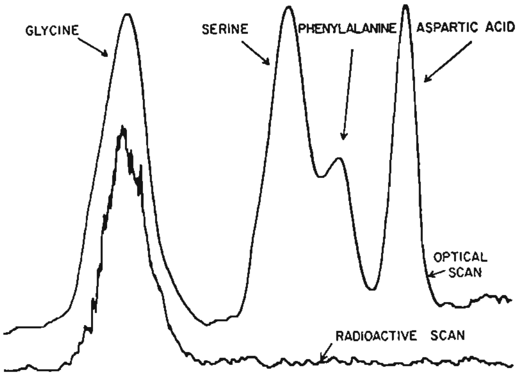

FIG. 6. Radioactive and optical scan for labelled amino acid mixture.

of areas determined this way, with planimetry, and with the method in which the areas under the density curves are cut out and the resulting paper areas weighed give results which agree within 5 percent.

Figure 5 illustrates a pattern produced with a hanging strip type paper electrophoresis cell (Spinco Model R) when 0.01 ml of serum from a patient who had infectious mononucleosis was scanned. This can be considered a typical paper electrophoresis pattern and analysis by this method.

It is frequently desirable to correlate radioactivity with the presence of certain components. A mixture of amino acids (glycine, serine, phenylalanine, and aspartic acid) containing some additional carbon-14-labeled glycine was separated on Whatman 3MM filter paper in a hanging strip paper electrophoresis cell with one normal acetic acid as the electrolyte. After the strip was dried in the oven, it was sprayed with ninhydrin to produce colored bands. The strip was then placed in the scanner and scanned with a 580 mu interference filter to produce the optical scan pattern shown. Without removing the strip from the carriage the photocell housing (M) and element (Q) were removed and replaced with the Geiger tube and shield. The output was fed directly to the rate meter which in turn was fed to the Brown recorder (by-passing the logarithmic amplifier). Figure 6 shows the resulting radioactivity scan pattern which was thus plotted in exact registration with the optical pattern, showing that all the radioactivity present was associated with the glycine.

ACKNOWLEDGMENTS

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Friction Apparatus for Very Low-Speed Sliding Studies

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The phenomenon of stick-slip, which manifests itself in the squeaking of rubbing surfaces and is of considerable practical importance, can be advantageously studied at very low sliding speeds. An apparatus has been developed in which a flat surface is driven at speeds on the order of 10^{-7} to 10^{-4} cm/sec, the driving force being a weight. The speed is controlled by the viscous drag of a paddle in a bath of pitch. There is no appreciable elastic restraint in this drive, so that stick-slip vibration of the moving surface does not occur. A stationary rider is pressed against the moving surface by a dead weight. The friction is measured by the elastic deflection of a ring, the stiffness of which controls the tendency of the rider toward stick-slip vibration. Results are briefly described.

COULOMB'S friction law states that the coefficient of friction f of contacting surfaces is independent of their relative velocity v. This relationship, to a first approximation, is indeed found to hold for a wide variety of sliding surfaces over a wide range of velocities. However, deviations from this law are invariably observed and have practical as well as theoretical interest.[1,2] One important consequence of deviations from Coulomb's law is that relaxation oscillations, generally referred to as stick-slips, may be set up, and these oscillations produce the familiar squeaking and squealing of poorly lubricated surfaces. Analysis has shown[3] that a prerequisite for the occurrence of stick-slip is that, at the sliding velocity employed, the coefficient of friction should decrease as the velocity is increased, i.e., df/dv should be negative.

Many investigations involving measurement of friction as a function of velocity have been undertaken in an attempt to elucidate the stick-slip phenomenon, and velocities ranging all the way from 10^{-3} to 10^{4}

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* Now with the Westinghouse Electric Corporation.

[1] J. R. Bristow, Proc. Roy. Soc. (London), A189, 88 (1947).

[2] J. T. Burwell and E. Rabinowicz, J. Appl. Phys. 24, 136 (1953).

[3] H. Blok, J. Soc. Automotive Engrs. 46, 54 (1940).

cm/sec have been used.[4,5] These and other studies have suggested that velocities much smaller still than 10^{-3} cm/sec would give additional important information. However, it is difficult to obtain such velocities in a straightforward way, e.g., by reducing the speed of rotation of a driven shaft with a long train of gears, because eventually the slowly driven surface will itself stick-slip. During the stick portion of the cycle elastic energy is stored in the driving system and then suddenly released during the slip. At these low speeds it is difficult to devise an adequate damping system.

