FRICTION INSTABILITIES OF SOLID CARBONS

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Introduction

Solid carbons and c/c composites are widely used in friction applications owing to their outstanding friction and thermal properties. One of the more unique aspects of solid carbons is that strength can actually increase with increasing temperatures. This attribute, and the fact that temperatures above 2500˚C can be withstood, makes this class of material serve extremely well as a structural refractory. These properties coupled with low density have made c/c composites the premier materials for friction discs in aircraft brakes.

During brake applications in aircraft, temperatures at the friction interface may exceed 1000˚C with normal operation. The most often cited friction behavior related to elevated temperatures has been transitions from desorption, or variations from oxidation [1-7]. Those studies focused on the nature of friction coefficient and wear rate changes in different temperature or atmosphere operating regimes. In summary, it has been clearly shown that coefficient and wear rate increase significantly as temperatures exceed 150˚C and moisture is driven off. This moisture desorption transition can be abrupt, and has been found to occur independent of friction test method. During braking a 7 to 8-fold increase in coefficient can occur in a fraction of a second as shown in Fig. 1.

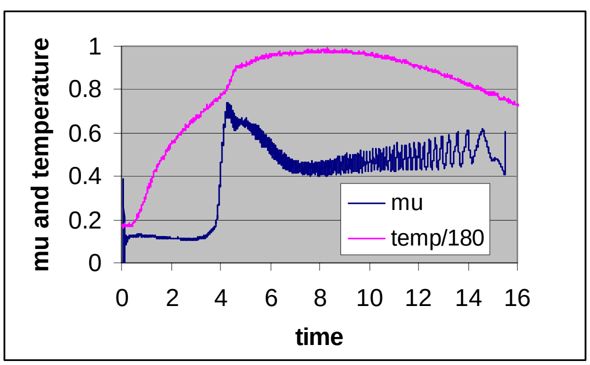

Figure 1. Dynamometer stop shows abrupt increase in friction when near-surface temperature exceeds 130°C for C/C composites. Cause: moisture desorption transition.

At higher temperatures (~600˙C) there has been reported to be a transition from desorption of oxygen [5]. However sub-scale-braking studies have indicated that an abrupt transition does not exist as has been shown for moisture desorption [8]. The role of temperature induced oxidation has been suggested to give rise to increased wear rates due to conversion of solid carbon to CO or CO_2. There is other evidence suggesting that this type of oxidation mass loss occurs mostly at the exposed surfaces of the discs, particularly when oxidation protection is absent [8]. However, the oxidation of carbon does indeed play a role in friction performance. It is clear that oxygenated functional groups form on the surface of the solid carbon, with the end result being alteration of surface properties. Additionally, there is likely to be some oxidation mass loss at the friction interface, particularly when braking is complete and discs separated. This minor oxidation will lead to weakening of the near-surface structure. Just how surface weakening will influence friction performance remains uncertain. It has recently been reported that friction disc temperatures are related to the thermal properties and sliding conditions during braking and, in combination with humidity, these parameters can cause considerable variation in friction performance [8].

In a study of graphite at high temperatures Rowe showed how strength is increased and friction coefficient decreased with increased temperatures (external heat source)[9]. Friction coefficient of out-gassed specimens was shown to fall from ~0.4 to 0.2 at temperatures between 800˚C and 1800˚C. Unfortunately, no information regarding sliding speed or rate of frictional work was reported. Strength was reported to increase with increasing temperature only when adsorbed gasses had been removed. The author used this information to argue that the removal of adsorbed or intercalated gasses were the mechanism for strength increase with temperature. However, there is no direct evidence that confirms this mechanism today despite the 40 years since the communication. There is an interesting implication in the reported temperature influence on friction and strength. Specifically, it is often found that increased strength is associated with increased wear resistance and decreased friction coefficient.

More recent research regarding the high temperature performance of c/c composites has been reported [10]. A combination of friction-generated heat and external heat sources was used to test friction and wear at temperatures up to 1000˚C. For materials without chemical treatment friction coefficient was shown to drop from a high of 0.8 (at moisture desorption transition) at 200 ˚C to a low of <0.2 at 1000˚C. Chemical treatment was used to keep friction at a low level throughout the temperature range used. Unfortunately, no information regarding sliding speed or rate of frictional work was reported.

