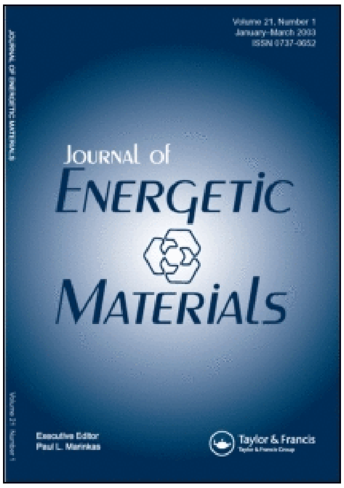


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# Aspects of the Tribology of the Plastic Bonded Explosive (PBX) 9404

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# Aspects of the Tribology of the Plastic Bonded Explosive (PBX) 9404*

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*The coefficient of friction, μ, of PBX 9404 was measured on stainless steel, aluminum, polytetrafluoroethylene (PTFE), and the explosive itself between ambient and 135° C at a rotational speed of 0.0025 rad/s. The mean surface roughness,*



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*$R_a$, of the various materials was analyzed by an optical profilometer. For PBX 9404 on stainless steel, $\mu$ increased from 0.22 at 25°C to 0.34 at 95°C, then decreased to about 0.23 at 125°C. With aluminum $\mu$ increased from about 0.08 at 25°C to 0.48 at 115°C, then decreased slightly. Against PTFE $\mu$ was sigmoidal, increasing from about 0.3 at 25°C to about at 0.49 above 115°C. Against PBX 9404 itself, $\mu$ averaged 0.54 independent of temperature, but tended to increase during the measurement, probably because of adhesion of nitrocellulose to itself.*

**Keywords:** PBX, initiation, mechanical properties



## Introduction

Serious explosive accidents have occurred as a result of oblique impact on a surface. Violent deflagration is believed to result from frictional heating during skidding on the surface. Several tests to determine the onset of reaction due to oblique and crushing impact including skid tests [1], Susan tests [2], and Steven tests [3] have been developed by various organizations to evaluate this hazard. A small-scale BAM friction test often is used to estimate the sliding force required to produce a reaction in an explosive on a ceramic plate [4]. PBX 9404 will react violently when the BAM friction test ceramic pin is dragged across its surface at a normal pressure of approximately 2.25 MPa (325 psi). Until recently most of these tests were done under ambient conditions. To understand the dominant microscopic mechanism of initiation during impact, Steven tests on LX-04 and PBX 9404 heated to 150–170°C were compared with ambient results. The results showed that LX-04 was much less sensitive to impact (the impact threshold increased significantly: 45 m/s at ambient to >125 m/s at 150°C), while the PBX-9404 impact threshold increased only slightly (35 m/s at ambient to 48 m/s at 150°C) [3]. Models for initiation depend on shear, deformation, and friction. Data for the modulus and ultimate properties of LX-04 are available [5,6] as a function of temperature, but friction data are limited to near ambient conditions [7,8]. Less information is available for PBX 9404 [9,10]. In a previous study the coefficient of friction for LX-04 on steel, PTFE, and the explosive itself decreased with increasing temperature [11], consistent with the Steven test results. The present study sought to determine whether or not the coefficient of friction of PBX 9404 as a function of temperature was sufficiently different from LX-04 to correlate with the Steven test results on this explosive.

## Experimental Procedures

### *Friction Measurements*

Parallel plate fixturing for a Rheometrics Mechanical Spectrometer model 800 was modified to measure the torque associated with a given normal force on cylindrical disks of PBX 9404 explosive $2.530 \pm 0.0007$ cm in diameter by $0.320 \pm 0.001$ cm thick. Samples of the explosive were bonded to the removable aluminum plate of the upper fixture with Scotch double stick foam tape. The counter surface, except for PBX 9404 explosive against itself, was machined into a 5.08 cm diameter disk with a 2.02 cm diameter lower section that was secured into the lower RMS fixture. The test setup is shown in Figure 1. The test was started with no contact between PBX 9404 and the rotating counter surface. The rotational speed for all testing was 0.0025 rad/s. Once the transducer had auto zeroed, the sample and foam tape were lowered to approximately 0.020 mm below the contact distance. Compression of the foam usually resulted in between 20–200 g normal force, $N$, being applied to the counter surface, which decreased slowly as the foam relaxed. The resulting torque, $T$, increased slowly for a few seconds and leveled out. The coefficient of friction, $\mu$, was calculated from

$$\mu = \frac{3T}{2N\mathrm{R}}, \tag{1}$$

where R is the radius of the explosive disk [12,13]. Typical results for PBX 9404 on aluminum are shown in Figure 2. As can be seen in the figure, the coefficient of friction calculated according to equation (1) quickly becomes nearly constant, even though the normal force and torque may vary slightly. Toward the end of the one-minute contact time, the sample was raised to a height slightly

