Stick and Slip

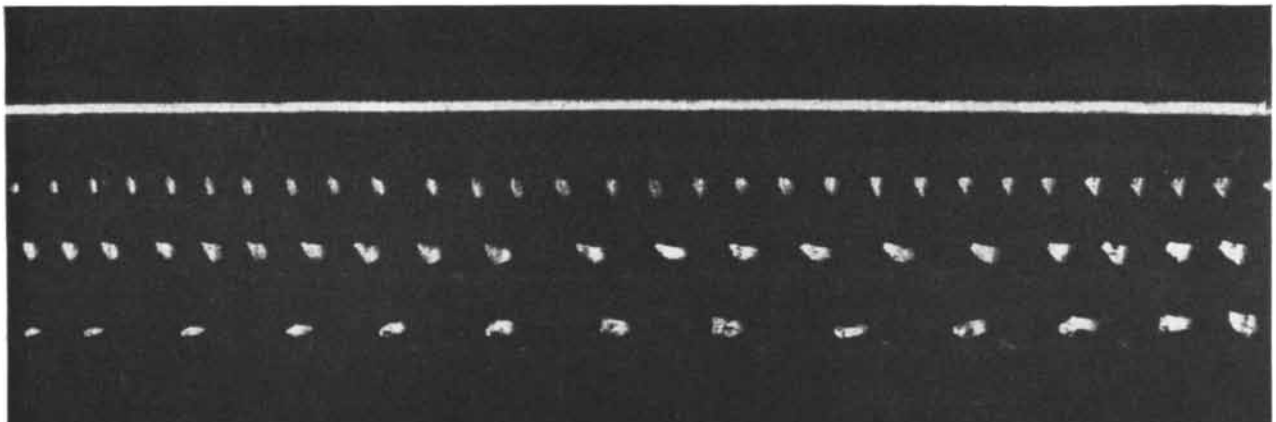
When two substances rub against each other, they frequently stick and then slip. The phenomenon accounts for the squeak of bearings, the music of violins and many other sounds of our daily experience

by Ernest Rabinowicz

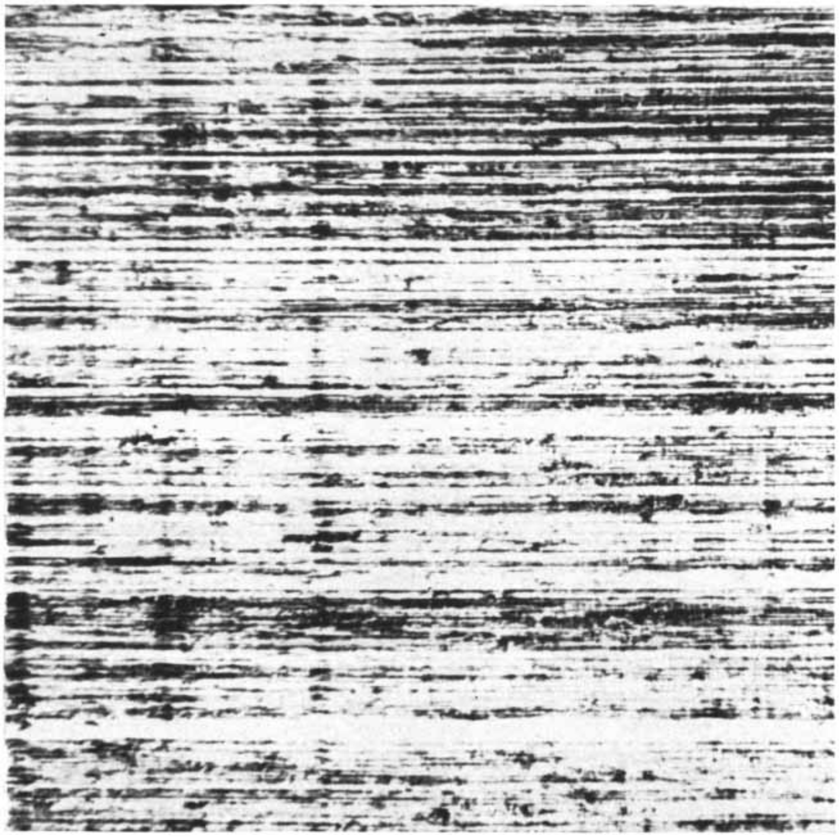
The two types of force that are met most frequently in mechanics are gravity and friction. The former has been studied by great men of science in every age. The latter has been largely neglected, it being assumed that the sliding process holds little intrinsic interest and that three simple laws, all discovered before 1800, adequately describe the force of friction. However, the advent of modern machinery, working with very close tolerances under new and widely varying conditions, has shown up the inadequacy of our knowledge of the sliding process. To give but two examples, jet engines and heat-exchanger pumps in nuclear power plants present lubrication problems never before encountered. Consequently the laws of friction have recently been restudied, and new facts discovered. This article will deal with the stick-slip phenomenon, an important by-product of sliding which produces most of the creaking, squealing, chattering and squeaking we hear in our everyday lives.