In most cases where friction of solid carbon has been reported the sliding speeds used were relatively high. Most friction systems, such as electric motor brushes, shaft bearings or friction discs operate at sliding speeds on the order of 1 m/s. Of course the latter example operates throughout a range from 0 - 40m/s. Since c/c discs are widely used in aircraft brakes it is surprising that there is no information in the literature regarding the static or low speed friction coefficient. One focus of this paper is to show that significant friction variations occur in the low speed range that are influenced by temperature.

A typical method for determining the static friction coefficient of a material is to measure the normal and tangential forces required for the initiation of sliding motion. This is shown graphically in Fig. 2, and can be accomplished on a pin-on-disc friction device in either rotational or linear modes. As a tangential force is applied, the friction at the two surfaces resists motion until a maximum force is reached (F_m). Then sliding begins and the force required to maintain motion drops. In this scenario low speed sliding is measured. How the friction force evolves from maximum to kinetic values is poorly understood. Moreover, how the kinetic friction coefficient changes with increased sliding speed will depend on a number of factors and is not reported for solid carbon materials. This velocity-friction relationship finds relevance in stick-slip related friction instabilities.

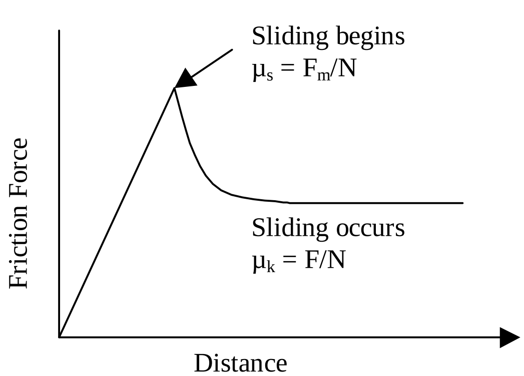

Figure 2. Schematic showing change from static to kinetic friction.

Many published tables can be found that give values for kinetic and static coefficients of friction for a wide range of materials. The fact that no static coefficient is reported for industrial graphite and other solid carbons suggests that it is little different from the kinetic value. The results shown in this paper demonstrate that is not the case, and that the kinetic value may be substantially affected by sliding speed.

Experimental

Friction testing was performed on two different devices to identify the temperature and velocity influence on the friction coefficient of C/C composites. Experiments using a sub-scale aircraft dynamometer were performed using torque control. The braking conditions (energy dissipation rate, humidity, surface history) that caused temperatures to exceed that required for performance above the moisture desorption transition were used. This typically involved temperatures well above 200˚C and required use of moisture-controlled atmosphere.

To study temperature affects in a temperature controlled environment a small furnace was designed and built for use with a conventional pin-on-disc friction tester. A schematic of the furnace is shown in Fig. 3, and the tribometer in Fig. 4. The furnace is installed into the tribometer and replaces the spindle and motor assembly shown in the picture. The carriage assembly slides laterally to allow for reciprocating friction testing.

Experiments at low sliding speeds and elevated temperatures were performed on a needled felt c/c composite using the custom furnace and reciprocating mode. Contact forces of 20 N were used to give a nominal

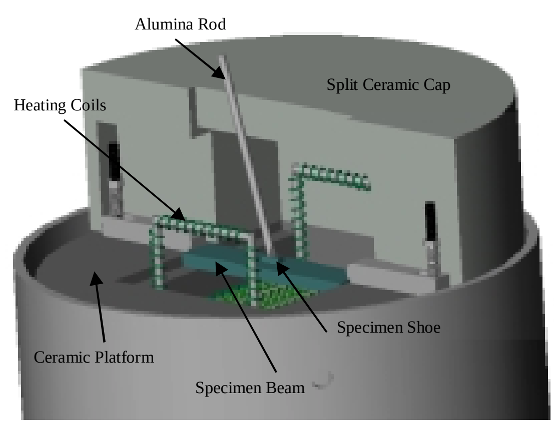

Figure 3. Schematic of high temperature furnace for friction tests in reciprocating mode.

