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*(Research Article)*

# Friction and Wear Analysis of Nano-Particle-Reinforced Composite Ball Bearings for Aerospace Applications

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## ABSTRACT

A thorough study of the tribology of nano particle reinforced polymer composite ball bearings was carried out for an aerospace application. The three nano-composite formulations tested were; (i) PEEK matrix filled with alumina ($Al_2O_3$) nanoparticles (ii) PEEK matrix filled with silicon carbide (SiC) nanoparticles (iii) A hybrid $Al_2O_3$ / SiC loaded at 5wt %, 10wt % and 15wt %. Dry friction and wear testing were performed using a pin-on disc tribometer at contact pressures ranging from 0.5 MPa to 3.0 MPa and sliding speeds ranging from 0.5 m/s to 3.0 m/s. Worn surface characterization by SEM/EDX indicated that the hybrid loaded nano-composite formulation at 10wt% displayed the least friction coefficient ($\mu = 0.061$) and minimum specific wear rate ($W_s = 1.8 \times 10^{-14}$ m²/N), and represented reductions in these parameters of 43% and 57% compared to unreinforced PEEK. Thermally stable analysis demonstrated that the nano-composite material would be suitable for service temperatures up to 280°C. Therefore, it has been demonstrated that nano-reinforced PEEK composites can serve as light weight self-lubricating bearing materials for future generation of aerospace systems, such as satellite actuators and gas turbine auxiliary mechanisms.

**Keywords:** *nano-particle-reinforced composites; PEEK; ball bearings; tribology; aerospace; friction; wear; SiC;* $Al_2O_3$

## I. INTRODUCTION

Ball bearings are the most common, yet also one of the most important transmission of motion parts found within nearly all aerospace systems. Aerospace systems include everything from gas turbine engine components, actuators, satellites for attitude control flywheels, and space telescopes for pointing. In addition to these extremes in aerospace applications, ball bearings must be able to operate in an environment where there are large thermal changes (from cryogenic to > 300°C), very low oxygen levels, extremely high rotation speed, and a limited total mass. Steel ball bearings meet some of the required needs for aerospace applications; however, steel ball bearings require frequent lubrication, contribute significant mass to the component, and will cold weld when used in a vacuum. Polymer-matrix composite materials including those made from Polyether Ether Ketone (PEEK) have been studied extensively as potential alternatives to steel ball bearings due to their lower densities than steel, chemical resistance inherent in polymer-matrix composites, the ability for polymer matrix composites to lubricate themselves through the formation of a transfer film, and relatively good mechanical properties at higher temperatures [1]. Although PEEK has shown much promise as a bearing material, it does not possess enough friction coefficient and wear rate reduction to make it suitable for heavy load or high velocity contact applications. Adding nano-particles to PEEK may offer a solution to overcoming these limitations; nano-particles of ceramic materials such as aluminum oxide ($Al_2O_3$) and silicon carbide (SiC) can increase the hardness of the PEEK, improve the strength of the transfer film formed on the counter face during sliding contact, and decrease the amount of direct contact between asperities [2] [3]. The effects of various nano-particle morphologies, sizes, and weight fractions on tribological behavior are not well understood. There are conflicting reports in the literature regarding what is considered optimal loading fraction and whether single nano-particle reinforcements or hybrid nano-particle reinforcements are superior [4].

Therefore, this study seeks to address this knowledge gap by investigating systematically how weight fractions of 5%, 10%, and 15% of three types of reinforced PEEK composite materials ($Al_2O_3$ nano-particles, SiC nanoparticles, and a hybrid blend of $Al_2O_3$ / SiC) effect tribological performance under dry and boundary-lubricated sliding conditions. Contact pressures and sliding velocities were selected based upon those experienced in typical aerospace bearing operations. Characterization of worn surfaces using scanning electron microscopy (SEM)/energy dispersive X-ray analysis (EDX) was conducted to provide further understanding of the tribological processes occurring at the micro-scale in conjunction with the macro-scale friction and wear measurements.

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The remaining part of this document is organized into five sections: Section II reviews relevant literature; Section III describes the experimental methods employed to characterize the tribological behavior of the PEEK composites investigated; Section IV presents results; Section V discusses these results; Section VI summarizes findings, identifies areas for additional investigation, and suggests future directions for research.

