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ULTRASONIC TRANSDUCER OF DYNAMIC FRICTION

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Summary:

The paper describes design of new patented Acoustic Emission Friction Brush Probe for solid surface characterization. During constant speed brush movement over the analyzed surface, the brush fibers in contact with surface generate acoustic emission (AE) signal. AE signal is evaluated using DSP based AE analyzer DAKEL-XEDO. Simultaneously with AE, the integrated probe measures the normal and tangential forces acting on brush. Probe has been tested on etalons of surface roughness. The probe has been developed in the frame of common Czech - French collaboration program BARRANDE for a human skin characterization in dermatology, but other technical applications in material science are mentioned. Designed probe represents simple and cheap alternative to the atomic force microscope (AFM).

1. INTRODUCTION

Properties of a solid body surface (surface roughness, coarseness, abrasiveness, surface profile and topology, friction coefficient, surface adhesion and tension, etc.) are often characterized by static or dynamic friction measurements. Friction can be defined as the resistance to the movement of one body in relation to another body with which it is in contact. Generally, there are three basic natures of friction (so called internal friction in material is omitted) :
1. Sliding or kinetic friction - produced by two surfaces sliding across each other
2. Rolling friction - resistance produced when a rolling body moves over a surface
3. Fluid friction or viscosity - friction produced between moving fluids or between fluids and a solid.

The degree of friction between two objects is greatest when they are at rest (this is called the static friction or friction at rest). Once the object is moving, the level of friction is reduced (this is called the dynamic or kinetic friction or friction of motion). The direction of the static frictional force is along the contact surface and opposite in direction of any applied force. The magnitude of the static friction force f_s is given by

$$f_s = \mu_s N , \qquad (1)$$

where μ_s is static friction coefficient, and N is normal force acting between two objects. The direction of the kinetic frictional force is opposite the direction of motion of the object it acts on. The magnitude of the kinetic friction force is proportional to normal force N and the coefficient of kinetic friction μ_k

$$f_k = \mu_k N \qquad (2)$$

The coefficients of friction depend on the nature of the surface. The frictional force is nearly independent of the contact area between the objects. The frictional force equals the applied force (in magnitude) until it reaches the maximum possible value $\mu_s N$. Then the object begins to move as the applied force exceeds the maximum frictional force. When the object is moving the frictional force is kinetic and roughly constant at the value $\mu_k N$ which is below the maximum static friction force. The plot in Fig.1 of the frictional force vs. the applied force illustrates some of the friction features.

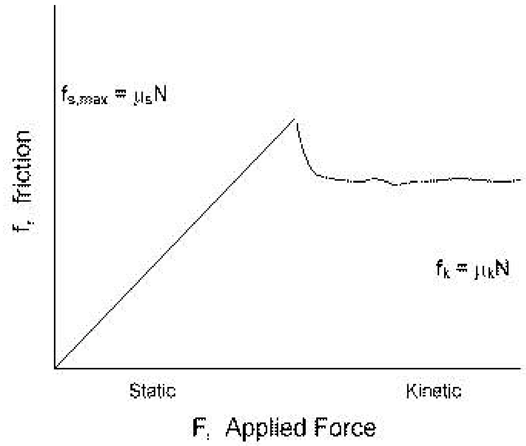


Fig.1: General plot between frictional and applied force

Friction depends upon the properties of the two surfaces in contact. The irregularities in the surfaces (their degree of roughness) cause resistance to movement. Friction then is a measure of the force pressing the two objects together. The force of friction is a common but complex force. Friction can be measured in terms of a coefficient of friction, this is the ratio of the force needed to move two objects in contact with one another and the force holding the two objects together. The exact knowledge on how friction works is still a topic of great scientific interest. Kinetic friction coefficient, usually lower than static one, is measured throughout the displacement of body over the surface by constant velocity *v*. It depends as on normal acting pressure and movement velocity as on properties of both surfaces in contact (molecular adhesive forces, roughness, hardness, lubrication, etc.). Conventional testing of kinetic friction between two surfaces in contact consists in line displacement of solid body on a frictional surface under constant normal pressure force (usually realized by weight), and tangential (shear) force is measured by appropriate dynamometer.