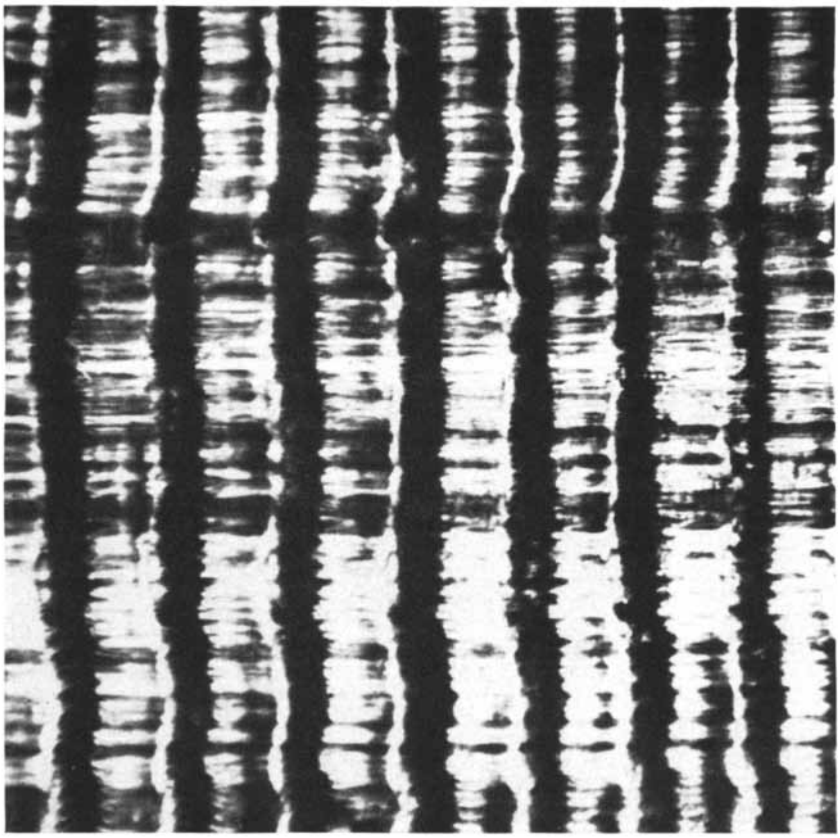
The three laws describing the force of friction say that when one solid body slides over another, the frictional force (1) is proportional to the load, or pressure of one against the other, (2) is independent of the area of contact, and (3) is independent of the sliding velocity. The first two laws were stated by Leonardo da Vinci and rediscovered in the 1690s by Guillaume Amontons, a French engineer working under the sponsorship of the French Royal Academy of Sciences. The third law was first expressed in 1785 by Charles Augustin de Coulomb, the French physicist better known for his researches in electrostatics.