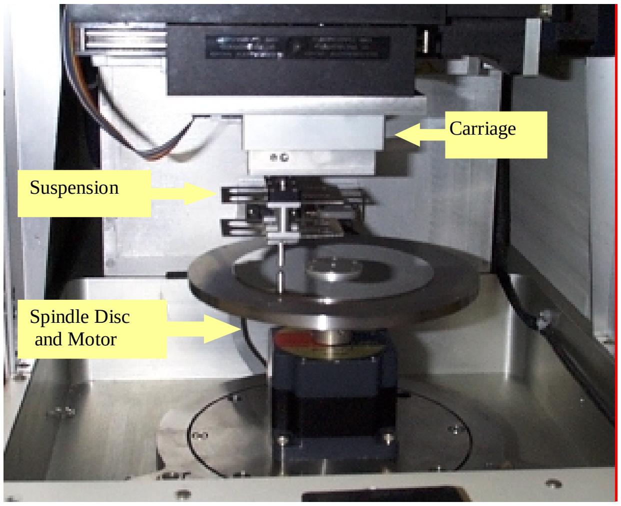

Figure 4. Carriage, suspension and spindle assembly of the pin-on-disc tribometer.

contact pressure of 1 Mpa between the sliding shoe and platform, both made from the same c/c composite. A sliding speed of 3 mm/sec was used over a path of 35 mm during the linear, reciprocating friction tests. Contact force was momentarily removed at the end of each pass to allow the alumina rod to realign for a reversal of direction. This allowed for measure of both static and kinetic friction coefficients. These were performed at least eight times for statistical significance. Interface surfaces had been run-in by at least 50 passes at room temperature. Several trials were performed with speeds of 10 mm/sec but no differences in the results were observed.

Results and Discussion

The friction performance of c/c composites has been extensively studied using a brake dynamometer. When brake energy and energy dissipation rates are low, little rise in disc temperature is observed. The data in Fig. 5 show a temperature rise up to 65˚C occurred during a simulated taxi stop. Under those conditions friction performance is below a moisture desorption transition and friction coefficient (mu) is low, approximately 0.13. This repeatable performance occurs independent of the c/c composite material used as long as surface temperatures remain low and water vapor (or other condensable vapors) is available. The data shows how velocity is reduced from 2590 mm/s (540 rpm) to zero while mu remains stable. This stability is highly desirable, though higher mu is needed for optimizing brake system design.

Closer inspection of the data shows that at the lowest velocities mu remains stable. At velocities between 200 and 0 mm/s mu is found to be ~0.13. During this portion of the stop temperature variation is insignificant. Now one may begin to speculate that friction is independent of

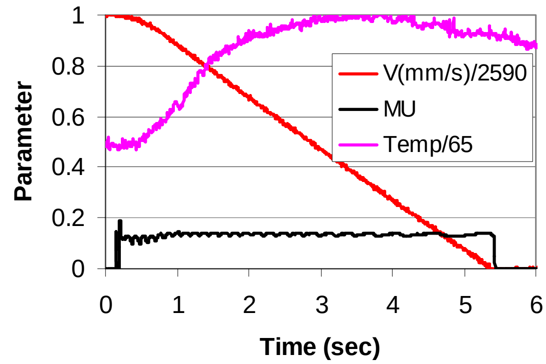

Figure 5. Temperature, velocity and mu during simulated taxi stop.

velocity. However, more stop data should be examined. In addition, from the dynamometer system it is not feasible to determine the static friction coefficient.

Raising initial velocity from 540 rpm to 2900 rpm with the same brake torque causes a substantial increase in temperatures. The results shown in Fig 6. are from the same discs, and temperatures are measured ~1 mm below the friction interface. A maximum temperature of 400˚C is measured about half way into the stop. Surface temperature is expected to be significantly higher, particularly during the beginning of the stop. As the stop nears completion energy dissipation rates diminish and temperature gradients through the thickness of the disc are reduced. The surface and near surface temperature will be similar at the end of the stop if thermal diffusivity is high enough (as for the material tested). Measured temperature near the stop end is ~320˚C. Friction coefficient during most of the stop is much higher (0.45) than that from the lower energy stop.

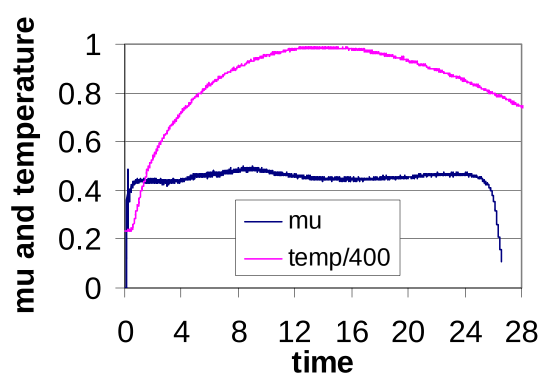

Figure 6. Temperature and mu during simulated landing stop.

