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DYNAMIC FRICTION OF NANO-MATERIALS

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A modified Kolsky bar method consisting in the dynamic loading in shear of a pre-compressed thin-wall sample has been developed. The technique allows the identification of the transient response from static to kinetic friction under sliding velocities of about 2-6 m/s. The normal and tangential tractions are measured independently and hence a dynamic friction coefficient identified. The sliding velocities obtained with the Kolsky bar are smaller than those obtained in pressure-shear friction experiments. Hence, the techniques are complementary and provide valuable information for the formulation of friction laws at sliding velocities, pressures and temperatures typical of manufacturing processes, dynamic shear fracture, metal forming, etc. The friction properties of two nano-ceramics sliding against metals, cermets and other ceramics are here reported.

INTRODUCTION

Because of their unique mechanical properties, nano-materials have attracted wide attention in the last few years. Potential applications range from high speed machining tools to prosthetic devices. In high speed machining applications, increasing manufacturing productivity is achieved by increasing cutting tool life. Dynamic friction mechanisms play a very important role in these applications. A wide variety of experiments are required to fully characterize the friction phenomenon.

Attempts have been made to experimentally investigate the dynamic friction phenomenon at different sliding velocities and pressures. The pin-on-disk test is a widely used method to study friction and wear of materials. It is designed for low-velocity friction experiments. Pressure-shear plate impact friction experiments (1, 2) were employed to study time-resolved friction at sliding interfaces. The configuration offers the simplicity of allowing the interpretation of the experimental results by using the framework of elastic plane wave analysis. A novel experimental technique (3, 4 and 5) has been developed and used to study dynamic friction of metals and cer-

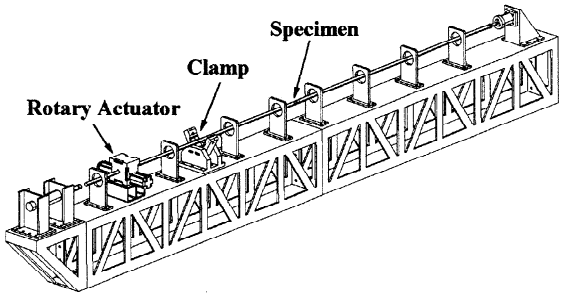


FIGURE 1: Schematic drawing of the modified Kolsky bar.

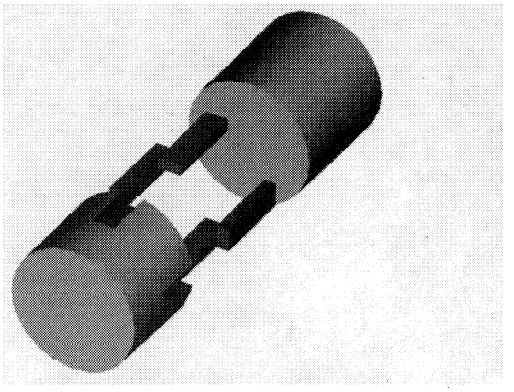


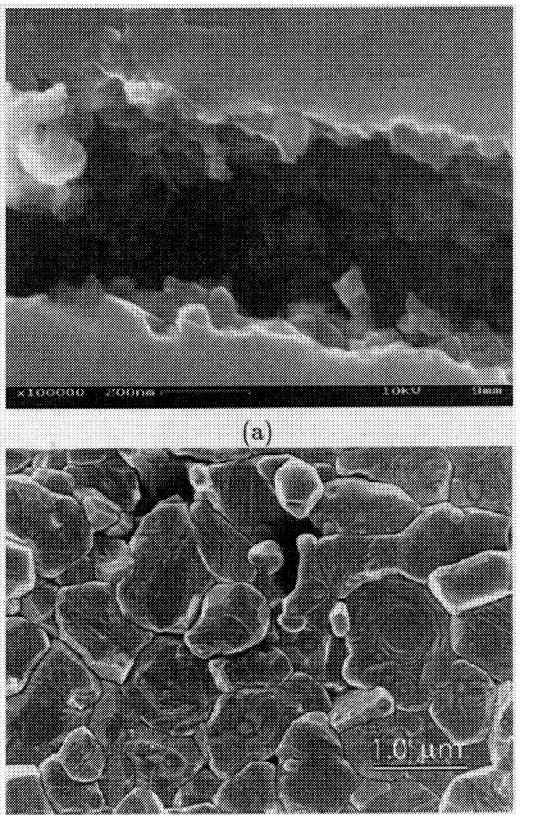
FIGURE 2: Geometry of nano-material samples as inserted between sleeves.