A simple model of the friction force can be built up assuming that the coefficient of friction is the sum of two terms, molecular and mechanical [1]

$$\mu = \mu_{molecular} + \mu_{mechanical} \quad (3)$$

Molecular interactions take place in the surface 'film' and affect the surface layers to a depth of a few hundredths of micrometers. It is known that they arise from the electromagnetic forces (Van der Waals forces) between atoms and molecules at the contact surfaces. Mechanical interaction takes place in layers with a thickness of a few micrometers. As these processes occur at different levels, they are uncorrelated and hence can be separated. The equation (3) suggests a very complex relationship between the normal load and the coefficient of friction; both components of μ include a pressure term, as well as extra terms for hysteresis loss during sliding, the surface roughness, and the strength of the molecular bond, amongst others. By adding a lubricant such as oil between the two surfaces, the coefficient of friction between may be drastically reduced.

The other physical effects accompanying friction are observed and evaluated for surface characterization [2]. Especially, the vibrations and acoustic emission induced by dry friction is monitored. Vibrations (relatively low frequency signals in the range up to 20 kHz) are excited by surface roughness. Vibration signal is sensed by accelerometer mounted to the moving body or to the bottom, stationary friction surface base. Acoustic emission (AE) produced by dry friction has its origin predominantly in stick-slip body movement over the surface (released contacts in many surface points are exciting stress waves as quasi-point sources) [3]. AE signals, registered by a general purpose AE transducer connected to appropriate AE analyzer, have relatively wide-band frequency content ranging mostly from 1 kHz to ones of MHz depending on frequency characteristics of AE transducer and device, and on a wave-path from friction surface to a wave sensor. High-pass filtering at frequencies 30 - 100 kHz is usually used to suppress low frequency, high amplitude vibration signal and disturbing background noise. AE transducer is usually fixed on a moving body or bottom friction surface base at some distance from both surfaces, which are directly in contact.

In some laboratory experiments, AE transducer is coupled with stylus scanning tested surface. Stylus acts as a waveguide in this case. Different stylus materials (usually hard materials ranging from metals and ceramics to glass, sapphire, diamond or other crystals) and various radii and forms of quasi-point contact with tested surface (ranging from sharp tip or needle to a ball) are used in such measurements. Stylus displacement tests give more immediate information on surface properties along the scanning line (or more lines if two-dimensional scanning is performed). These tests are similar to some principles of surface profilometry, where the registered vertical displacement of stylus is proportional to the local surface roughness profile.

The newest contact methods of surface property studies are known as atomic force microscope or more generally scanning probe microscope (AFM or SPM) based on diverse sensing heads. The main principle of that consists in 2-D surface scanning by a single stylus or a thin hard wire (having only few atoms on their tip) contacting tested surface. AFM's are highly precise, very sensitive, expensive and bulky laboratory instruments allowing to scan only few square millimeters of studied surface of a small body supported by a rigid base.

Recently the group of surface scientists from Sandia National Laboratories (Albuquerque, New Mexico, USA) has demonstrated that friction can arise between two surfaces even before they press against one another, through the formation of adhesions on the molecular level [4]. In classical physics, the amount of friction between two objects is proportional to the force that squeezes them together, called the "load". This empirical observation called Amonton's Law works well for large objects, but it doesn't work at the molecular level. Two surfaces that are less than about 1nm apart can actually attract each other via molecular interactions, creating a paradoxical situation known as "negative load," where the surfaces have to be pulled apart rather than squeezed together. AFMs have one drawback: when the tip gets too close to the surface, the molecular forces make it jump into contact, thus passing right through the interesting negative-load regime. To overcome this problem, authors [4] designed an apparatus that carefully controlled the gap between the probe and the surface. As a result, a study was possible for the first time how friction varies with a negative load. The results depended strongly on the chemistry of the surface, a one-molecule-thick layer of alkanethiol lubricant attached to a gold film. This layer is like a "molecular brush," consisting of long molecules that fasten to the gold at one end. Depending on the chemical makeup of the free end of the molecule, the hairs of the brush interact differently with a glass probe. When the "fibers" ended with a methyl group, the attraction was weak, and the amount of friction at negative loads was insignificant. But when the "fibers" ended with a carboxyl group, they formed hydrogen bonds with the probe and tugged strongly at it, creating measurable friction even at negative loads. This is an important, really fine experimental contribution to an atomic friction research. The next step would be to reproduce these results in computer simulations, which could tell whether the models accurately predict the friction observed experimentally. The good knowledge on friction at the atomic level is necessary to construct various micro-machines on computer chips. Strong adhesion prevents the gears from turning smoothly or turning at all.

