



# The influence of surface properties on sliding contact temperature and friction for polyetheretherketone (PEEK)



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## ABSTRACT

Polyetheretherketone (PEEK) polymers are increasingly used in tribological applications. An important aspect of PEEK tribology is the surface temperature reached during sliding. At present, most knowledge of frictional heating in PEEK is based on post-hoc analysis of debris and wear surfaces. In this study, infrared thermography was used to observe the full field temperature map of PEEK against sapphire counterface during ball-on-disc sliding. The measured temperatures matched closely those predicted by flash temperature models. Additionally, friction studies were performed with steel and sapphire counterfaces. It was observed that PEEK debris readily deposited on steel but not on sapphire. The friction studies also indicated a greater adhesive friction response for PEEK against steel compared to PEEK against sapphire. The transfer of PEEK material to the steel surface may elevate the temperature at the sliding interface. Analysis of transfer films on steel suggests that the transferred PEEK was oriented in the direction of sliding. The deposition of debris and formation of oriented films resembled a high temperature drawing process, which was likely to be due to localized frictional heating. The results of this study illustrate the important role transfer films play in determining both the friction and temperature of the PEEK wear interface.

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## 1. Introduction

### 1.1. Frictional heating

When two surfaces are rubbed against each other, frictional heat is generated and temperature at the rubbing interface rises. Depending on test conditions and material properties of the rubbing pair, the interfacial temperature,  $T_s$ , can be substantially higher than the stated test temperature. This is particular true when rubbing surfaces are rough. For rough surfaces, the real contact area is often much smaller than the nominal contact area [1–3]. The asperity contact pressures are thus much greater than that predicted by Hertzian contact mechanics. The high local pressure and friction can give rise to very high local temperatures [4].

The actual magnitude of  $T_s$  is important for an accurate description of polymer wear phenomena. Polymers are typically

good insulators. Thus heat cannot be conducted away easily and  $T_s$  can be high enough to soften or even melt the polymer surface. Severe wear associated with melting are likely to be initiated by the buildup of small thermal transients [5]. Many studies have observed rippled and stretched wear features that suggest the rubbing surface was strained when in a rubbery state [6–8]. Analysis of wear debris often shows changes in molecular structures that indicate surface temperatures near melting were reached [9,10]. Ludema and Rhee utilized mass spectroscopy to examine decomposition products during severe polymer wear [11]. The detection of chemical vapors corresponding to melting implied that melting temperatures  $T_m$  have been reached at the rubbing interface. Archard determined maximum temperatures for polymer rubbing pairs based on a model for load-controlled friction [12]. He observed that predicted temperatures near the glass transition temperature  $T_g$  corresponded with severe wear in Perspex sliding pairs. Ettles suggested that for polymers, a limiting temperature exists based on a thermal softening point [5]. This thermal control model has been supported by empirical observations of polymer friction [5,13,14]. Despite the important role played by temperature in polymer friction and wear, most of the available temperature data are based on post-hoc analysis or inference from analytical or

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numerical models.

The interfacial temperature due to frictional heating can be estimated based on material properties and sliding speeds. The sharp temperature rise at the contact is termed the flash temperature. Models based on a moving heat source [4,12,15–17] have been proposed to describe situations with a variety of Peclet numbers and shapes of heat source [18]. Early work attempted to confirm these models through the use of buried thermocouples, dyes, and temperature sensitive films [18]. However, advances in infrared (IR) thermography have enabled *in situ* studies of frictional heating to be performed with great accuracy. Results can then be directly compared with flash temperature models [19–22].

*In situ* frictional heating studies of polymers so far have focused largely on rubber and other soft elastomers [19,22–24]. These materials have low elastic moduli. Thus they have large real contact areas and high friction can occur at low pressures and sliding speeds. These test conditions however differ vastly from operational conditions commonly experienced by many engineering polymers. For instance, a thrust washer configuration may operate with a nominal pressure of ~1 MPa and speeds of 4 m/s [25]. In this work, PEEK polymer, a high performance engineering polymer, was studied across a range of pressures and speeds in which frictional heating was believed to become significant. A ball-on-disc geometry was used where the ball was made of PEEK. The resulting contact pressure may be much greater than is typical of pin on flat or thrust washer configurations. During sliding, the surface temperature was monitored.

