# UNDERSTANDING THE TRIBOLOGICAL BEHAVIOR OF ALUMINUM MATRIX COMPOSITES REINFORCED WITH $TiO_2$ NANOPARTICLES

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## ABSTRACT

Metal matrix composites are becoming more important and well-liked in a variety of technological fields due to their remarkable strength, low density, improved resistance to wear and corrosion, and remarkable strength. These days, a variety of methods, including squeeze casting, spray deposition, infiltration techniques, liquid and powder metallurgy, and spray deposition, are used to create these composites. Every one of these methods has its limitations, particularly when it comes to creating a smooth interface between the reinforcement and the matrix. This element is the main factor that has a major impact on the final mechanical properties of the metal matrix composites that are created. However, this limitation can be overcome by creating MMCs by the liquid metallurgical process. This work investigated the sliding wear properties of hybrid polymer nanocomposites against varying counterface roughness and under different loading conditions. In particular, TiO2 nanoparticles had a negative impact on epoxy-based composites unless the disc surface was adequately rough. In other cases, they had a favorable effect. When polyamide nanocomposites came into contact with smooth and rough disks, especially at higher applied contact pressures, the addition of nanoparticles and other fillers resulted in less wear and friction. By providing the required support for displaced TiO2 nanoparticles to achieve the rolling motion, the reinforced film lowers abrasion and friction. Therefore, understanding the interactions among different tribo-fillers under specific scenarios or contact conditions is vital to creating composite materials with remarkable resistance to wear.

**Keywords**:
$TiO_2$ nanoparticles, metal matrix composites, polyamide nanocomposites and different tribo-fillers.

## I. Introduction

The study of material learning deals with the application of material properties in numerous engineering and scientific domains. Materials science, a branch of engineering, studies how a material's atomic composition affects its visible characteristics. It blends physics and materials science concepts. Materials science is becoming a popular subject of study at many institutions as a result of a recent shift in the media's focus toward nanoscience and nanotechnology. It is also a crucial part of failure analysis and logical outline. The field of materials science is in charge of observing and researching the essential characteristics and attributes of materials. A defining factor is frequently the choice of material at a given time. Good examples of expressions like this are Stone Age, Bronze Age, and Steel Age. The study of ceramics manufacturing and related metallurgy falls under the umbrella of materials science, an area of applied science and engineering. It is among the more traditional areas of applied science and engineering. Directly from mining and, most likely, from the use of fire and pottery production, metallurgy gave rise to materials science [1]. The discovery by American scientist Josiah Willard Gibbs in the late 1800s of a connection between a material's physical properties and the thermodynamic properties of its atomic structure in various states represented a major breakthrough in our understanding of materials. The space race directly led to the development of the core ideas of modern materials science. This covers the knowledge and advancement of material compositions as well as the application of carbon and silica materials in the building of spacecraft for space travel. Dynamic developments like plastics, semiconductors, and biomaterials have affected and been influenced by the area of materials science [2]. Because of their remarkable wear and friction properties, polymer composites have recently attracted increasing attention from the automotive and aerospace industries for application in tribological components. When it comes to this, polymer composites are superior to metals in two main ways: first, they are significantly lighter, and second, they can be designed to have self-lubricating properties. From a tribological perspective, hard nanoparticles are frequently recommended as filler material for polymer composites. This is primarily because the higher surface areas of tiny particle fillers allow them to form stronger bonds with the polymer matrix. Furthermore, in comparison to bigger fillers, they are less prone to abrade the counterface [3]. Improvements in wear rates and friction are commonly linked to the formation and maintenance of a transfer film because polymer composites are regularly used in sliding contact, typically against a metallic surface. When polymer material is applied to a metal surface, a film is created [4]. In this case, nano-sized particles are beneficial because they may efficiently combine with the wear debris generated, producing a transfer film of superior quality. In the same way, extremely small particles might lessen the polymer's and the film's ability to stay together, which would reduce friction. It is noteworthy to emphasize that, in addition to the polymer matrix and sliding wear conditions, the type of nanoparticles utilized may also have an impact on the transfer film's quality. For this specific purpose, scientists have looked into a variety of nanoparticle types thus far. The discussion of enhancing tribological behavior frequently revolves around the development of transfer films. While the design of the polymer is a subject of extensive research, it is important to recognize that the properties of the sliding metallic counterface also play a major role in the formation and preservation of the transfer film. They also showed that a silica-based transfer film is produced when micron-sized carbon fibers and SiO2 nanoparticles are added to the polymer matrix. This coating improves the tribological performance of the polymer and lessens oxidative wear on the metallic surface. This is due to the metallic counterface's tribo-oxidation, which limits the creation of a transfer film by preventing material transfer from the polymer. The complexity of the issue is highlighted by the multiple hypothesized mechanisms by which nanoparticles improve the tribological performance of polymers. There is currently a lack of understanding on the potential scope of these procedures [5]. concurrently and in a manner that amplifies the impacts of one another. Therefore, the goal of this study is to examine how surface roughness, the presence of nanoparticles, and inherent characteristics of polymer composites interact to affect transfer film formation and, in turn, tribological performance. To this end, we investigate the effects of incorporating TiO2 nanoparticles into epoxy and polyamide composites on the characteristics of the transfer layer that is formed after these materials slide over both smooth and rough steel discs. We then compare these findings to the wear and friction rates that have been noted. The jobs that are left are arranged as follows: The literature review is summarized in Section 2 and the materials and processes are explained in Section 3. Section 4 presents an analysis and graph of the results, and Section 5 offers the article's overall conclusion.