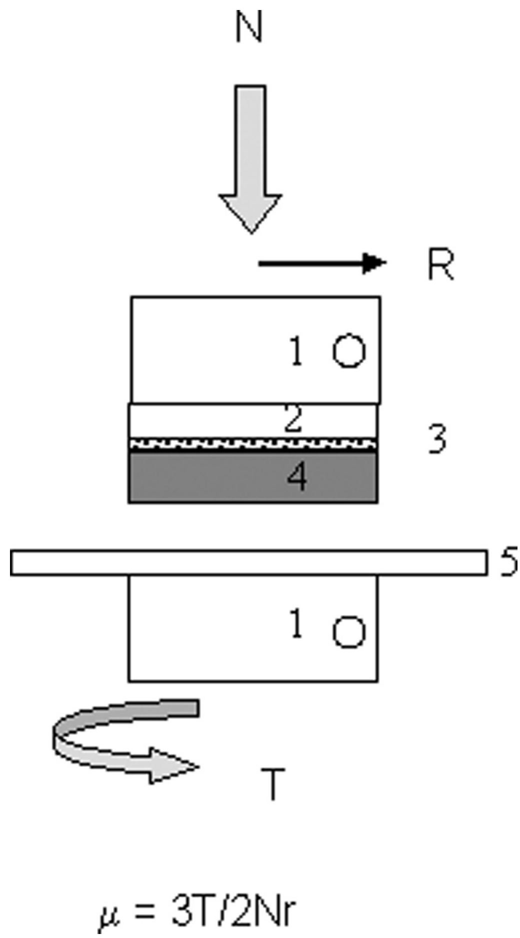


**Figure 1.** A friction measurement apparatus was developed based on the parallel plate fixtures for the Rheometrics Mechanical Spectrometer model 800. 1 = upper and lower test fixture; 2 = removable aluminum plate that is secured into the upper fixture by tightening the screw represented by a circle; 3 = 3 M foam adhesive tape to aid in (4) sample (5) counter surface alignment.

above the surface to ensure that the normal force and torque values returned to zero and the temperature was incremented 10°C. A torque and normal force measurement was taken every 0.0375 s.

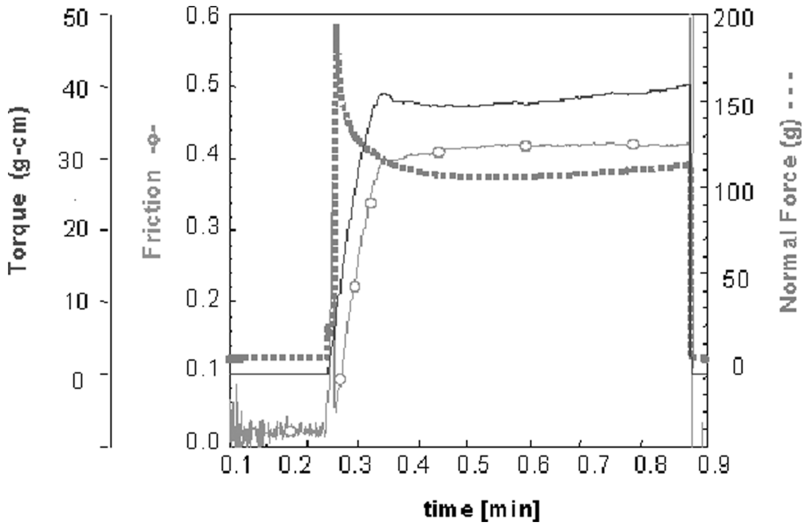


**Figure 2.** Typical results from torque and normal force measurements for PBX 9404 on aluminum at 85℃. The coefficient of friction was calculated from equation (1) for each value of torque and normal force.