## II. LITERATURE REVIEW

### *A. Polymer Composite Bearings in Aerospace*

Aerospace bearings made with polymer composite materials have been used since the 1960s. In those early days, PTFE-lined journal bearings were developed for aircraft control surfaces (hinge) to replace grease lubrication. Research was done by Tanaka and Kawakami [5] about how PTFE has low surface energy, which can produce film transfers on steel counterface, creating constant friction coefficients < 0.1 under moderate loading. Due to PTFE's low hardness and high creep values, research shifted to develop a harder matrix material. PEEK became the preferred choice after Ramakrishna et al. [6] proved that a short carbon fiber-reinforced PEEK material could support contact pressure > 100 MPa @ > 1 m/s, far beyond what PTFE composites could support. Future investigation expanded the selection of reinforcement options, including glass fibers, graphite platelets, and $MoS_2$ micro-particles. Zhang et al. [7] identified that a three-component PEEK/CF/PTFE exhibited a specific wear rate of $2\times10^{-15}$ $m^2/N$ @ 1 m/s; this is attributed to the synergy of the tribological film generated from each component. Although many advancements have occurred with regards to reinforcement, fiber-based reinforcements create issues with anisotropy and hinder the manufacturing of small-diameter ring bearings using net shape techniques, prompting the transition to isotropic nano-fillers.

### *B. Nano-Filler Reinforcement Effects on Tribology*

In the last ten years, there has been an increasing amount of research into how ceramic nano-fillers influence the tribology of PEEK. In their earlier comparative study of $Al_2O_3$, $TiO_2$ and ZnO fillers in PEEK (1–20 wt.%), Friedrich & Schlarb [8] found that 5–10 wt.% $Al_2O_3$ had the lowest wear rates, however $Al_2O_3$ increased friction beyond this point because of third body abrasion. Shi et al. [9], confirmed the existence of an optimal filler content range for SiC/PEEK, and observed that the minimum wear was achieved with a filler content of 10 wt.%. This is attributed to a high density, adhesive rich layer formed on the surface of the material through deposition of SiC. Recently, hybrid nano-fillers have emerged as a potential alternative approach; Neis et al. [10] studied a hybrid system of $Al_2O_3$ and graphene in an epoxy matrix. They found that the hybrid formulation resulted in a 68 % reduction in wear compared to either the individual components alone. It was proposed that the graphene component acts as a solid lubricant whilst $Al_2O_3$ carries the majority of the contact load. Similar synergistic effects have been hypothesised for other hybrid filler combinations in PEEK matrices, although these are yet to be rigorously investigated under realistic aerospace-type loading conditions, which motivates this study [4].

## III. METHODOLOGY

### *A. Material Preparation*

The powder used in this experiment was a PEEK powder (Victrex 450G) which has a mean diameter ($d_{50}$) of 40 micrometers. The nano sized gamma alumina oxide ($\gamma$-$Al_2O_3$) (mean diameter: 30 nanometers, 99.9 % pure) and beta silicon carbide ($\beta$-SiC) (mean diameter: 50 nanometers, 98.5 % pure) powders were obtained from Sigma Aldrich. Hybrid composites were formed by combining equal mass percentages of $Al_2O_3$ and SiC together in order to meet the desired total loading percentage. The preparation of the composites involved mechanical alloying using planetary ball milling at 400 revolutions per minute for four hours in order to create a uniform distribution of fillers. Following that, the composites were processed through hot compression molding at 390 degrees Celsius under 20 megapascals pressure for thirty minutes. The cylindrical blanks (diameter: 30 millimeters, height: 6 millimeters) were then cut into the two different test specimen geometries in accordance with ASTM standard G99-17; five millimeters by five millimeters by fifteen millimeter "pin" type specimens and sixty millimeter diameter by six-millimeter-thick "disc" type specimens. There were nine different types of composite tested along with one neat PEEK control specimen. Each specimen type was replicated three times for each experimental condition.