## II. Literature review

An technique that improves our comprehension of the tribological properties of Al-TiO2 nanocomposites with varying concentrations of TiO2 assessed under varying sliding loads was presented by Najjar et al. [6]. It also enhances the ability to predict their performance. Excellent TiO2 nanoparticle dispersion inside the matrix was achieved by fabricating Al-TiO2 nanocomposites via the accumulative roll bonding (ARB) process. The pin-on-disc test was utilized to determine the wear rates and coefficient of friction. The coefficient of friction and the rates at which wear occurs were predicted using a neural network model. The observed relationship between the composite's shape, hardness, and microstructure—as well as the variations in its tribological properties over time—led to this decision. The experimental findings demonstrated that wear rates decrease until they reach a plateau as the number of ARB passes increases. This is because the Al matrix's saturation of grain refinement and the composite's homogenous dispersion of TiO2 nanoparticles are to blame. The usefulness of evolutionary and statistical methods for improving the wear resistance of SiC and TiO2 nanoparticle-supplemented AA7178 metal matrix composites was investigated by Bharat et al. [7]. Stir casting was used to create the composites, and a pin-on-disc device was used to analyze the materials' wear characteristics. Scanning electron microscopy (SEM) analysis showed that the reinforcement particles were evenly distributed across the aluminum matrix's surface. Electron backscatter diffraction (EBSD) research has demonstrated that adding nanoparticles to composites produces a final product with a more refined grain structure. The results showed that the sliding distance, applied load, and speed had the greatest effects on the wear rate of the basic alloy matrix, AA7178 with 3wt% TiO2. Similarly, these parameters mostly influenced the wear rate of AA7178, which had a 3wt.% SiC nanocomposite. Shet et al. [8] concentrated on using the liquid metallurgical process to create composites of Al 6063 reinforced with TiO2, based on the information presented. With increments of 2, the amount of TiO2 particle inclusion in the composite will be changed between 2 and 8 weight percent. More research will be done on the microstructure, wear traits, and hardness of the Al 6063 alloy as-cast and Al 6063-TiO2 composites. Furthermore, the Taguchi and Anova methods will be employed for the study and analysis of the broken surfaces. Elumalai et al.'s [9] study examined the wear properties of dry sliding pure monolithic magnesium and magnesium-titanium dioxide (Mg-TiO2) composites. The materials were tested against an oil-hardened nonshrinking die steel (OHNS) counter-disc using a pin-on-disc tribometer. Normal load applied was between 0.5 and 2 kg, and sliding velocity was between 1.5 and 2.5 m·s−1. The worn track diameter was measured at 90 mm, and the sliding distance was fixed at 1500 m. The pin samples were characterized in order to evaluate wear rate, coefficient of friction, wear fractographs, and other microstructural, nanomechanical, and tribological properties. Scanning electron microscopy (SEM) was used to analyze the worn-out surfaces of each pin sample in order to identify the different types of wear and wear processes. We measured the chemical composition of each element via energy-dispersive spectroscopy. Using the nanoindentation method, the effect of TiO2 reinforcements on the nanomechanical behavior was examined. The nanoindentation strengths of the Mg–1.5TiO2, Mg–2.5TiO2, and Mg–5TiO2 composites rose by 11.9%, 22.2%, and 35.8%, respectively, in comparison to pure Mg. The presence of TiO2 particles and the robust interaction between TiO2 and magnesium particles at the interface may be responsible for this improvement. When the typical load was changed, the wear test results showed that the wear rate varied significantly more than the sliding speed. However, when the normal load and sliding velocity were changed, a significant change in the coefficient of friction was observed.