mets. It was found that the modified Kolsky bar technique is a simple and accurate technique for studying dynamic friction. In this investigation, dynamic friction tests were carried out using two nano materials, $nano - Al_2O_3/SiC$ and $nano - TiO_2$. They were slid against two metals, shock resistant steel and Ti-6Al-4V, a cermet, WC/Co, and a nano-ceramic, Al_2O_3/SiC. Surface roughness changes were studied with AFM to analyze micro-surface topography changes during the dynamic friction process. All these experiments were conducted at room temperature without lubrication, i.e., dry friction.

EXPERIMENTS

A modified stored-energy Kolsky bar (3,4), designed for dynamic friction and pressure shear recovery test, is shown schematically in Figure 1. Due to the limitation of producing small nano-material samples, the four-contact-squared sample, as the one shown in Figure 2, was used. A Fuji pressure sensitive film is used to check whether or not the contact pressure is uniform. The same uniformity is kept in all the experiments. If the pressure pattern is non-uniform, the samples have to be positioned again or further lapped until a uniform pattern is achieved.

Each sample was lapped, before each test, to ensure the flatness and parallelism of their surfaces. The specimens were cleaned using acetone in an ultrasonic bath for 30 minutes. After that,



(b)

FIGURE 3: **(a)** SEM micrograph showing the microstructure of $nano - TiO_2$. **(b)** SEM micrograph showing the microstructure of $nano - Al_2O_3/SiC$.

the samples were marked and labeled carefully. Atomic Force Microscopy (AFM) was used to analyze the surface properties before and after the tests. On each test, the surface profile, a 3D micrograph and the average roughness in that area were taken from each scan, in each sample. After the specimen is glued, the pressure distribution on the contact area checked, and the surfaces cleaned, the test is conducted. The contact pressure is set to the desired value by means of the axial load actuator, see Figure 1. Then the clamp is closed and the torque stored to give the desired sliding speed. After releasing the stored energy, by breaking the clamp pin, the incident pulse, reflected pulse and transmitted pulse are

recorded in an oscilloscope. The friction coefficient and the sliding velocity can be obtained from the transmitted pulse and reflected pulse using one-dimensional elastic wave propagation theory. The derivation of formulas used in the data reduction can be found in reference (5).

The microstructure of $nano - TiO_2$ and the $nano - Al_2O_3/SiC$ are shown in Figure 3. The $nano - TiO_2$ has an average grain size of 90 nm, a Vickers hardness of 11.5 GPa and a fracture toughness $K_{IC} = 1.5$ MPa$\sqrt{m}$. The $nano - Al_2O_3/SiC$ was made by adding 5% $nano - SiC$ to Al_2O_3. The average grain size of Al_2O_3 and SiC second phase particles is 1 μm and 0.1 μm, respectively. The $nano{-}Al_2O_3/SiC$ has a Wicker hardness of 9 GPa and a toughness $K_{IC} = 5$ MPa$\sqrt{m}$.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 is a plot of sliding velocity and friction coefficient histories for experiments 35 ($nano{-}Al_2O_3/SiC$ sliding against WC/Co) and 40 ($nano{-}Al_2O_3/SiC$ sliding against Shock Resistant Steel (RC-56)). The friction coefficient is computed as the ratio between interface shear traction and normal traction. Since the incident pulse has a rising time, the shear stress increases progressively while the normal stress is maintained constant. As a result, the friction coefficient raises with the incident pulse until sliding occurs. This corresponds to the friction coefficient peak observed in Figure 1. A strong decay is measured in the next 100 microseconds reaching a steady state value that corresponds to the dynamic friction coefficient at the maximum sliding velocity given by the other curve plotted in Figure 4. Due to this behavior, the first peak represents the static friction coefficient (μ_s) and then, after a transient time, the sliding velocity remains constant providing a measure of the kinetic friction coefficient (μ_k). At the end of the pulse, the sliding velocity decreases and the coefficient of friction raises again slightly. Depending on the initial surface roughness and the material properties, the second static friction coefficient may be larger or smaller than the first one. For metal/metal dynamic friction experiments, only when one surface of the pair is mirror-polished, the second static friction coefficient is found to be larger than the first one (3,4). Espinosa et al. (3) found that this is mainly due to the evolution of surface topography during sliding.