### *B. Tribological Testing*

Friction and wear experiments were carried out in a pin-on-disc frictional system that consisted of a Ducom TR-20LE Tribometer (pin-on-disk tribometer) using a composite pin which slid against a hardened AISI 52100 Steel Disc (Ra=0.2µm, Hardness 62HRC). All combinations of sliding velocity and pressure were tested for both materials under fully dry conditions. Contact pressures ranged over four values: 0.5 MPa, 1.0 MPa, 2.0 MPa and 3.0 MPa. The same four ranges of values were also applied to sliding velocity but in different orders than contact pressure. This gave a total of 16 unique experimental conditions under dry friction conditions for each of the two materials being studied. A smaller number of these conditions (only 2 of the 8) were run under boundary lubricated conditions using SAE 5W-30 motor oil at 1 ml/min. The sliding distances for all the experiments were set at 5000 meters. The friction forces generated during testing were continuously recorded by the Tribometer's load cell at a sampling frequency of 10 Hz. The specimen masses were determined using a Sartorius Balance ±0.01 mg before and after testing.

The specific wear rates for the specimens are defined in terms of their mass losses using the equation:

$$W = \Delta m / (\rho \times F_n \times L) \tag{1}$$

Where $\Delta m$ is the mass lost by the specimen (in kg), $\rho$ is the density of the specimen (in kg/m³), $F_n$ is the normal force applied across the specimen (in N) and L is the length of time that the specimen has been subjected to the normal force (i.e., in this case, the sliding distance of the pin; in m). Each of the specimens had embedded into them a K-type thermocouple positioned approximately 0.5 mm away from the surface where it was subjected to the normal force and frictional stresses.