The data for just the last second of the stop is plotted in Fig. 7. In this time period temperature changes very little, remaining close to 320˚C. During this same time the velocity falls linearly towards zero. However, the coefficient of friction is found to drop significantly during this short time period. This behavior is seen frequently under these conditions. Moreover, this suggests that friction coefficient varies with velocity at elevated temperature.

The same data is also plotted as a velocity-mu relationship in Fig. 8. There it is shown how the friction coefficient diminishes from ~0.45 to ~0.08 while temperature is at 320˚C. The graph has been extrapolated to zero velocity by simple curve fit to the data. This type of performance, where mu is significantly changing with velocity, was not exhibited during the lower energy stops. The greatest difference in measured conditions is the temperature that the sliding surfaces achieve as a result of the frictional work performed. The taxi stop exhibited much lower values. This type of performance can be considered a form of fade, albeit occurring at low speeds. It reveals a new

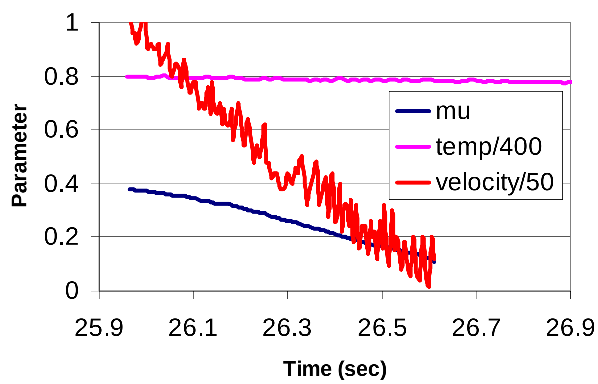

Figure 7. Velocity, temperature and mu at the end of a landing stop. (velocity in mm/s)

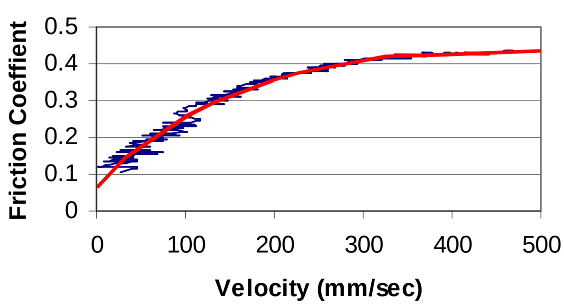

Figure 8. Velocity dependence of mu at the lowest speeds of a landing stop, temperature at ~320˚C.

form of friction variation in c/c composites. In addition, this can aid in developing a clear understanding of friction mechanisms in solid carbon materials.

Using the tribometer both static and kinetic friction coefficients were measured from a single pass in reciprocating mode. Data from four passes are shown in Fig. 9 for c/c at room temperature. Similar results for temperatures at 200˚C, 400˚C and 600˚C are presented in Figs. 10-12. In all cases the static coefficients are distinctly greater than the kinetic values. The room temperature result indicates that the static mu is ~0.18 and kinetic mu is ~0.15. This difference in values is significant, yet common for most friction couples. The transition from static to kinetic is rapid, and is influenced by the suspension system used.

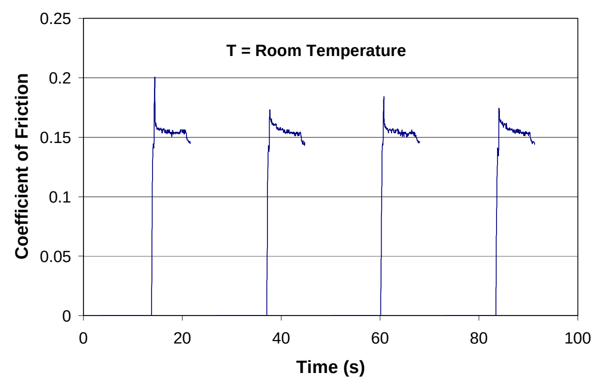

Figure 9. Friction test data from c/c composite at room temperature, 4 passes (24˚C).