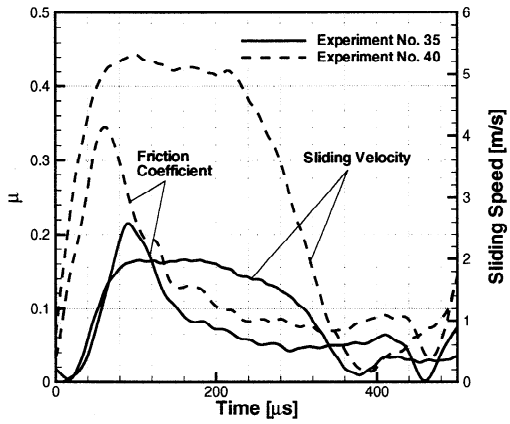


FIGURE 4: Typical experimental results.

Table 1 summarizes all the nano-material friction experimental results. For the Al_2O_3/SiC sliding against WC/Co, the dynamic friction coefficient is only 24 % to 55% of the static friction coefficient. This is mainly due to significant changes in surface roughness. By examining the results of Al_2O_3/SiC sliding against shock resistant steel under two different surface treatments, it is very interesting to see that the surface roughness does not affect the static friction coefficient while it affects the dynamic friction coefficient significantly. The dynamic friction coefficient of samples lapped with 12.5 μm SiC particles is smaller than that of samples lapped with 2 μm diamond slurry. Also the difference in the dynamic friction coefficient of samples with rough surfaces is significantly different as a function of sliding velocity. Smaller values are measured with increasing sliding velocity. A possible explanation is that the main mechanism controlling static friction is the elastic interaction among micro-asperities of the two contact surfaces. By contrast, the dynamic friction is controlled by the micro-deformation and failure of

TABLE 1: Summary of the $Nano - Al_2O_3$ and $Nano - TiO_2$ Experimental Results.

Materials		Pressure	Sliding Velocity	μ_s	μ_k
Sample	Plate	[MPa]	[m/s]	–	–
†Al_2O_3/SiC	WC/Co	74.4	2.0	0.22	0.05
†Al_2O_3/SiC	WC/Co	111.66	4.2	0.12	0.03
†Al_2O_3/SiC	WC/Co	184.1	4.3	0.20	0.12
†Al_2O_3/SiC	Shock Resistant	70	5.25	0.30	0.06
†Al_2O_3/SiC	Shock Resistant	98.7	0.7	0.25	0.17
†Al_2O_3/SiC	Shock Resistant	110	4.6	0.28	0.07
†Al_2O_3/SiC	Shock Resistant	117	1.5	0.29	0.16
†Al_2O_3/SiC	Shock Resistant	124	2.0	0.30	0.17
‡Al_2O_3/SiC	Shock Resistant	50.8	4.4	0.30	0.20
‡Al_2O_3/SiC	Shock Resistant	57.3	2.0	0.28	0.20
‡Al_2O_3/SiC	Shock Resistant	105	3.1	0.23	0.28
‡TiO_2	$Ti - 6Al - 4V$	27.8	5	0.17	0.15
‡TiO_2	Al_2O_3/SiC	104.4	6.2	0.15	0.10

† *Lapped with 12.5 μm silicon carbide.* ‡ *Lapped with 2 μm diamond slurry.*

the surface asperties. For rough surfaces, the contact area is small, so the pressure concentration is very high and the micro-asperties can deform plastically and being plowed easily; thus, resulting in large surface inelasticity. For the finely lapped surfaces, the pressure is not as concentrated; hence, less plasticity and/or fracture occurs. In the case of two hard materials, it was observed that during the whole friction process, the surfaces did not undergo significant roughness changes. Consequently, the dynamic friction coefficient is quite close to the static friction coefficient. The experimental results for TiO_2 sliding against Al_2O_3/SiC and TiO_2 sliding against WC/Co also show this trend.

CONCLUSIONS

The novel friction experiment designed by Espinosa et. al (3,5) can be used to investigate the dynamic friction phenomena of nano-material with sliding velocities up to 7 m/s. The dynamic friction coefficient is normally smaller than the static friction coefficient and highly velocity dependent. It is found that surface topography affects the dynamic friction coefficient much more than the static friction coefficient.

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