Method used in [4] enables the "friction imaging" by means of the Lateral Force Microscopy (LFM) where the frictional forces resulting from the AFM probe scanning over a sample are measured. When the probe crosses an area of the sample, which has a higher frictional coefficient, the cantilever will display a greater amount of torque. The opposite is true for areas with lower coefficients of friction. Here 'high' and 'low' are relative terms, for instance a 'sticky' contaminant may have a 'higher' coefficient of friction than the surrounding substrate.

Except of classical friction measurement (displacement of a body over the surface), all other reviewed methods give only local (one contact point of stylus or wire with the surface) instantaneous information which is then spread over the line or area by scanning. For area characterization, large amount of data must be analyzed.

2. CONSTRUCTION AND OPERATION PRINCIPLE OF THE ACOUSTIC BRUSH PROBE

The low resolution alternative to AFM for the course characterization of surface properties has been designed - assigned as "friction brush probe" (or Acoustic Brush Probe - ABP) [5]. It represents new type of direct mechanical contact sensor designed for non-local surface characterization during the sensor movement along a surface line or other path. The basic element of probe is a fiber brush (line or multi-line bundle of thin fibers) joined with AE sensing element. The probe is mounted to the line or area-scanning device. During constant velocity brush movement over the analyzed surface, many of brush fibers are subsequently coming into and released from direct contact with the surface. These rapid processes of fiber-surface interaction (friction) are randomly exciting AE sensing element (released flexural energy of individual fibers is transferred into e.g. piezoelectric transducer), which produces quasi-continuous AE signal. Following signal analysis gives an integral characterization of surface along the brush movement path. Simultaneously with AE signal, the classical friction parameters - tangential and normal forces acting on the probe - are sensed by external force sensing elements mounted on a probe holder or, in a combined probe version, directly by force sensing elements integrated with AE transducer in a common probe case. This enables direct correlation of AE signal parameters with classical integral surface friction variables, which are less sensitive to small surface disturbances.
Schematic draw of ABP construction is shown in Fig.2.