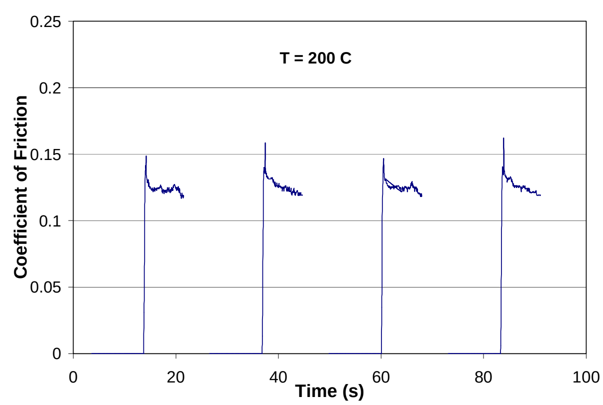

Figure 10. Friction test data from c/c composite at 200˚C, 4 passes.

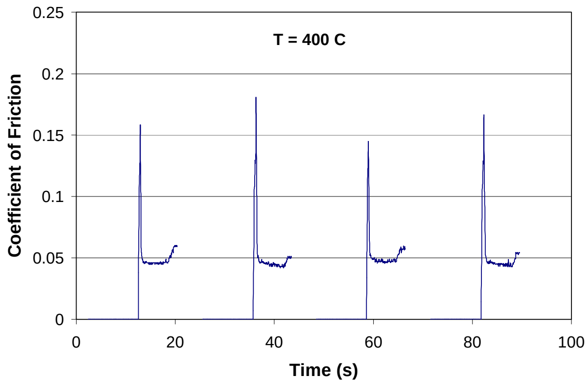

Figure 11. Friction test data from c/c composite at 400˚C, 4 passes.

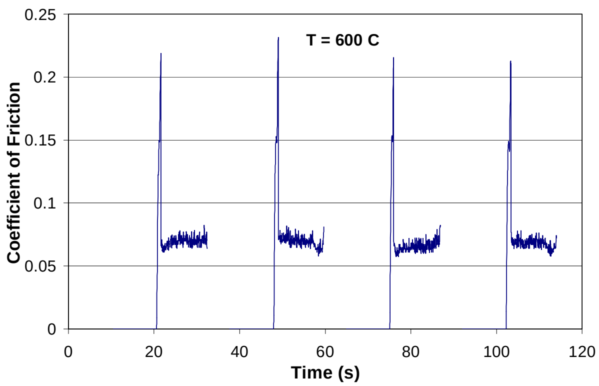

Figure 12. Friction test data from c/c composite at 600˚C, 4 passes.

Results from elevated temperature friction testing reveal a tremendous drop in kinetic friction occurs as temperatures increase. At 200˚C a slight decrease is exhibited (Fig. 10). The greatest reduction is found at 400˚C where a kinetic value of ~0.05 is measured (Fig. 11). Kinetic coefficient of friction then rises slightly to ~0.08 at temperatures of 600˚C (Fig. 12). As the graphs clearly show, the kinetic mu drops while little change in static mu is exhibited. In addition, the data shows that reproducible results were obtained with the system. Data was also collected at temperatures intermediate to those shown. All results are summarized in Figs. 13 and 14.

The data from the above friction tests were averaged using the 8 sets of passes at each temperature. The results for the static friction coefficient are shown in Fig. 13 with the average value and the min/max values indicated by the error bars. Static mu drops from room temperature to a low at 200˚C and then rises to a high of ~0.2 at 600˚C. The average value is always above 0.15, and the spread in the data at each temperature is significant.

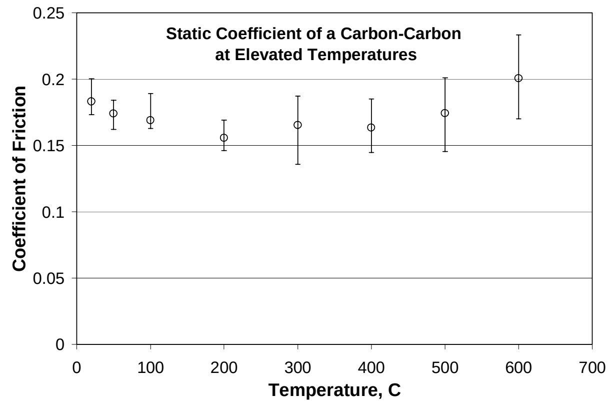

Figure 13. Static friction coefficient of c/c as a function of temperature.