A 2-minute hold time was allowed during which the contact position was redetermined so that approximately the same compression of the fixture could be obtained at the next temperature. After the 2-minute interval, the next experiment began. The temperature variation in the oven during a measurement was 0.2°C or less. All experiments with PBX 9404 explosive were conducted remotely in a 1.27 cm thick steel cell to protect the operator from the unlikely possibility of an explosion. The experiments were automated using the Rheometrics Orchestrator program, except for the repositioning of the *z*-axis, which was accomplished by a remote electronic control switch, instead of the up-down switches on the instrument.

### *Surface Profiles*

Surface profilometry was performed on PBX 9404 and the counter surfaces using a Conoscan 3000 instrument manufactured by

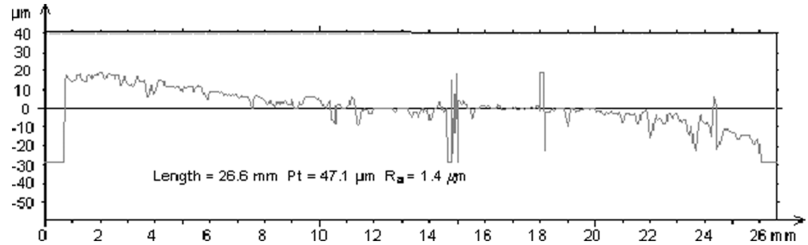


**Figure 3.** This surface profile of pressed PBX-9404 gave $R_a = 1.37\,\mu\text{m}$.

Optimet Optical Metrology. This conoscopic holographic technique measures the interference of ordinary and extraordinary rays off the sample through a birefringent crystal against a calibration to produce a surface profile [14,15]. The roughness $R_a$ is the mean of the $z$-axis profile calculated from

$$R_a = \frac{1}{L}\sum_i |z(x_i)|, \tag{2}$$

where $z(x_i)$ is the height of the surface at $x_i$ and $L$ is the length over which the measurement was made. A typical example of the results of such measurements is shown in Figure 3 for pressed PBX 9404 explosive. $R_a$ values for stainless steel, aluminum, and PTFE counter surfaces were 0.40, 0.31, and $R_a = 0.054\,\mu$m, respectively.

### *Materials*

PBX 9404 is an explosive composed of approximately 3% by weight nitrocellulose (11.8–12.2% nitrogen), 3% chloroethyl phosphate (CEF) plasticizer, and 94% by weight of a 70.5/23.5 mixture of class 1 and class 5 HMX explosive [16]. Usually a small amount of diphenyl amine is added as a stabilizer for nitrocellulose (NC). The surface roughness ($R_a$=1.37 $\mu$m) of one of the pressed PBX 9404 pellets is shown in Figure 3. PBX 9404 samples from lot no. C-120 were compression molded in a cylindrical die at 85°C for three 3-minute cycles at 200 MPa (30,000 psi) with approximately 1-minute relaxation at atmospheric pressure between pressing cycles. The density of PBX 9404 pressed disks, calculated from length, diameter, and weight measurements, averaged $1.831 \pm 0.004$ g/cc with an average radius of $1.2652 \pm 0.0003$ cm. Stainless steel, aluminum, and PTFE plates were machined from stock. Small amounts of flash at the edges of PBX 9404 were removed by sanding.

## Results and Discussion

Figure 2 shows the normal force and torque measurements of PBX 9404 against aluminum at 85°C. As was typical with aluminum, stainless steel, or PTFE, the sample and foam were compressed rapidly by the lowering of the cross head, resulting in rapid rise of the normal force followed by slow decay probably associated with creep and set of the foam tape. The torque and coefficient of friction increased slowly as the lower fixture rotates for about 5 s, probably also associated with the relaxation of the foam tape, the onset of motion at the interface, and transient phenomena. Within a short time an almost constant value of $\mu$ is reached as the counter surface slides across the explosive. No evidence of a static peak in the friction measurements was observed for PBX 9404 on aluminum or stainless steel. Near the end of the measurement time, the cross head is raised so that the normal force and torque return to zero prior to incrementing the temperature.

Typical coefficient of friction data for PBX 9404 against each different substrate at 55°C are shown in Figure 4. As can be seen in the figure, after the initial transient, a limiting value of $\mu$ is observed for both metals and PTFE. PTFE shows a peak characteristic of a static value for $\mu$, followed by a nearly constant dynamic coefficient of friction. A dramatic change in the transient characteristics occurred with PBX 9404 on itself. Also the limiting coefficient of friction for the explosive on itself was above 0.5 and not always constant. This type of behavior is associated with NC binder adhesion to itself across the moving surfaces. A similar effect was observed in LX-04 on itself up to about 115°C [11].