If the three laws are correct, friction depends only on the applied load, and the coefficient of friction (the ratio friction-force-to-load) for any given materials should be constant under all conditions. The first two laws generally hold true, with no more than 10 per cent deviation. But it has been known for some time that friction is not independent of sliding speed. The coefficient of friction between two bodies may vary as much as 30 to 50 per cent according to the speed of motion. In 1835 A. Morin of France proposed that, since the frictional force resisting the start of sliding for two bodies at rest was obviously greater than the resistance after they were in motion, there should be two coefficients of friction: a static one, for surfaces at rest, and a kinetic one, for surfaces in motion. Today, as a result of work by a number of investigators, we know that both the static and the kinetic coefficients themselves vary. The kinetic coefficient drops off as the sliding speed increases. And the static coefficient depends to some extent on the length of time the surfaces have been in contact—a fact which can be attested by anyone who has ever had occasion to loosen a stubborn screw or nut that has been in place for a considerable period. Thus the only satisfactory way to represent the friction coefficient for any pair of surfaces is by two plots, one of the static



CHALK MARKS on a blackboard demonstrate stick-slip. The top mark was made by a piece of chalk held at an acute angle to the direction of motion; the marks below it, by pieces of chalk held at an obtuse angle to this direction. In the latter marks the chalk stuck to the blackboard, then slipped, then stuck again and so on. The more tightly the chalk is held, the smaller the distance of slip.





METAL SURFACES cut by a machine tool are enlarged. At top is aluminum with the smooth finish of steady cutting. At bottom is titanium with a poor finish due to stick-slip.

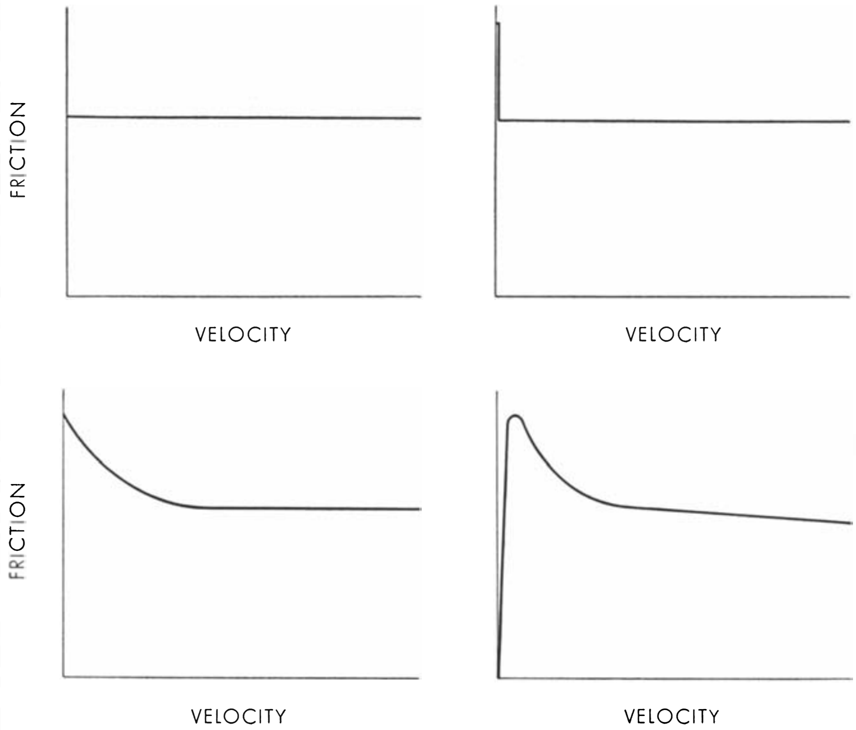
coefficient as a function of time of contact, the other of the kinetic coefficient as a function of sliding velocity.

It is the breakdown of the third "law" of friction—the variation of frictional force with velocity—that is responsible for stick-slip, the phenomenon we shall now consider. Suppose we attach a block to an anchored spring and place it on a longer slab which we set in motion at a slow speed. At first the block is dragged along on the moving slab: it will not be held back by the spring, *i.e.*, slide on the slab, until the spring's pull is equal to the static coefficient of friction. The pull of the stretched spring reaches that value when the block arrives at the point *A* [*see drawing at bottom of page 114*]. Now the block begins to slip on the moving surface. As soon as it does, the lower kinetic coefficient of friction takes over, and the block slides rapidly toward the left. When it has moved back to point *C*, it comes to rest. Here the higher static coefficient takes charge, and the block again sticks to the surface and is dragged to *A*. Then it slips back to *C*. This is a simple laboratory demonstration of the stick-slip phenomenon, so named in 1939 by F. P. Bowden and L. L. Leben, physical chemists at the University of Cambridge, who built an apparatus to study the process.