The preparation and wear parameters of the composite material were examined by Karthik et al. [10]. This is an aluminum matrix that has equal amounts of graphite and titanium dioxide (both in nano size) at 7%. With a pin-on-disc apparatus, weights of 5N, 7N, and 10N were applied at velocities of 1.5 m/s, 2 m/s, and 2.5 m/s in order to conduct a wear test. When the load is 5 N, the sliding velocity is 1.5 m/s, and the sample weight is 5 grammes, the condition that yields the lowest specific wear rate is met.

## III. Materials and methods

Table 1 lists the components of the polymer composites that were examined in this study. Polyamide 66 and epoxy are used to generate the polymer composites that are the subject of this discussion. We will refer to them as EP and PA, respectively, for the purpose of clarity. Pitch-based short carbon fibers and TiO2 nanoparticles (Kronos 2310) are the fillers utilized in this context; they act as reinforcements, and graphite flakes (Superior 9039) act as a conventional solid lubricant. As can be seen in Table 1, each sample is assigned a number, 0 or 1, depending on whether TiO2 nanoparticles are present or absent. In particular, polytetrafluoroethylene (5 volume percent) replaces TiO2 nanoparticles in EP0. The Archimedes method was used to calculate the density values that are displayed in Table 1. The fillers used in the SCF are 90 μm in length and approximately 14.5 μm in diameter on average. By way of contrast, the average diameters of the graphite flakes, PTFE powders, and TiO2 nanoparticles are

20 µm, 4 µm, and 300 nm, respectively. Twin-screw extrusion at 292◦C melting temperature and injection molding at 500 bar pressure were used to create the PA composites. The screw speed was set to 80 cm3/s, while the mould temperature was set to 70◦C. Conversely, the EP composites were created by mechanically combining materials and then curing them with a polyamine hardener.

Table 1: Tabulation for polymer matrix composite with its compositions

| **Parameters** | | **Materials** | | | |
|---|---|---|---|---|---|
| | | PA0 | PA1 | EP0 | EP1 |
| Composition (Volume %) | Matrix | 80 | 75 | 75 | 75 |
| | SCF | 15 | 15 | 15 | 15 |
| | Graphite | 5 | 5 | 5 | 5 |
| | PTFE | 0 | 0 | 5 | 0 |
| | Nano $TiO_2$ | 0 | 5 | 0 | 5 |
| Density (g/cm$^3$) | | 1.209 | 1.302 | 1.284 | 1.393 |

AA7178, a base alloy matrix from Venuka Engg. Pvt. Ltd. in Hyderabad, India, was utilized for this investigation. TiO2 nanoparticles (30–50 nm) obtained from NRL in Jharkhand, India, were employed as the reinforcing material. Using a Swam Equip model, the stir-casting method was used to create the nanocomposite. Table 2 lists the alloying elements present in the AA7178 matrix. The 450°C furnace was used to heat the TiO2 nanoparticles, which ranged in size from 30 to 50 nm, for half an hour. They were then included using a stir casting method with a Swam Equip make into the base alloy matrix A7178. Particle preheating improves wettability, which strengthens the link between the particles and matrix material and raises the final product's quality overall. A swirling motion in the molten base alloy was produced by heating the stirrer blade to 200°C. TiO2 nanoparticles were subsequently added to the mixture steadily and continuously. The impeller was attached to a motor that spins at 650 revolutions per minute in order to introduce particles into the molten liquid. This required ensuring consistency of particle dispersion throughout the melt. Argon gas was kept flowing continuously to stop oxidation. The melt was poured into a cylindrical mold chamber that measured 150 mm in length and 25 mm in diameter after the particles had been added. Graphite powder was applied to the chamber's interior surface. The literature states that three distinct composites were produced by synthesizing them with varied concentrations of TiO2 (0, 1, 2, and 3 weight percent).