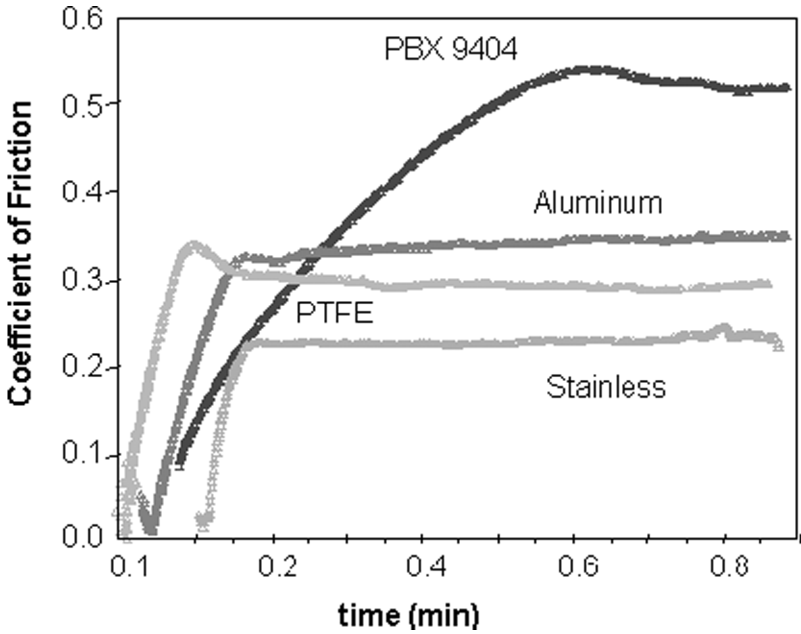


**Figure 4.** Except against PBX 9404 itself, the coefficient of friction as a function of time for PBX 9404 came to a nearly constant value on different counter surfaces at 55°C.



### *PBX 9404 on Stainless Steel*

Figure 5 shows the coefficient of friction calculated from equation (1) as a function of time from about 20 s into each test run until just before the normal force was removed. In most cases the friction coefficient was reasonably constant at a given temperature. Only near the maximum value for $\mu$ (95°C) do the coefficients deviate more than a few percent over the time of the measurement. The average torque and normal force for each measurement are plotted in Figure 6. As can be seen from the figure, for a deformation of approximately 0.02 mm, the normal force decreased with temperature from about 250 g to just slightly over 50 g at 135°C. Because the normal force applied to the specimen cannot be reproduced exactly at each temperature, the torque is higher when the

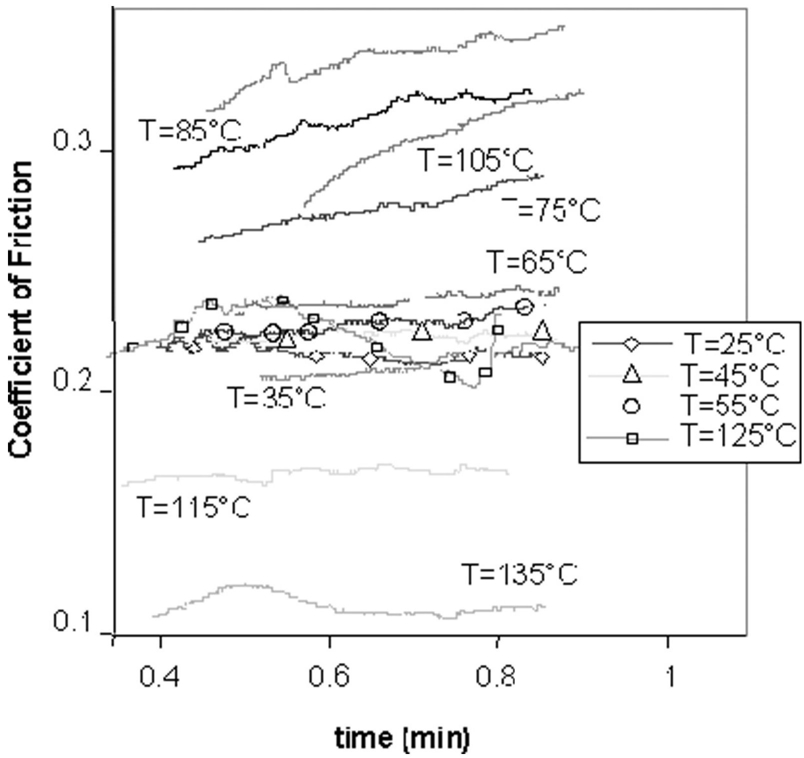


**Figure 5.** The dynamic coefficient of friction for PBX 9404 on steel at each temperature was nearly constant after an initial transient (not shown).