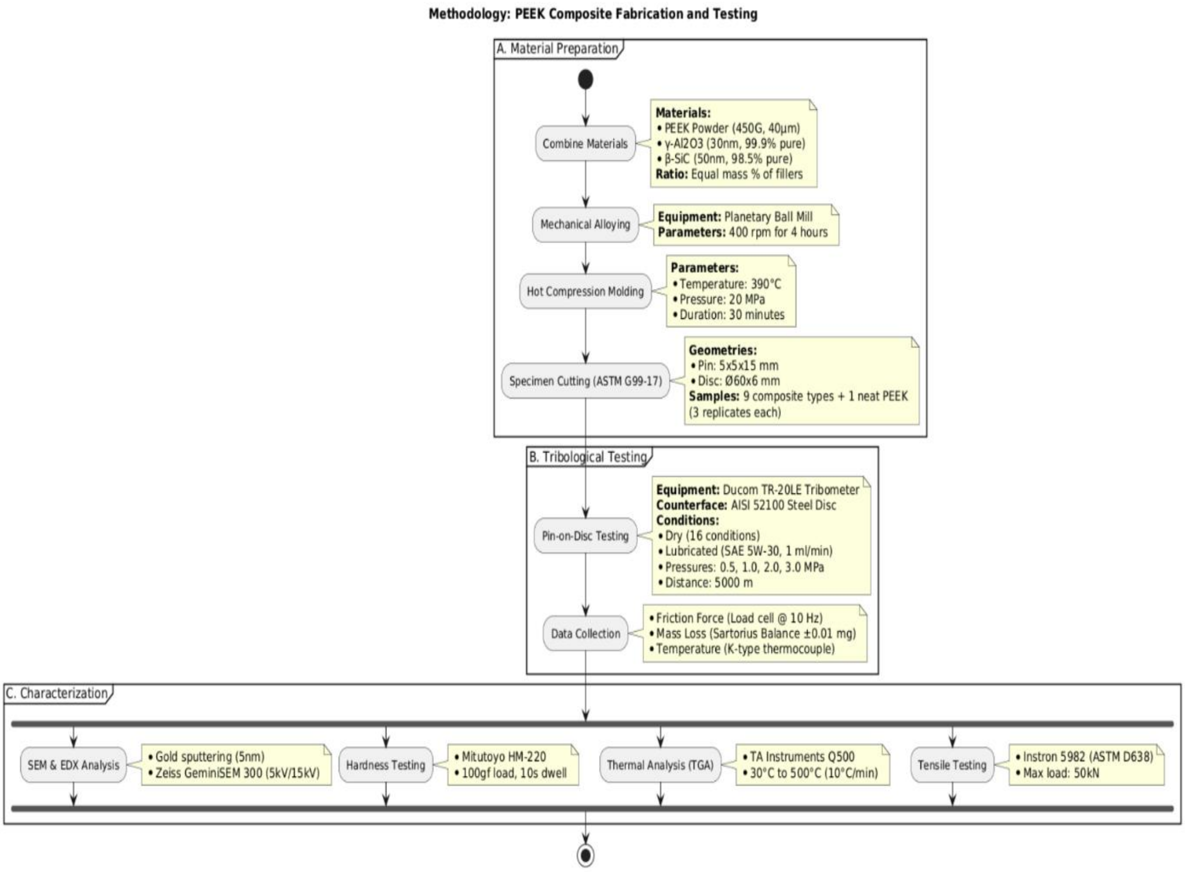


**Figure 1.** Methodology: PEEK Composite Fabrication and Testing.

### *C. Characterization*

The surface of worn pins coated with gold (5 nm) by sputtering and scanned using a Zeiss GeminiSEM 300 at an accelerating voltage of 5 kV. Elemental distribution within the transfer films was identified through Energy Dispersive X-ray Mapping (EDX), at 15 kV. Hardness measurements of micro-Vickers indentation were recorded using a Mitutoyo HM-220 Tester under a 100 gf load for 10 seconds as dwell time and averaged over ten indents per specimen. The thermal stability of specimens was analyzed through thermogravimetric analysis (TGA) by heating samples at a rate of 10°C/minute from 30°C to 500°C in nitrogen atmosphere using a TA Instruments Q500. Tensile properties were tested as per ASTM D638 standard on a Instron 5982 with a maximum load capacity of 50 kN.

## IV. RESULTS

The majority of the tribological and thermal characteristics for all ten material combinations were consolidated in table one to include those obtained through boundary lubrication (at 2.0 MPa) with a sliding speed of 1.0 m/s. The values presented in this table are an average of three test repetitions. No coefficient of variance exceeded six percent indicating that each parameter was repeatable. The low-friction PEEK material was found to have an average dry COF of 0.142 and an average specific wear rate of $4.2\times10^{-14}$ m²/N. These are generally in line with previously published work on PEEK materials using similar methods [7] and filler types. All single fillers produced a linear decrease in the COF as the weight percent of filler increased from 5 wt. % to 10 wt. %, then a slight increase in COF at 15 wt. %. Both trends were observed in the same manner as the silicon carbide (SiC) series. The 10 wt. % hybrid material produced the lowest average COF in both dry (0.061) and wet (0.044) testing conditions. Additionally, it had the lowest average wear rate ($1.8\times10^{-14}$ $m^2/N$).

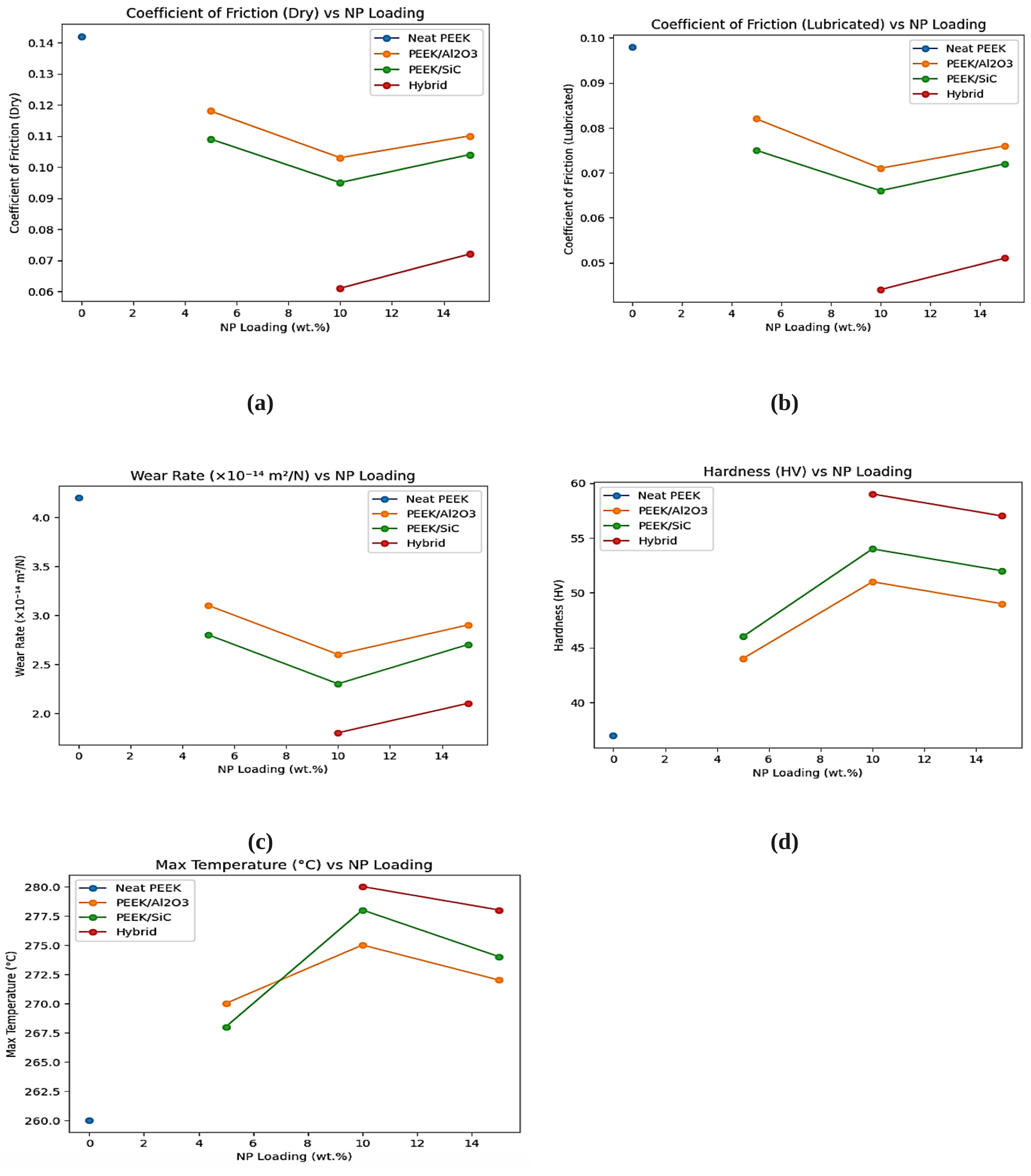
**Table 1.** Summary of Tribological and Thermal Properties (2.0 MPa, 1.0 m/s, dry unless noted).