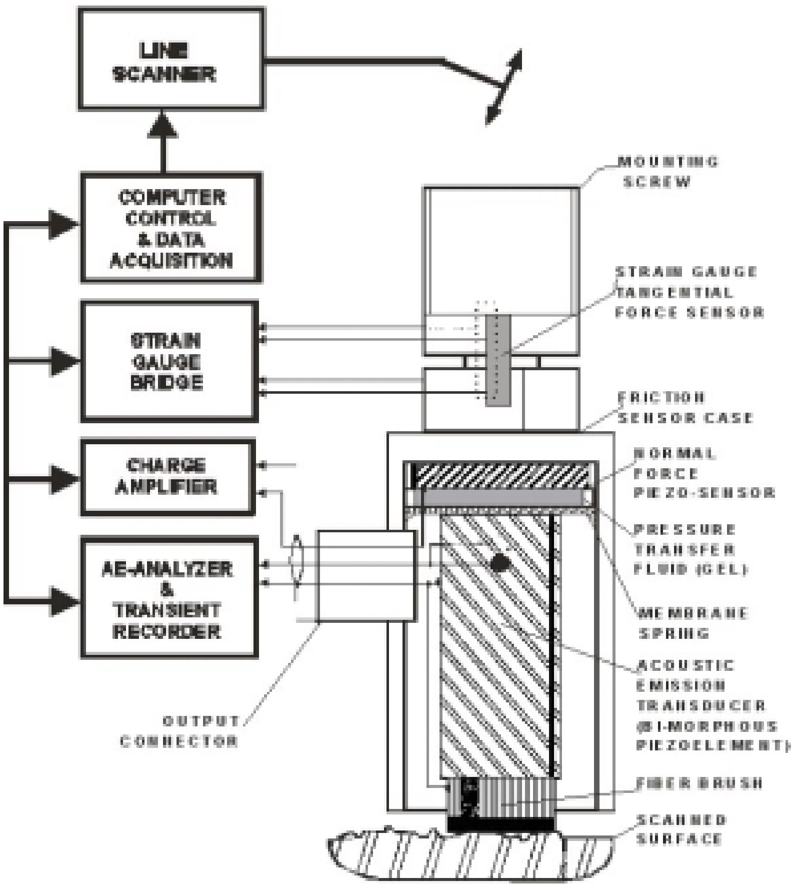


Fig.2 : Schema of the friction brush probe

The basic ABP consists of metallic sensor case with universal mounting screw coupling the probe to appropriate moving head of external scanning device. The tip of fiber brush is in direct mechanical contact with analyzed body surface during the constant velocity probe movement over the surface. The contact is provided by normal force *N* acting on the probe through scanning device head. The brush (fiber bundle) is acoustically (mechanically) joined to acoustic emission (AE) sensor (e.g. thin PZT bi-morphous piezoelement) with electrical output attached to appropriate external AE signal analyzer. Throughout the brush movement along the surface, AE transducer transfers the induced vibration and dry friction effects into electrical signal, recorded and processed by AE analyzer. Common AE signal processing method is adopted in analyzing device (DAKEL - XEDO digital AE analyzer) including signal amplification and filtration (high-pass filtering is used to suppress low frequency components of noise and vibrations). Standard and extended AE signal parameters (e.g. number of threshold counts, RMS, integral energy, average signal level, event counting and signal envelope parameters, as other selected signal features in time, frequency, time-frequency or wavelet domain) are evaluated in a computer, and used to characterize and compare number of analyzed surface features and to correlate them with another physical and chemical surface properties (e.g. with commonly used shear and normal friction forces).

In the extended ABP design, the integrated tangential (shear) and normal force sensing elements are considered: The normal force sensing system is realized by deflection measurement of spring membrane fast joined with AE sensor (the membrane serve as a AE sensor holder). Deflection of membrane is converted to electrical signal (e.g. by membrane strain gauge) fed into first channel of strain analyzing device (e.g. strain gauge bridge). Output signal, proportional to normal force *N* acting through the brush on the surface is again input to computer. Tangential force f_t is sensed by measurement of AE transducer deflection using piezoresistive strain gauges. Electrical signal, proportional to f_t is fed into second channel of strain analyzing device. Resulting f_t signal is further processed by computer. The computer collects data from AE and loading force devices and also controls scanning device.

The two prototypes of simple and extended ABP, realised in IT are shown on Fig.3

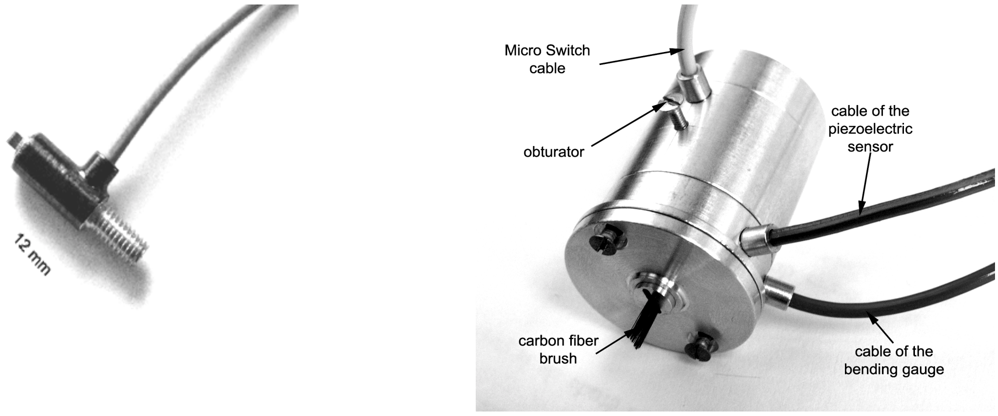


Fig.3 : The prototypes of Acoustic Brush Probe (12 mm and 40 mm length, respectively)