normal force is higher, varying from 40 to 6 g-cm. The coefficient of friction for PBX 9404 on stainless steel for a given temperature was calculated from the average of the linear portion of traces in Figure 5. The results are plotted in Figure 6. As can be seen from the figure, PBX 9404 passes through a maximum friction coefficient at about 95°C. The counter surface was weighed before and after these tests, and less than 1 mg of explosive had been transferred to the stainless steel, indicating minimal wear under these conditions.

It has been observed that the friction coefficient often follows the viscoelastic loss modulus of polymers [17] and composites [18]

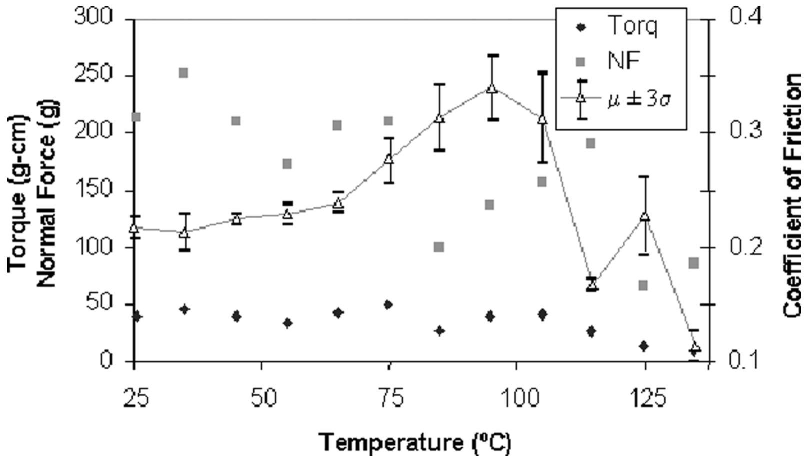


**Figure 6.** Average torque values followed the normal force for PBX 9404 on steel in the steady-state region of the measurements. The coefficient of friction as a function of temperature was always relatively low, increasing initially and then dropping off slightly.



on metals. The viscoelastic properties of nitrocellulose and several plasticizers, though not CEF, have been reported [19,20], and the loss modulus of PBX 9404 has also been measured [10]; however, no peak was observed in or around 95°C.

### *PBX 9404 on Aluminum*

The dynamic coefficient of friction of PBX 9404 on aluminum at representative temperatures is shown in Figure 7. Values of μ were nearly constant after the initial transient (not shown). Only values of $\mu$ at 125 and 135°C did not approach a constant value during the measurement. The standard deviation in the coefficient of friction is about the same as for the stainless steel counter surface. Figure 8 is a plot of the average friction coefficient for PBX 9404 on aluminum over the temperature range tested. Friction at the aluminum/PBX 9404 interface increased quickly above 35°C from about 0.1 to about 0.35 at 45°C, then continued to increase slowly up to 0.48 at 115°C