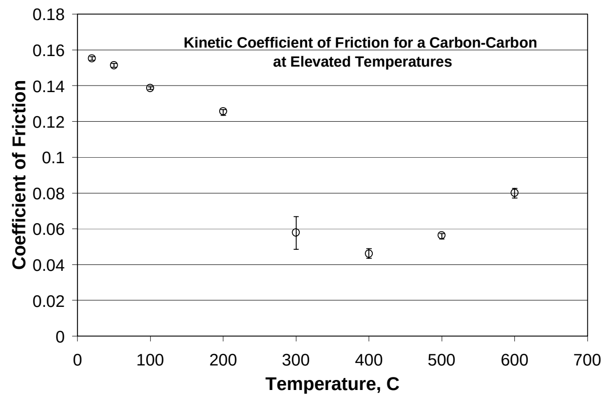

Figure 14. Kinetic friction coefficient of c/c as a function of temperature at low speed.

The results in Fig. 14 clearly indicate that a strong temperature dependence in the kinetic friction coefficient exists at the speed tested. In addition, the spread in the data at each temperature is very small. The minimum value of 0.05 at 400˚C is similar to that measured when graphite powder is placed on the surface of a c/c specimen [11]. Future examination of friction surfaces may indicate if a significant amount of debris particles are removed from the material at this temperature leading to a lubricating effect.

Another feature of the data is that the difference between static and kinetic mu increases at elevated temperature. At room temperature, the ratio of kinetic to static mu is 0.86. This decreases to a minimum of 0.28 at 400˚C. This is an unusually large difference worthy of further investigation. Perhaps the higher temperature causes a weakening in the carbon structure, resulting in more debris generation that serves as a lubricant. This could explain the very low kinetic mu observed. This scenario implies that a critical temperature exists for a minimum in near-surface strength.

Higher temperatures would then need to cause an increase in strength for this explanation to hold true. An oxidation mechanism is ruled out by two factors. Temperatures above 400˚C show an increase in mu, but oxidation rates are becoming significant at that temperature. Secondly, a test was performed with an argon purge and no difference in results was obtained.

Conclusions

The data presented has brought out another variation in friction performance of c/c composite beyond those reported in the past regarding moisture desorption transitions. The results show that friction mechanisms exist for c/c composites that are sensitive to temperature and sliding velocity. Both the dynamometer and the elevated temperature reciprocating tests show that friction coefficient drops to very low values at temperatures above 300˚C when sliding speeds are on the order of millimeters per seconds. In addition, the gap between static and kinetic values is affected by temperature.

The friction performance of c/c composites is very much influenced by the presence of vapors. Specifically, when friction conditions lead to a rise in temperature above ~100˚C the kinetic coefficient is normally increased to a value of 0.4 to 0.8. This is apparent in the data of Fig. 6 where temperatures above 100˚C occur during the entire stop, and mu is greater than 0.4. When a stop occurs with temperatures below 100˚C mu is low and constant (Fig. 5). Other friction variations have been reported but there are no clear trends to suggest what parameters influence some of the changes exhibited [12]. The results reported here reveals that friction variations exist that depend on both temperature and sliding speed.

The significance of these results lie in what can be deduced regarding the nature of the friction films and wear debris existing on a c/c composite. One scenario is that there is a temperature dependence in the near surface strength that influences the manner in which debris is generated during sliding. Low speed sliding at temperatures of ~300˚C results in low mu and this can be explained by the rapid generation of graphitic wear debris lubricating the interface. A second scenario, consistent with the results here and in the literature, is based on the concept that the friction film is a "viscous" layer. This layer would result in frictional resistance that is shear rate and temperature dependent. The data in this report indicates a non-linear dependence exists.

Additional insight into the braking behavior during hot taxi stops is gained when considering the above experimental results. High temperatures that result from landing stops could lead to low speed brake fade. This fade does not necessarily warrant serious concern since the velocity required is so low. However, in design of the clamping force fixture it is important to know the full range of brake effectiveness. A final point to consider is the consequence of a high ratio of static to kinetic friction coefficient such as that seen at elevated temperatures. Recall that stick-slip behavior is influenced by this phenomena. It is highly likely that some form of low speed brake vibration (shudder, growl etc) could result from such a dramatic difference in kinetic and static mu in brakes with c/c discs.

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Acknowledgments

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