THE DRIVING MECHANISM

A driving mechanism was finally devised which keeps this stored energy to a minimum (Fig. 1). The moving friction specimen is a block screwed rigidly to a carriage which rests on two cylindrical rollers offering negligible resistance to its travel. Fastened underneath the carriage is a detachable keel immersed in a cup of pitch, which in turn is fastened to the base, the latter being a heavy block carried on antivibration mounts. Attached to the carriage is a flexible wire that passes over a pulley and carries a weight pan at its end to provide the pulling force.

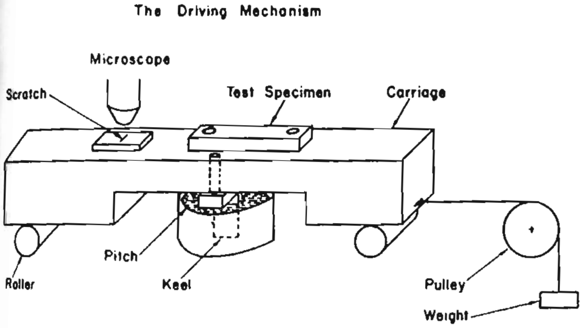

Fig. 1. The driving mechanism used in the very low speed friction apparatus.

The pitch is initially heated and poured into the cup with the keel in place, and when the carriage needs to be removed it is simply detached from the keel by undoing two set screws, the keel remaining undisturbed in the pitch. Using a pitch of softening temperature 180–200°F and a keel with a cross section of $\frac{1}{2}\times\frac{3}{16}$ in., we have found it possible to obtain speeds of from 6×10^{-7} to 1.3×10^{-4} cm/sec by varying the depth of immersion of the keel from $\frac{1}{2}$ to $\frac{1}{32}$ in., and the pulling force from 150 to 1500 g.

To measure the displacement of the moving specimen, a fine scratch on a small glass block cemented to the carriage is observed through a microscope equipped with a micrometer eyepiece. The smallest observable displacement is 5×10^{-5} cm. It was found that at the lower speeds it takes some 30 minutes before a uniform speed is obtained and the driving mechanism is therefore set into motion before the friction experiment begins.

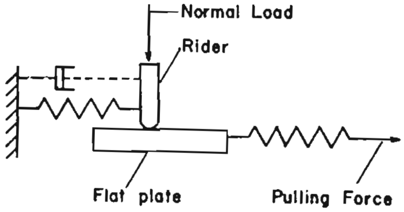

Fig. 2. A schematic representation of a friction apparatus showing the two springs, one each in the driving mechanism and in the measuring device, which can store energy for the stick-slip process. Damping, represented by the dashpot, is sometimes applied.

THE MEASURING DEVICE

Although we have eliminated stick-slip from the driving mechanism, we have not necessarily ensured smooth sliding, because, since a certain amount of elasticity is mandatory if the friction force is to be measured by means of an elastic deflection, stick-slip can originate in the measuring device of such a friction apparatus shown in Fig. 2. However, theoretical and experimental studies suggest that through the use of a sufficiently stiff spring this stick-slip can be completely eliminated or, at any rate, greatly reduced.

In our apparatus, the upper or fixed friction specimen is a hemispherically ended rider held firmly in a flexible arm, which is attached by means of an outrigger (to align the forces) to a stiff strain ring (Fig. 3). The opposite point on the strain ring is fixed to a stiff arm and both the stiff arm and the flexible arm are held on a shaft supported in two ball-bearing pillow-blocks. To balance this assembly and at the same time minimize the normal load on the bearings, the assembly is supported near its center of gravity by a soft spring. The upper anchorage of the spring can be moved up and down in its columns, and also incorporates a fine adjustment so as to permit the rider carefully to be brought just into contact with the lower friction specimen. The normal load between the specimens is

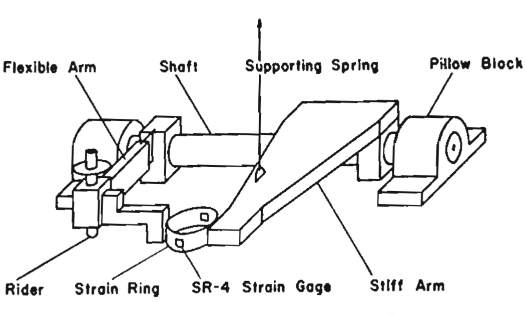

Fig. 3. The measuring device used in the very low speed friction apparatus.

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[4] F. P. Bowden and D. Tabor, *The Friction and Lubrication of Solids* (Oxford University Press, New York, 1950).

[5] Johnson, Swikert, and Bisson, NACA Technical Note 1442 (1947).