At the point *B* on the scale, halfway between points *A* and *C*, the pull of the spring is equal to the kinetic coefficient of friction. If the static coefficient were the same as the kinetic, the block would be dragged to this point and then stay there, sliding on the moving slab beneath it. As it is, the block oscillates about this position, sticking and slipping by turns. The situation is complicated by the fact that during motion the friction coefficient varies with changes in the sliding velocity, but whether stick-slip may occur can be determined in any given situation simply from the direction in which this relation is changing [*see chart at lower right on page 112*].

What does all this have to do with machinery? Few mechanisms in common use contain sliding surfaces attached to springs. The answer is that whenever solid bodies are pressed together, there is some elastic displacement or deformation of the material, resulting in an effect like the operation of the spring in the foregoing laboratory demonstration.

Common examples of stick-slip are the creaking of doors, the chattering of window sashes, the violent shuddering



EVOLUTION OF THE FRICTION CONCEPT is illustrated. In the late 18th century it was thought that the coefficient of friction remained constant as the relative velocity of the sliding substances was increased (*upper left*). In the early 19th century it was postulated that there were two kinds of friction: static and kinetic (*upper right*). Friction was greatest when two substances were moved from a state of rest, and fell off immediately when they began to slide. Around 1940 it was shown that friction fell off gradually with the increase of velocity (*lower left*). Today it is known that friction first increases with velocity and then falls off (*lower right*). When the changing relationship between friction and velocity has the slope to the left of the peak in this curve, substances slide steadily. When it has the form of the steeper part of the slope to the right of the peak, stick-slip occurs.

of drawbridges, the squeaking of bicycle wheels and the squealing of automobile tires. Stick-slip has its uses. Without it a violinist could produce no music, and he takes good care to promote it by rosining his bow. But in most situations stick-slip is a nuisance or worse. A tool cutting metal should slide smoothly into the material; when its slide is interrupted by stick-slip the cut will be rough and uneven [*see photographs on page 110*]. In the driving mechanism of a phonograph turntable stick-slip would ruin the sound. And during World War II the problem of stick-slip in one delicate situation was a matter of life and death. The turning of a submarine's propeller shaft produces stick-slip noise which can be detected with sonic listening gear. Since the war the Office of Naval Research has sponsored research on stick-slip at the Massachusetts Institute of Technology.

Friction, most investigators now agree, arises from the adhesion of molecules in the surfaces in contact with each other. The bond between the surfaces may be so strong at some points that tiny fragments are torn off one and stick to the other. Experiments with radioactive tracer material have proved this. If the end of a radioactive rod is rubbed along a flat surface, small particles are transferred and make the surface radioact.ve. This is an excellent experiment for showing the stick-slip phenomenon. A piece of photographic film is laid on the surface that has been rubbed with the rod. After it has been exposed for several hours to the radioactive track left by the rod, the film is developed. The image of the track turns out to be not a continuous line but a series of spots [*see photograph on page 118*]. The sliding rod end stuck and slipped, leaving considerable material where it stuck and very little where it slipped. Exactly the same thing happens when you rub a piece of chalk, tilted in the direction of motion, over a blackboard: you will get a stuttering line of dots.

In any adhesive process the bond becomes stronger the longer it is left undisturbed. This is why the static coefficient of friction increases with time of

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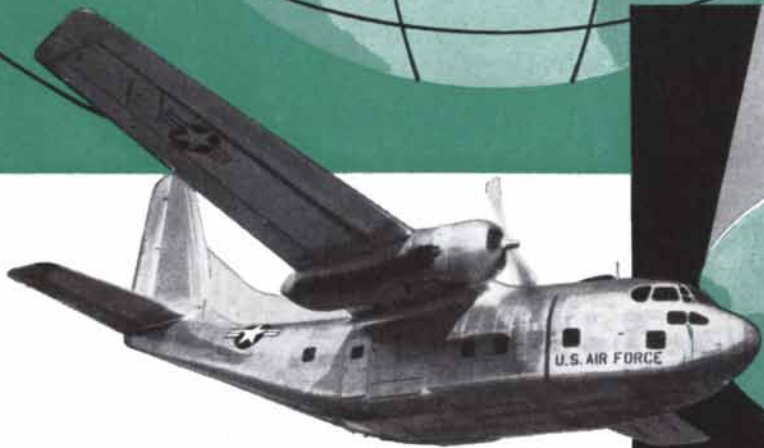