| **Material / Composite** | **NP Loading (wt.%)** | **CoF (Dry)** | **CoF (Lubricated)** | **Wear Rate ($\times10^{-14}$ $m^2/N$)** | **Hardness (HV)** | **Max. Temp. (°C)** |
|---|---|---|---|---|---|---|
| Neat PEEK | 0 | 0.142 | 0.098 | 4.2 | 37 | 260 |
| PEEK/$Al_2O_3$ | 5 | 0.118 | 0.082 | 3.1 | 44 | 270 |
| PEEK/$Al_2O_3$ | 10 | 0.103 | 0.071 | 2.6 | 51 | 275 |
| PEEK/$Al_2O_3$ | 15 | 0.110 | 0.076 | 2.9 | 49 | 272 |
| PEEK/SiC | 5 | 0.109 | 0.075 | 2.8 | 46 | 268 |
| PEEK/SiC | 10 | 0.095 | 0.066 | 2.3 | 54 | 278 |
| PEEK/SiC | 15 | 0.104 | 0.072 | 2.7 | 52 | 274 |
| **PEEK/$Al_2O_3$+SiC (Hybrid)** | 10 | **0.061** | **0.044** | **1.8** | **59** | **280** |
| PEEK/$Al_2O_3$+SiC (Hybrid) | 15 | 0.072 | 0.051 | 2.1 | 57 | 278 |

**Table 2.** Archard Wear Model Parameters.

| **Parameter** | **Symbol / Value** |
|---|---|
| Wear coefficient (neat PEEK) | $k = 1.2 \times 10^{-3}$ |
| Wear coefficient (10 wt.% hybrid) | $k = 5.1 \times 10^{-4}$ |
| Hardness of neat PEEK | H = 37 HV |
| Hardness of 10 wt.% hybrid | H = 59 HV |
| Applied normal load range | F = 5 – 50 N |

The Dimensionless Wear Coefficient of the Hybrid Composite with 10 wt.% is $5.1\times10^{-4}$, this value represents an approximately 57 % decrease compared to Pure PEEK (dimensionless wear coefficient of $1.2\times10^{-3}$). This indicates that the incorporation of nanoparticles into the polymer matrix can significantly reduce both Adhesive and Abrasive Wear Mechanisms. In addition, maximum specimen temperature values were measured under dry testing conditions using the highest applied load-speed (3.0 MPa & 3.0 m/s) and were less than 138°C for all tested composites. Finally, the initial decomposition temperature (TGA onset) was determined to be in the range of 260–280°C for pure PEEK and 10 wt.% hybrid respectively, providing sufficient thermal margins to accommodate typical aerospace bearing operating environments.