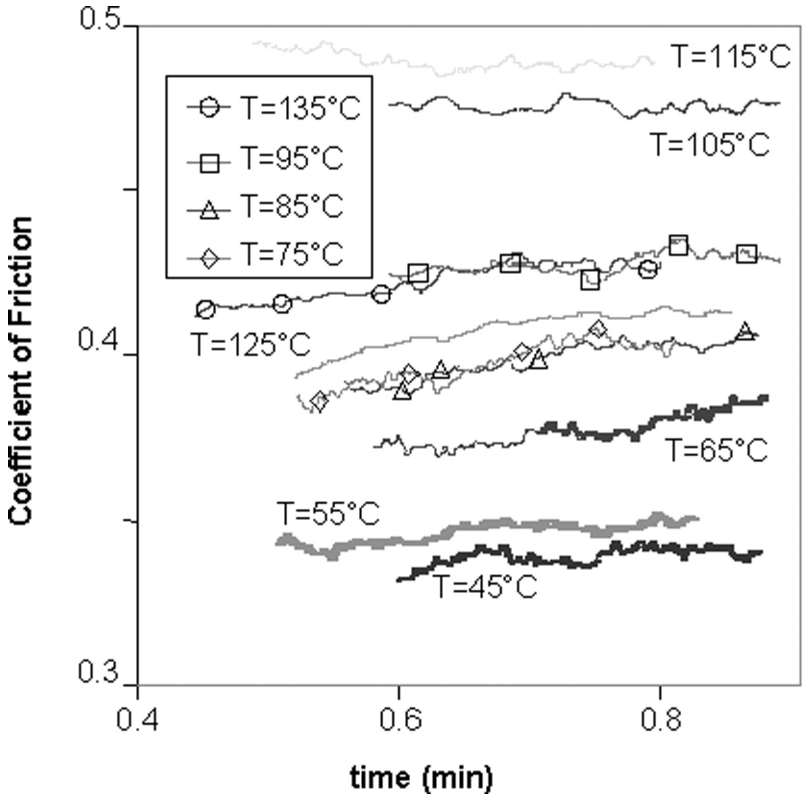


**Figure 7.** The coefficient of friction for PBX 9404 on aluminum at each temperature, calculated from equation (1) was nearly constant after an initial transient (not shown).



followed by a slight decrease at 125°C. It is interesting to note that the loss modulus of PBX 9404 shows a peak at about 30°C consistent with the increase in friction at about this temperature [10].

### *PBX 9404 on Polytetrafluoroethylene*

Polytetrafluoroethylene (PTFE) is used in shock and impact experiments to mimic the impact characteristics of an explosive [21]. PTFE is well known for its low friction coefficient against

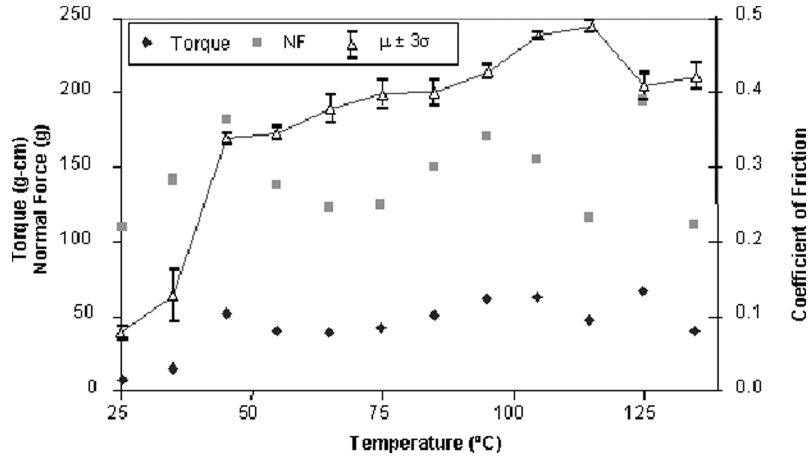


**Figure 8.** Coefficient of friction as a function of temperature of PBX 9404 on aluminum increased with temperature. Average normal force and torque data are also shown.



metals and hard surfaces [22]. The mechanism of friction reduction on hard surfaces is due to transfer of a thin PTFE film to the hard substrate that fills in asperities on the hard surface and serves as a lubricant. The PTFE parallel plate originally used in these experiments would not retain its shape over the temperature range. Because of concern over nonuniform contact, a PTFE disk was etched with tetra etch surface treatment and bonded to an aluminum plate using Epon 815/RF 20 epoxy/amine adhesive to prevent the PTFE from warping. Unfortunately both surfaces were etched so the interface was etched PTFE rather than PTFE. Since PBX 9404 is a relatively soft surface, the film transfer mechanism proposed for metals may not be effective. As seen in Figure 9, etched PTFE was ineffective as a lubricant for PBX 9404 since the coefficient of friction was always 0.25 or above compared to 0.1 or lower for most metals. Interestingly enough, these measurements showed a pronounced static peak. The peak was 10–20% greater than the dynamic coefficient at temperatures up to 95°C. Above this temperature the static peak dropped to about 5% of the