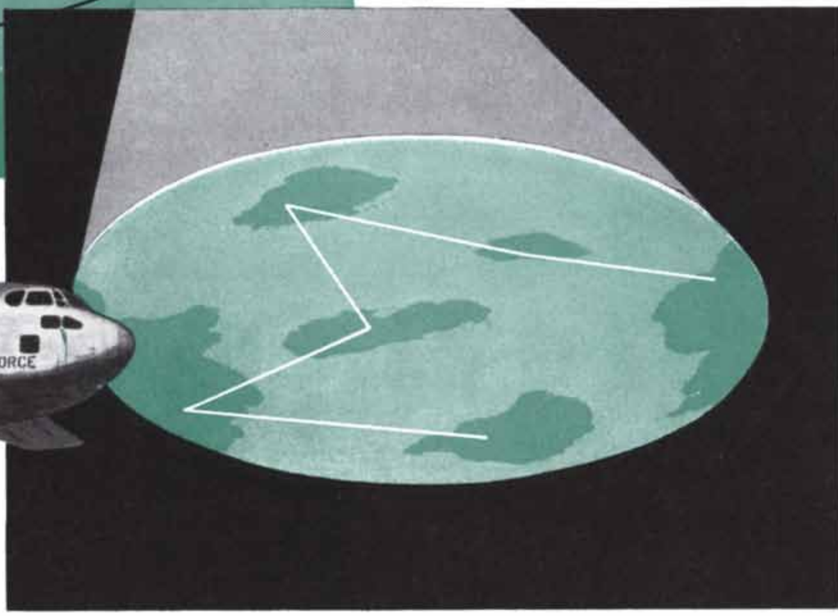

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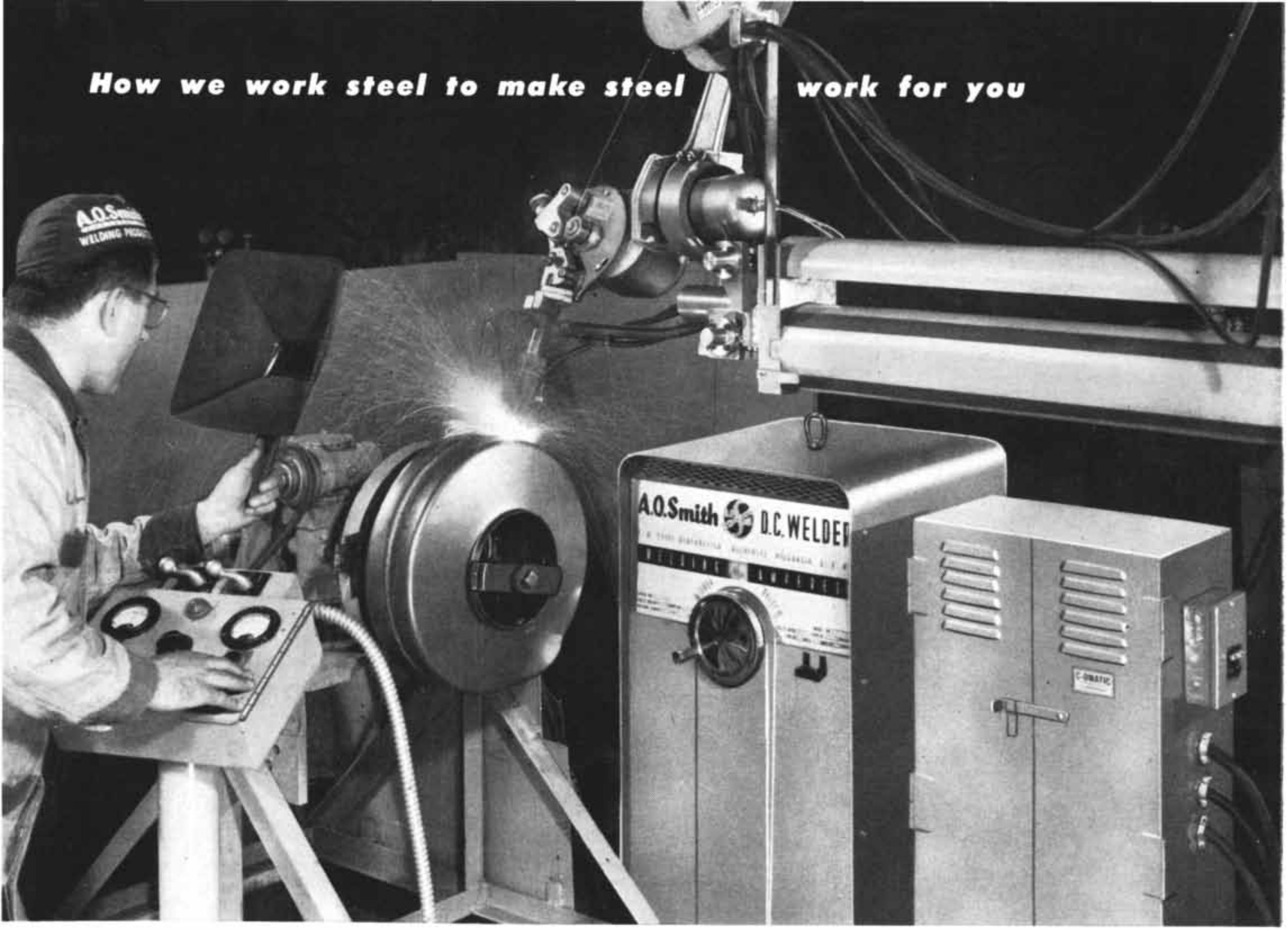