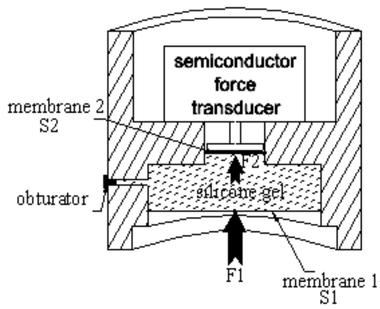
The normal force multiplication element is used in the second (extended) probe design [6]. It consists of two membranes with different diameter (area S_1 and S_2 , respectively)

$$\frac{S_1}{S_2} \approx 3{,}67 \quad ,$$

so the amplification of force acting on micro - force semiconductor transducer is obtained

$$F_2 = F_1 \times \frac{S_1}{S_2} \quad .$$

The schematic view on membrane amplifier is drawn in Fig.5:



3. DIFFERENCES AND ADVANTAGES OF NEW PROBE COMPARED TO EXISTING SOLUTIONS

ABP is a small compact sensing head, which can be easily attached to any device performing head displacement over the surface. No special devices are required for ABP output signal processing - any common AE analyzer can be used to process AE signal (fully digital analyzer with digital signal recording capability is recommended). Standard devices like strain gauge bridges, charge amplifiers, etc. are suitable for evaluation of force sensing elements output in the combined probe version. ABP brings averaged information on tested surface, different from other devices. Output mesoscopic surface characteristics from ABP reveal more detailed information than classical friction force measurements and fewer details than e.g. SPM. Lower amount of output data is just suitable for real time processing and result evaluation. Testing speed and reliability is higher than that of SPM. Instead of very complex information obtained by SPM or profilometry, only few signal parameters (in time, frequency, time-frequency or wavelet domain) can be assumed for rapid integral surface characterization. Diverse properties of ABP (its resolution, sensitivity and other parameters) may be reached by proper selection of brush fibers (fiber material, fiber length and diameter, number of fibers, fiber bundle geometry) and also by a choice of AE sensing element and its joining with fiber brush. One modification of ABP is designed with interchangeable contact brush tip. Low weight and dimensions of ABP along with its easy mounting capability enables proper design of head moving device (e.g. miniaturized). Most suitable for rapid surface characterization is linear ABP movement along the surface but providing that brush geometry is properly designed, other head movement can give different information on the surface (area scanning, curvy-linear displacement, head rotation eventually combined with its displacement along a curve, etc.). A special ABP design is also assumed performing rotational brush sweeping of the surface (e.g. in surface corrosion detection). In this case, a circular or cylindrical brush is rotating together with AE sensing element (e.g. commutation electrodes are used to transfer electrical signal from rotating piezoelement). ABP output is highly sensitive to any surface disturbances and friction changes, and a number of molecular adhesion features can be revealed by proper choice of brush material. Curved and strongly non-uniform surfaces may be characterized using ABP mounted on properly designed scanning device.

4. CONCLUDING REMARKS

A choice of brush-fiber material is of great importance as it determines molecular adhesion forces in friction. Elastic moduli and cross-section of fibers (brush rigidity) influence local tangential forces acting on fibers, and energy stored and released during brush movement over surface. Hence, both the tangential force and AE signal are dependent on brush rigidity. Low axial modulus and lower fiber cross-section (low brush rigidity) result in lower f_t and lower AE activity excited by surface friction. Fiber cross section and stiffness determine also resolution of surface characterization (scale of details). Circular cross-section of fibers and rectangular form of brush (fiber bundle) are assumed in most cases but other forms may be considered, too. Concerning brush fiber material, the most practical (optimal) results are achieved choosing relatively short (some millimeters), low diameter (1 to 10 microns) glass or high modulus carbon fibers in a bundle containing thousands of fibers. Depending on tested surface properties, other materials (polymer or natural textile fibers, ceramic or metallic fibers including whiskers and some crystal fibers) may give also satisfactory results in special cases.

Design of an appropriate AE sensing element and of brush coupling to it determines information on studied surface features contained in output AE signal (probe sensitivity to surface roughness and friction, frequency band, etc.).

ABP is suitable to design standard qualitative and quantitative methods of rapid body surface characterization and comparison (e.g. of its friction properties). Standard measurement conditions and devices, along with resulting quantities and their evaluation procedures must be well defined for this purpose.

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