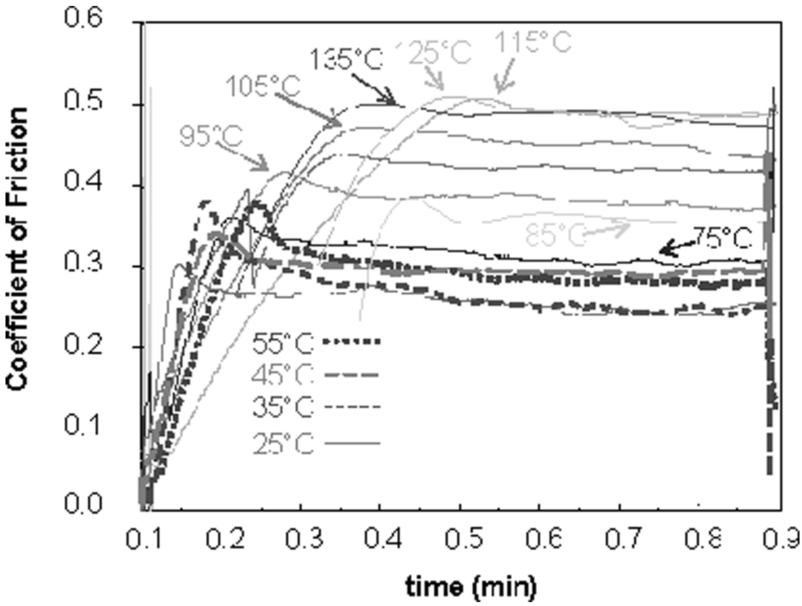


**Figure 9.** PBX 9404 coefficient of friction against PTFE showed both static and dynamic frictional behavior, especially at lower temperatures.



dynamic coefficient of friction. This peak appears to be associated with the surface treatment of the PTFE. In LX-04 run against untreated PTFE, no peak was observed. However, when LX-04 was tested against etched PTFE, the peak appeared. The effect was short lived, and the dynamic coefficient returned to a reasonably constant value shortly after the maximum was reached. Similar effects of surface treatment in reinforced rubbers has been reported [23].

As the temperature increased, the dynamic coefficient of friction takes a sigmoidal shape, as seen in Figure 10. From a relatively low value of $0.25 \pm 0.01$ at 25–35°C, the coefficient rises steadily to about $0.49 \pm 0.01$ at 115°C and above. In PBX 9404 PTFE does not act as a lubricant at all and becomes worse with increasing temperature. PTFE undergoes a solid-solid phase transition at approximately 19°C [24] that is too

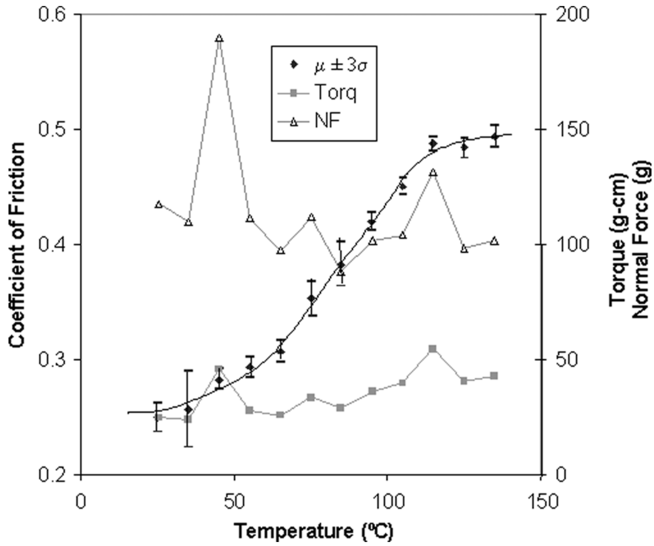


**Figure 10.** Average values of μ for PBX 9404 on etched PTFE increased with temperature in a sigmoid fashion between 45 and 115°C. Average torque and normal force values are also shown.



low to be responsible for any change in friction behavior in the temperature range tested. However, the loss modulus peak in PBX 9404 occurred at 30°C, about where the coefficient of friction begins to increase.

### *PBX 9404 on Itself*

Since explosives often fracture and turn into rubble on impact [25], the friction behavior of PBX 9404 explosive against itself is of interest. Since only 2.54 cm diameter samples of PBX 9404 were available, the lower explosive sample was attached to an aluminum insert with double stick tape. The friction coefficient of PBX 9404 against itself was quite high at ambient, $\mu(25°\text{C}) = 0.562$. Figure 11 shows the traces of the coefficient of friction of PBX 9404 against itself. Values of $\mu$ were reasonably constant for only the first three temperature increments