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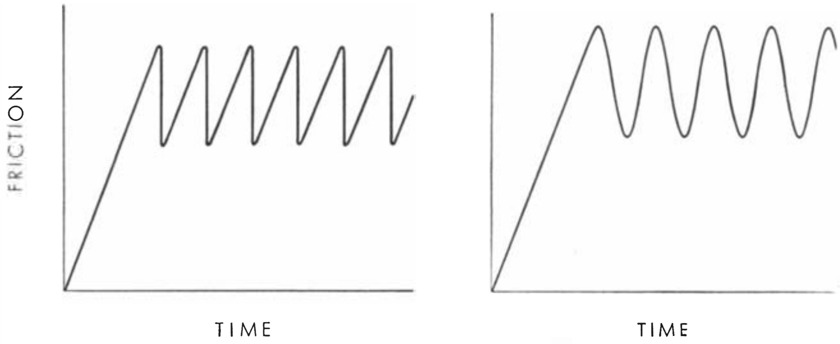


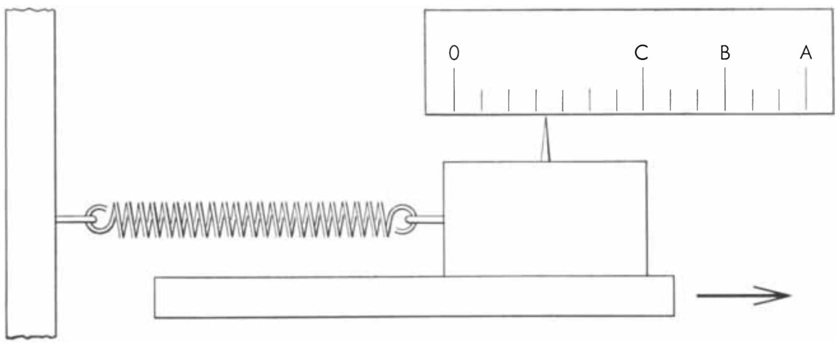
STICK-SLIP at low speed traces the curve at left. The sloping sections of the curve are stick; the vertical sections, slip. At high speed stick-slip traces the sinusoidal curve at right.

contact. In the case of sliding surfaces, the period of contact between points on the two surfaces is, of course, longer when the surfaces slide slowly than when they move rapidly. Consequently if the slide of one surface over another slows down, friction increases. This is the situation that favors stick-slip. However, laboratory tests have developed the unexpected finding that at extremely slow speeds the situation is reversed: as friction increases the sliding velocity also increases. The most plausible explanation seems to lie in the phenomenon called creep. All materials slowly change shape ("creep") even under moderate forces. An increase in force will increase the rate of creep. Thus in the case of surfaces sliding very slowly over each other, an increase in frictional force may produce a perceptible acceleration of the slide in the form of creep of one surface past the other. The limit of speed attained by the creep mechanism varies with the material, because soft materials creep faster than hard ones. The creep of steel is so slight that it cannot be observed. Lead can be made to slide by creep at speeds up to a millionth of a centimeter per second (about one foot per year); soap up to 10 centimeters per second.

