication conditions. DGEBA Epoxy composite was used, and silica powder was added as a filler. In addition, surface roughness tests and SEM analyses were also conducted to examine the friction mechanism on the worn surface of the material specimens after each experiment. The conclusion drawn by this study is given below.

- The addition of fillers and lubricant in the epoxy composite coating greatly affected the frictional behaviour. Minimum COF was observed in epoxy coating with the filler under lubrication conditions. For that case, up to 94.4% decrease in COF was observed in epoxy coating under dry conditions, a 48.33% decrease in COF than epoxy coating without filler under lubricated conditions and a 17.98% decrease in COF than epoxy coating with the filler under dry conditions was observed. It means that adding filler in the epoxy composite coating has better results than without. Moreover, lubrication also plays an important part in decreasing COF.
- It was also seen from the obtained results that COF is linearly increasing with the increase in temperatures. This is due to the thermal degradation of the epoxy matrix at higher temperatures which causes the plowing on the surface of the specimen. Hence the surface roughness increases, which increases the COF.
- It was observed from surface roughness analysis and SEM images that the surface of the sample is rougher in the case of epoxy without filler under dry conditions. On the other hand, a comparatively smooth surface pattern was seen in the case of the epoxy composite coating under lubrication conditions. It means that the addition of filler is important to improve frictional behaviour.

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CONFLICTS OF INTEREST

The authors declare they have no conflicts of interest to report regarding the present study.

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