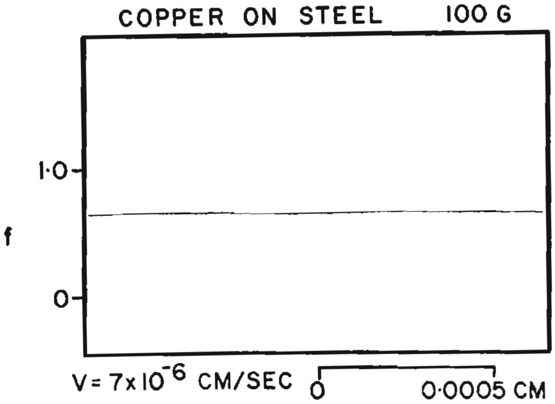

FIG. 4. Friction trace obtained using an unlubricated copper, hemispherically ended, rider, $\frac{1}{8}$ in. diameter, on a steel flat, load 100 g, velocity 7×10^{-6} cm/sec.

then determined by weights placed on a pan on the flexible arm directly above the rider.

The friction force is transmitted by the flexible arm wholly through the strain ring to the stiff arm and is measured by four *SR*-4 wire-resistance strain gauges cemented to the strain ring and connected to a Sanborn recorder. The stiffness of the ring is such that a friction force of 50 g—a common value—produces a deflection of 7×10^{-4} cm, and the sensitivity of the friction measuring device is about $\frac{1}{4}$ g.

During the long runs that are necessary, a method of checking on the drift of the recorder is desirable, and for this purpose a "dummy transducer" box was constructed. This contains high-precision fixed and adjustable resistors forming a bridge circuit comparable to that of the strain gauges on the ring, and a switch by means of which this circuit can be shunted at any time into the recorder channel in place of the strain gauges. At the beginning of a run, the box can be adjusted to give a reading equal to the no-load reading of the strain ring, and subsequent switching back to the box will disclose any drift in this zero reading.

EXPERIMENTAL DATA

Figures 4 and 5 show typical friction traces obtained with the apparatus. In Fig. 4 it may be noted that fine fluctuations are absent from the friction trace. This is a characteristic feature of these low-speed friction traces and it suggests that it takes a finite displacement before the rider has moved to a completely new part of the other surface, and has established a completely new set of metallic junctions with an accompanying new friction coefficient. Calculations based on the friction traces suggest an average junction size of 8×10^{-4} cm.[6]

Figure 5 shows a comparatively rare case where stick-slip has occurred. The small size of the slips is accounted for by great stiffness of the spring. A somewhat stiffer spring would probably have eliminated the slip completely, but at the sacrifice of sensitivity. It may be noted that the distance slid during the slip is only 2×10^{-5} cm, far smaller than average junction size.

DISCUSSION AND ACKNOWLEDGMENTS

The friction apparatus has shown itself capable of fulfilling the purposes for which it was designed, namely the measurement of friction coefficients at very low sliding speeds. A shortcoming of the present design is that friction in the pillow blocks leads to a small component that may increase or decrease the applied load somewhat, and in a new design, all movements necessary during the carrying out of an experiment should be accommodated by flex-plates whose resistance to motion is predictable and reproducible.

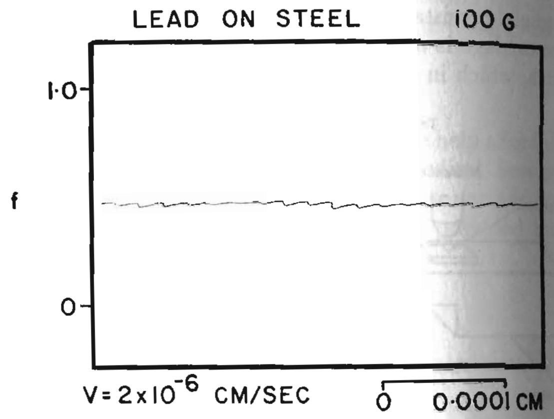

FIG. 5. Friction trace obtained using an unlubricated lead, hemispherically ended, rider, $\frac{1}{8}$ in. diameter, on a steel flat, load 100 g, velocity 2×10^{-6} cm/sec.

It appears that by varying the geometry of the paddle, far lower speeds may be attained, though at the lowest speeds long waiting is required before the friction coefficient levels off, for it seems to require sliding at a constant velocity over at least one metallic junction ($\sim10^{-3}$ cm) before a valid friction coefficient is obtained. Thus, for example, at a speed of 10^{-10} cm/sec, a time of about 100 days would be required, and this would restrict the rate at which data could be obtained.

The limited data obtained to date suggest that for most metals the friction coefficient is affected very little as the speed is varied in the range 10^{-4} to 10^{-6} cm/sec, but a much more extensive series of measurements is in progress and should serve to provide more detailed information.

Our thanks are due to Dr. J. T. Burwell, Jr., who suggested the investigation, and to the Office of Naval Research which sponsored it under project number NR065-335.

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[6] E. Rabinowicz (to be published).