Table 2: Tabulation for AA7178 matrix contains alloying elements

| **Elements** | **Weight (%)** |
|---|---|
| Zn | 7.1 |
| Mg | 2.7 |
| Cu | 2.0 |
| Fe | 0.45 |
| Si | 0.40 |
| Mn | 0.30 |
| Cr | 0.26 |
| Ti | 0.20 |
| Al | Balanced |

The manufactured samples were polished using emery paper ranging in grades from 600 to 1500. A 1.5-micrometer diamond paste-equipped disc polisher was used for this procedure. Keller's reagent, which included 190 milliliters of distilled water, 5 milliliters of nitric acid (HNO3), 3 milliliters of hydrochloric acid (HCL), and 2 milliliters of hydrofluoric acid (HF), was used to etch the sample. The purpose of this procedure was to clear any surface debris and reveal the grains. SEM was used to examine the microstructure and kind of wear of the nanocomposite. The precise phases that were present in the produced composite material were identified using X-ray diffraction (XRD). A Vickers Hardness Tester was used to determine the microhardness of the prepared samples. In compliance with ASTM E 384–99, the specimens were exposed to a 100–g force for 15 seconds. Three different locations were used for the experiment, and the average results were published. The Pin-on-Disc device was utilized to investigate the nano composite's wear and friction properties in a dry setting. EN31 steel was used to create the counter disk. To assess the rate of wear, the sample's weight was determined both prior to and following each tribo-test. The counter disk surface was cleaned with acetone after every experiment to get rid of any dirt [11]. Tribological studies were carried out in natural settings.

An authorized chemical supplier provided the reinforcing utilized in the laboratory-grade titanium dioxide (TiO2) powder [12]. The obtained TiO2 powder and its various properties are depicted in the picture below. Oxides of titanium are found in nature. Additionally, minerals including rutile, anatase, and brookite naturally contain TiO2. High luster, exceptional brightness, exceptional opacity and high color intensity, and good weather resistance are only a few of titanium dioxide's qualities. Figure 1 illustrates how TiO2 powder is reinforced.

Fig 1: The reinforcement of $TiO_2$ powder

To conduct the wear testing, a Wazau pin-on-disc tribometer was used. The polymers that were being studied were formed into pins with dimensions of 4 mm × 4 mm × 12 mm. In the experimental configuration, these pins were used. German standard 100Cr6 hardened steel was the disc material utilized in the configuration. In this work, the steel disc with a surface roughness (Ra) of approximately 30 nm was used to test the PA composites. For discussion purposes, the wear results of this study will be contrasted with information gathered from an earlier study in which the identical PA composites were subjected to the same loading conditions using the same experimental setup, but against a disc counterpart with a roughness of about 220 nm. For simplicity, the steel disc used in this study will be called "smooth," while the steel disc used in the study that was previously mentioned will be called "rough." It's critical to remember that these terms are used in connection with one another [13]. For instance, in this study, "rough" steel, defined as having a Ra of approximately 220 nm, is frequently thought to have a polished appearance. Figure 2 depicts the sliding wear set-up for the cross-sectional schematic model.