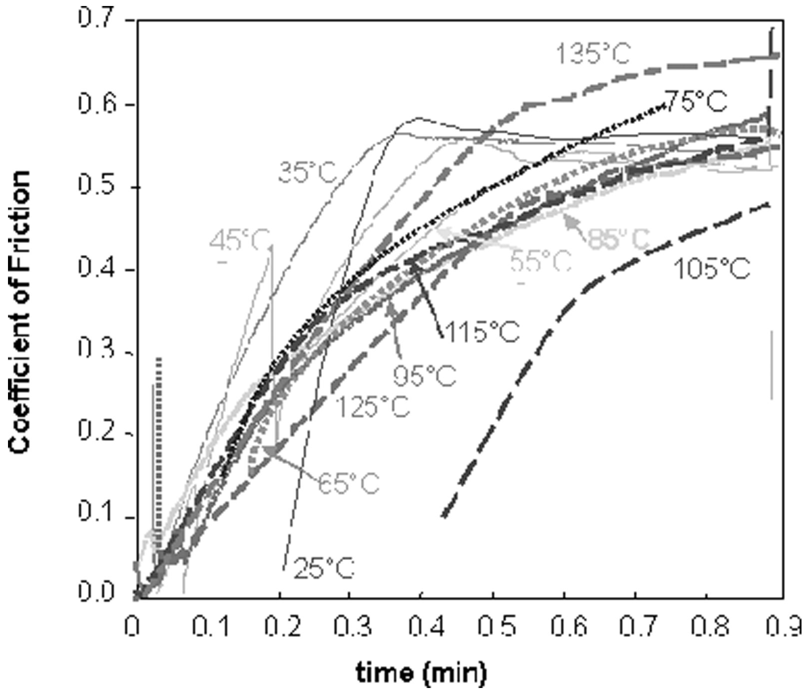


**Figure 11.** Above 45°C PBX 9404 friction against itself becomes time dependent, probably associated with adhesion of the polymer binder. Coefficients of friction estimated for PBX-9404 on itself did not approach constant values over the 1 minute measurement intervals at temperatures between $45 < T < 95$°C.



(25–45°C). At 50°C and above, the coefficient increased for almost the entire 60 s of the measurement. This probably indicates that the nitrocellulose binder is adhering to itself across the interface. Unlike LX-04 [9], where the adhesion across the interface stopped above 100°C, PBX 9404 continues to show high, nonconstant friction coefficients up to 135°C. Figure 12 shows the average value of $\mu$ as a function of temperature with error bars three times the standard deviation. The large error bars indicate that $\mu$ was not constant between 55 and 135°C. During deformation and the creation of rubble, the

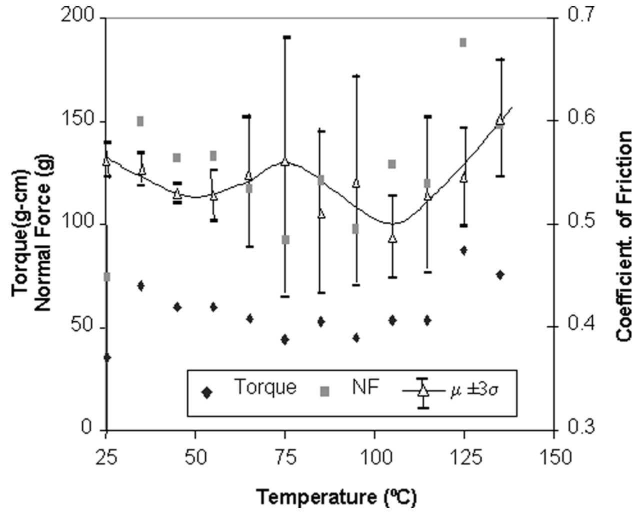


**Figure 12.** Values of the coefficient of friction of PBX 9404 on itself were averaged from the knee in each temperature trace in Figure 11 to just before the load was removed. Values were high and did not change dramatically over the temperature range from 25 to 135°C.



increase of frictional heating of PBX 9404 against itself would tend to increase the sensitivity of the explosive to this type of initiation mechanism at elevated temperatures.

## Conclusions

The parallel plate technique is an effective and simple way of measuring the coefficient of friction for PBX 9404 explosive on a variety of substrates as a function of temperature. No dramatic decrease in $\mu$ of PBX 9404 on aluminum, stainless steel, PTFE, and the explosive itself as a function of temperature was observed. Thus no substantial effect due to friction on impact sensitivity of this explosive at high temperatures should be observed, which is consistent with results at high temperature in the Steven test [3].

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