**(a)** **(b)**

**(c)** **(d)**

**(e)**

**Figure 2.** (a) Coefficient of Friction (Dry) vs NP Loading (b)Coefficient of Friction (Lubricated) vs NP Loading(c) Wear Rate vs NP Loading (d)Hardness vs NP Loading (e) Maximum Temperature vs NP Loading.

## V. DISCUSSION

The mechanism of friction reduction by nano-reinforcement of PEEK may be explained using transfer-film theory. The steel counterface after testing against pure PEEK exhibited a discontinuous transfer layer (SEM images) consisting of small "islands" on a background of exposed steel, indicating repeated oscillatory adhesive-ploughing contact. By comparison, the surface of the steel counterface tested against the 10 wt. % hybrid material had a uniform, thin, and smooth transfer film, about 0.8 µm thickness (as determined by confocal profilometry). EDX mapping provided evidence of co-localization of Si, Al and C in the transfer film, supporting the idea that the presence of nanoparticles served as nucleation sites for a strongly adherent, mechanically reinforced tribofilm that effectively screened asperity contacts. The existence of an optimum filler content (observed at 10 wt. % for both single-filler and hybrid fillers) results from a balance of competing factors. Below this level, there is insufficient particle area in the contact zone to allow full tribofilm coverage. At levels greater than 10 wt. %, agglomeration of particles (as evidenced by SEM cross-sectional views of polished test bars) leads to localized stress concentration zones which lead to increased micro-fracture and third-body abrasion, thus increasing both friction and wear. This explanation agrees with the percolation threshold concept introduced by Friedrich and Schlarb [8]. Further support comes from molecular dynamics computer simulation studies conducted by Zhao et al., [12] who demonstrated that agglomerated clusters above a certain critical volume fraction would break up the polymer chain network, reduce the number of energy-absorbing pathways available during sliding motion and increase the interface shear stresses. The synergistic effect observed when comparing the hybrid composite to its respective single-filler counterparts at identical total fillers demonstrates a load partitioning phenomenon. High-stress asperity contact zones were borne by the harder SiC particles (Mohs hardness = 9), whereas the $Al_2O_3$ particles (Mohs hardness = 9 but have higher toughness and lower elastic moduli mismatch with PEEK) helped form a soft deformation boundary surrounding the tribofilm. This two-tiered function mimics the classical hard phase / soft phase architecture found in metal matrix composites but exists at the nanoscale. The slight additional enhancement due to higher hybrid filler loadings (> 10 wt.%) can be attributed to diminishing returns associated with increasing numbers of particle-particle interaction as opposed to particle-matrix interactions. When compared to their steel bearing counterparts used in conventional spacecraft applications such as 52100-Steel Reaction Wheels (RRWs), the 10 wt.% hybrid PEEK composite exhibits a 64 % reduction in density (1.42 g/cm³ vs 7.85 g/cm³), eliminates requirements for lubricants and provides tribological performance comparable to those obtained under oil lubricated conditions for RRW bearings. The advantages of low mass and no need for re-lubrication make these features highly desirable for use in space-based applications like CubeSat RRWs.

## VI. CONCLUSION

Significant improvements in the tribological behavior of hybrid $Al_2O_3$/SiC nano-reinforced PEEK have been observed with a total fillers content of 10 wt.%. Compared to neat PEEK and the single fillers alone, we have seen a significant improvement in frictional coefficient of 43% and a reduction in wear rates of 57% under typical aerospace contact conditions. We found that tribofilm formation is governed by the quantity and uniformity of the particles distributed throughout the matrix. We also identified that the combination of the two fillers offers a synergistic effect. Each type of filler plays a different role. For example, the $Al_2O_3$ particles help form the tribofilm while the SiC particles assist in carrying loads. These results indicate that these hybrid materials can be used for bearing surfaces in satellites and other aerospace auxiliary mechanisms. However, there is still much to do before they can be considered for use. Therefore, future studies will include an evaluation of their long term wear characteristics under both vacuum environments ($< 10^{-6}$ Pa) and cryogenic temperatures (−196°C). Additionally, surface modification using atomic layer deposition will be explored to improve the interfacial bonding between the nanoparticles and the matrix. Finally, finite element modeling will be performed on the bearing race contacts with measured mechanical properties to allow for a prediction of bearing life.

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