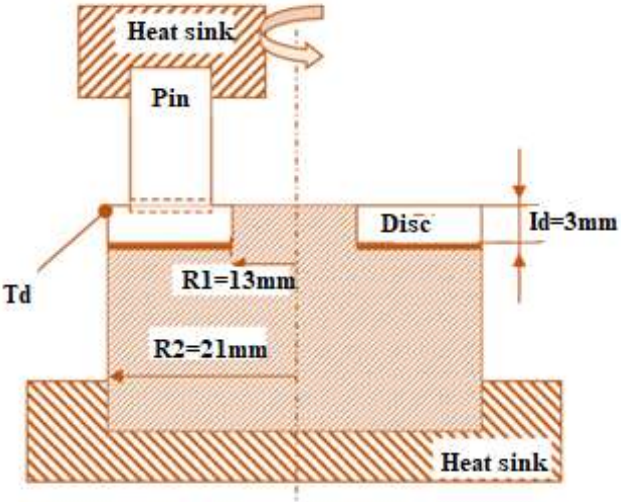

Fig 2: The sliding wear set-up for cross-sectional schematic model

Previous papers have already shown the wear results against both smooth and rough discs with respect to EP composites. To provide a more thorough knowledge of the underlying wear mechanisms, additional micro-analysis of the wear scars on the worn EP composites was carried out specifically for this work. Specifically, this study uses cross-sectional SEM analysis to look into how nanoparticles affect the growth of transfer film. With the addition of TiO2 nanoparticles and an analysis of the wear results of both the PA and EP composites versus smooth and rough discs, this work aims to advance our understanding of the mechanisms required to reduce friction and wear [14]. The sliding wear tests were run at a pace of one meter per second for a total of twenty hours. To match the pressures utilized in the previous study, the chosen normal loads were modified to provide pressures of 1, 2, or 4 MPa for the PA composites. An iron-constantan thermocouple was used to detect the steel disc's temperature, and the ratio of the applied load to the tangential force was used to calculate the friction coefficient. The layout diagram is shown in Figure 1. The iron-constantan thermocouple was positioned around 2 mm from the contact zone, close to the disc's edge, as can be seen in the diagram. This thermocouple keeps track of the disc's average temperature. The bulk of the frictional heat would travel to the steel disk since steel has far higher thermal conductivity than the polymeric sample. As a result, the temperature that was measured might be used to predict the temperature increase brought on by frictional heating. In other words, the temperature that is measured does not reflect the abrupt rise in temperature in the area of contact; rather, it represents the ambient temperature.

Following each wear test, the wear rate of the polymer was calculated using the following equation:

$$M_s = \frac{\Delta n}{\beta E_m L} \tag{1}$$

represents the applied (normal) load, Δn denotes the sample's mass loss, represents the sample's density, and L denotes the total sliding distance. These are the definitions of the variables in the equation. The average specific wear rate and steady-state coefficient of friction were obtained after the sliding wear condition was assessed twice. It is significant to note that one of the samples suddenly broke approximately 6.7 hours into the wear test of PA0 against the smooth disc with an applied pressure of 2 MPa. After around three hours of testing, when steady-state wear had already been established, the coefficient of friction in a steady condition was ascertained. By comparing the wear height loss between two samples at 6.7 hours of testing, the specific wear rate was calculated. It was anticipated that, when determined at 20 hours, the percentage difference in the particular wear rate would match the % difference in wear height loss at this point. A JEOL-5400 scanning electron microscope (SEM) was used to investigate the surfaces of the worn steel discs and the polymers. Furthermore, the investigation evaluated the thickness of the films and the existence or non-existence of TiO2 nanoparticles incorporated in the transfer films through the application of a comparable technique. Following the sliding wear tests, the steel discs were chopped and then set in 25 mm resin. This made it possible to reveal the cross-sectional surfaces, which were then polished with Struers Tegrapol. SiC grinding paper was used in the polishing procedure, which was followed by suspensions of 3 and 1 µm diamonds. A Zeiss Ultra SEM fitted with an energy dispersive X-ray spectroscopy (EDS) detector allowed for the analysis and acquisition of high magnification images of the transfer films' cross-sections.

## IV. Results and discussion

A thorough synopsis of all the sliding wear research data can be found in Figures 3 through 6. It is significant to note that the wear loss and friction results for the PA composites when tested against the rough disc have previously been reported in the previous study. In a similar vein, the EP composites' wear loss and friction results are available. The results obtained for the PA composites can be compared with the results of earlier studies on smooth discs to gain a better understanding of the degradation processes of the constituent polymers [15]. In the absence of TiO2 nanoparticles, Figure