## 1.2. PEEK tribology

Polyetheretherketone (PEEK) is a high performance semi-crystalline polymer from the polyaryletherketone (PAEK) family of thermoplastics [26]. PEEK is valued for its solvent resistance as well as high glass transition ( $T_g \sim 150^\circ\text{C}$ ) and melting ( $T_m \sim 350^\circ\text{C}$ ) temperatures [26]. These properties have enabled PEEK to be employed in tribological applications where temperatures and corrosive environments would preclude the use of many materials. PEEK has been used in oil and gas exploration [27], biomedical applications [28], and space environments [29] to name a few. Limits on operating conditions are often ascribed to excessive heating that results from friction [30]. To avoid such conditions, it is not uncommon for an upper value of pressure and velocity to be assigned to PEEK-based components [31–35].

A number of authors have focused on PEEK wear behavior [35–38]. Comparisons in terms of friction and wear resistance are often made with polytetrafluoroethylene (PTFE). PTFE on its own suffers from high wear rates [39]. Unfilled PEEK on the other hand has outstanding wear resistance but tends to have high friction coefficients [39,40]. PEEK is thus often filled with PTFE to reduce friction.

PEEK wear resistance is often attributed to an ability to form protective transfer films on harder metallic counterfaces [7,37]. Unlike PTFE that forms transfer films due to its unique banded crystal structure, there is no specific mechanism for PAEK film formation [41]. When PAEK is rubbed against metal, Bahadur suggested that compacted polymer debris becomes physically entrapped between asperities of the countersurface [42]. A polymeric film is eventually formed, and protects the bulk polymer from abrasive wear by covering hard rough asperities.

Many studies have attempted to understand the thermal and tribochemical effects of PEEK wear. Using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), Zhang studied the thermal properties of PEEK debris formed under various conditions [43]. It was believed that during wear, chain scission of the diphenyl ether segment occurs and oxidative

crosslinks are formed at free radical sites. They had observed changes in the pyrolysis behavior. In addition, the tendency for crystallization is impeded. These results were suggested to be due to the formation of crosslinked branches that restricted segmental mobility. X-ray photoelectron spectroscopy (XPS) was used to further support this hypothesis and found the severity of chain scission is pressure dependent [44]. The thermal properties of PEEK wear debris also indicate that they were formed near melting temperatures [9,43]. According to Bahadur, the chemical activity between fillers and counterface can enhance the tenacity of polymeric transfer films [45–47]. Jacobs showed that for sliding wear of PEEK in aqueous environments, chemically inert diamond-like coating (DLC) or alumina  $\text{Al}_2\text{O}_3$  counterfaces should be used in place of steel to reduce wear [48,49]. Rebelo de Figueiredo recently used Raman spectroscopy to detect adhesive transfer between neat PEEK and various counterfaces [50]. Low surface roughness and surface energy were believed to minimize the adhesion tendency as well as tribo-oxidative wear [50]. These observations all indicate that wear behavior of PEEK depends strongly on tribochemistry and temperature. However, these theories can be further supported by *in situ* studies.

The overall aim of this work is to understand how frictional heat manifests during sliding of polyetheretherketone (PEEK) polymers against steel and sapphire surfaces. The effect of contact temperature on friction were investigated. This was accomplished by measuring evolutions of friction and temperature in PEEK sliding contacts against steel and sapphire surfaces. The measured temperatures were compared with flash temperature predictions. The role of transfer films were discussed.

## 2. Materials and methods

PEEK balls were rubbed against steel and sapphire discs in a ball-on-disc configuration. Friction and interfacial temperatures were recorded at various sliding speeds and applied loads. Both steel and sapphire discs were used for friction measurements while only sapphire discs were used for IR thermography temperature measurements.

### 2.1. Materials

PEEK ball samples were made from a commercially available Victrex 450G injection molded bar stock. The 19 mm diameter balls were machined from a single 25 mm diameter rod on a 3-axis CNC lathe to ensure reproducibility between samples. Steel and sapphire discs for friction measurements were purchased from PCS. The material properties of the balls and discs are listed in Table 1. Contacts were formed when a PEEK ball was pressed against a disc. The ball was always stationary while the disc rotated at a programmed speed. The labeling PEEK-sapphire and PEEK-steel denote contacts formed with a PEEK ball, against a sapphire disc and a steel disc respectively.

### 2.2. Friction measurement

Coefficients of friction were measured using a mini-traction machine (MTM) from PCS instrument under pure sliding conditions [51]. Tests were done by pressing a 19 mm diameter PEEK ball on a rotating disc. A new disc specimen was used for each test. Discs were cleaned with toluene in an ultrasonic bath and washed with acetone before use. PEEK balls were rinsed in isopropanol and thoroughly dried before each test. All tests were conducted at  $25^\circ\text{C}$ .

In this study, the effects of speed and load on friction coefficient were investigated. Friction was measured across a range of loads between 1 N and 40 N at a fixed sliding speed of 100 mm/s. The

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