3 illustrates how the wear rate of PA0 dramatically increased when the contact pressure was adjusted from 2 MPa to 4 MPa against the rough disk. This change resulted from a significant increase in contact temperature, which increased from 46.07 ◦C to 94.98 ◦C as the contact pressure increased from 2 MPa to 4 MPa. The elevated contact temperature significantly accelerated the rate of wear of the PA matrix because of the significant drop in hardness beyond 50 ◦C. Interestingly, while the contact pressure (pv factor) was low (1 MPa) in the smooth disc tests as opposed to the rough disc testing, the wear rate of the PA0 composites was demonstrated to increase. On the other hand, under high contact pressure (4 MPa), the wear rate decreased significantly. In reference to the second situation, it was found that PA0's average contact temperature was 85.85 ◦C. This temperature was higher than 50 ◦C, which caused a noticeable softening and a noticeably accelerated wear rate. But because the contact temperature was still somewhat lower than it was in the rough disc test, the wear rate was not as high.

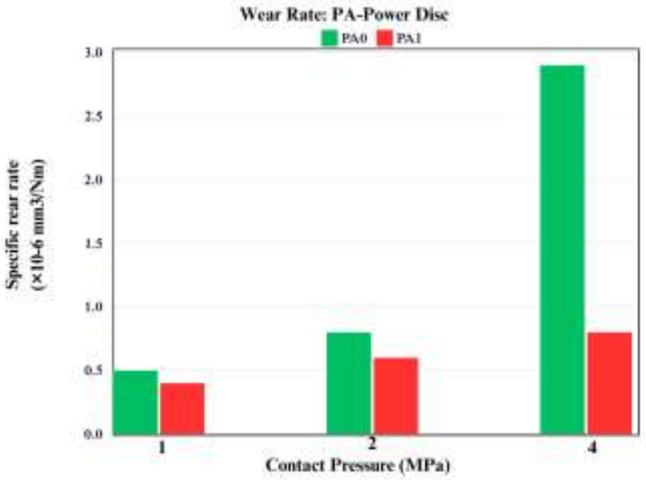

Fig 3: The sliding wear test results are shown as the average of two tests, with the error bars indicating the respective standard deviations. The PA composites' wear rates versus certain materials of rough steel disc

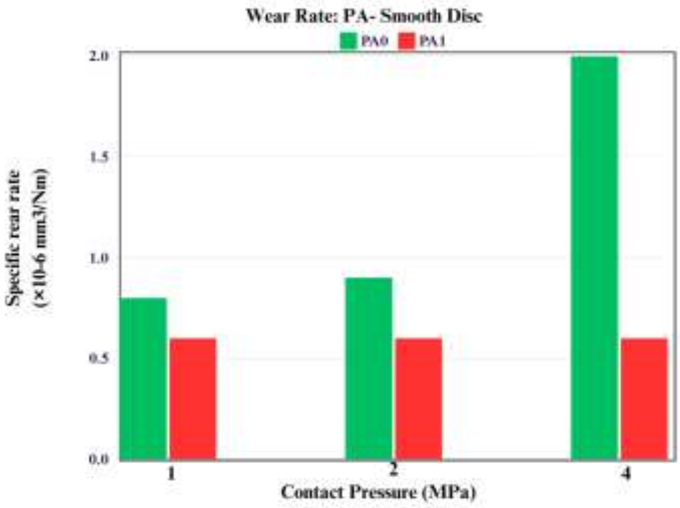

Fig 4: The sliding wear test results are shown as the average of two tests, with the error bars indicating the respective standard deviations. The PA composites' wear rates versus certain materials of smooth steel disc

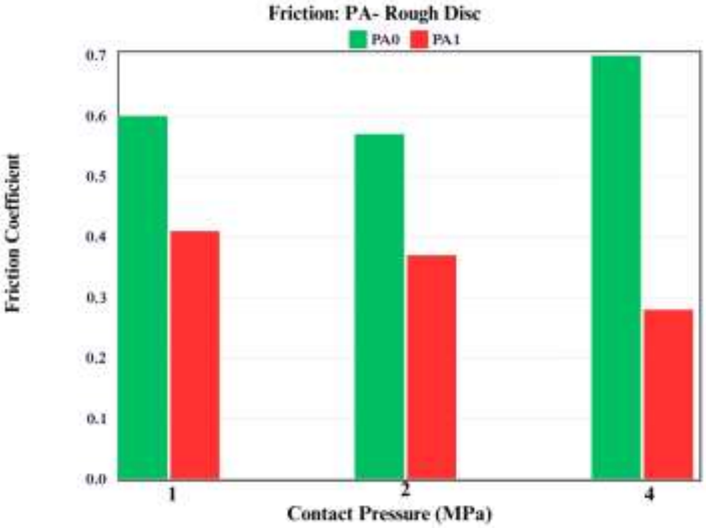

Fig 5: Friction coefficient of PA composite against rough steel disc

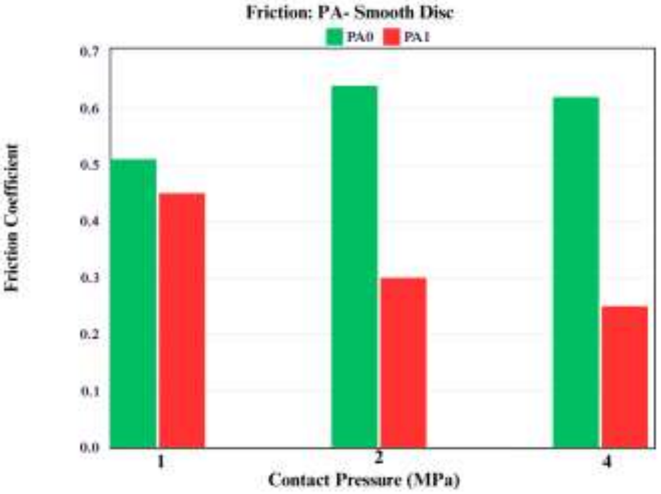

Fig 6: Friction coefficient of PA composite against smooth steel disc

Scholars have previously described interfacial adhesion as the number of contact sites between two surfaces that are increased when a highly polished surface comes into contact with a polymer. According to the research hypothesis, a more homogenous film was produced as a result of greater cohesion brought about by increased adhesion. In contrast, there were uneven areas on the films when tested against a rougher disc. However, this process is actually a combination of two mechanisms: compaction, which is the term for material compression, and adhesive wear of the polymer, which is the removal of material as a result of adhesive pressures. Simply said, loading conditions that encourage the production of a uniform transfer layer must offset the increased wear induced by adhesion in order for a smoother counterface to successfully minimize friction and the rate at which the polymer wears down. In any other case, a smoother disc would just accelerate the rate of wear of the polymer overall and increase adhesion wear.

## V. Conclusion

The purpose of this work is to investigate the causes of the notable variations in the tribological characteristics of epoxy and polyamide composites upon the addition of 300 nm-sized TiO2 nanoparticles. The composites are tested against steel discs with two different surface roughness levels while subjected to sliding wear conditions. The study's findings, which may be summed up by looking at the transfer films that were created, are as follows: When the steel surface roughness in polyamide composites is comparable to that of the TiO2 nanoparticles, the tiny protrusions on the steel surface can efficiently collect the wear-induced particles, including the TiO2 nanoparticles. As a result, a transfer film containing whole TiO2 nanoparticles is formed. There was no text provided by the user. The TiO2 nanoparticles in the polyamide composites will fragment before becoming part of the transfer film if the steel's surface roughness is significantly lower than the TiO2 nanoparticles'. Nevertheless, a TiO2-enriched transfer film continues to form. There was no text provided by the user. When TiO2 nanoparticles were added and the epoxy composites were employed with the rough disc, the results were favorable; however, the effects were different when the smooth disc was used. It was found that in the latter case, the concentration of TiO2 in the transfer film was not higher. There was no text provided by the user. Previous studies have connected the rolling effect caused by TiO2 nanoparticles to improvements in friction and wear of the materials being studied. On the other hand, the detrimental impacts on wear and friction have been linked to the rolling effect being hindered by a smooth opposing surface and bigger wear debris that is more difficult to remove than TiO2 nanoparticles. It is empty in the user's text. Combining the findings of our work with those of other studies, we propose that the rolling effect requires the production of a transfer film enhanced with TiO2. The presence of TiO2 nanoparticles can be very detrimental if a TiO2-enriched transfer film does not develop. This is because the much softer transfer film will be worn away by the TiO2's abrasive properties. Consequently, the polymer will be subjected to the steel counterface's roughness, which will accelerate the rate of wear.

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