These considerations present us with the paradoxical conclusion that there is really no such thing as a static coefficient of friction for most materials. Any frictional force applied to them will produce some creep, *i.e.*, motion.

Studies of sliding at very low speeds are important because they yield systematic information on friction-velocity relations which will enable designers of machines to select materials that will be immune from stick-slip over the range of speeds at which the mechanism is to operate. We also need a great deal more data on the friction coefficients of metals. It seems odd that in this age of metals, tables of coefficients listed in handbooks still have little to say about metals and apply largely to various woods, leather and stones—engineering materials of long ago.

Three main methods are available for curing stick-slip where it is not wanted. Firstly, we can alter the sliding speed. Sometimes this means slowing



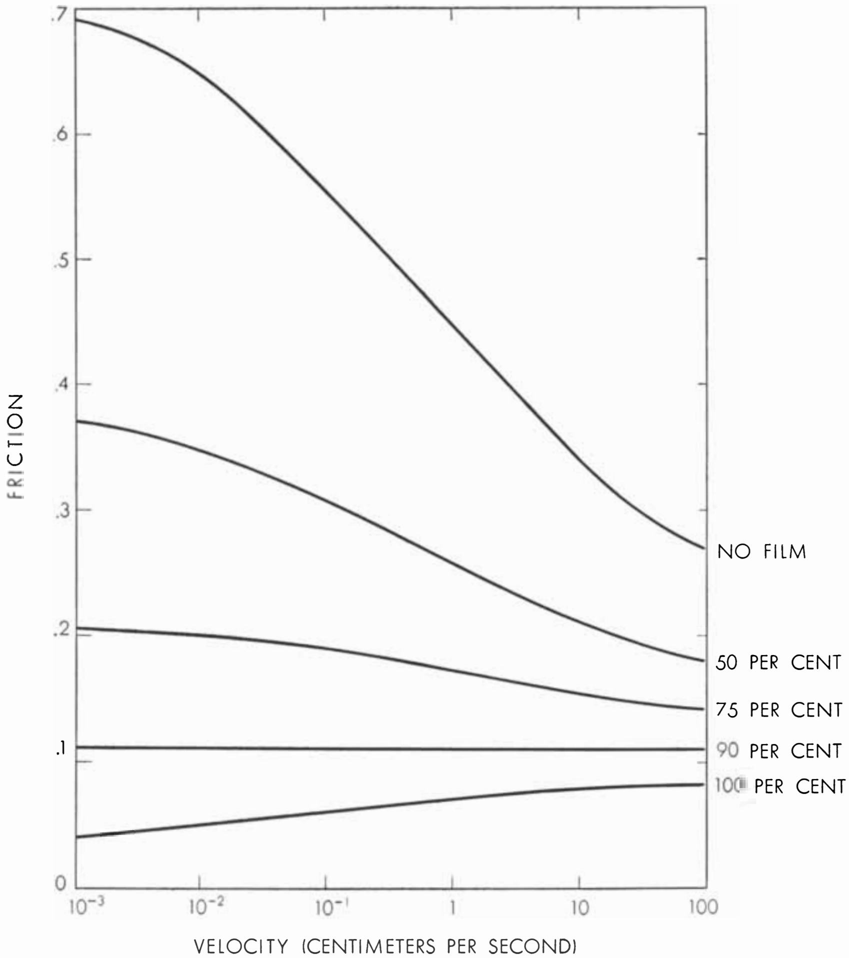
EXPERIMENTAL APPARATUS is used to show the principle of stick-slip. A block is attached to a spring. The slab on which the block rests is moved (*arrow*). If the static coefficient of friction were the same as the kinetic coefficient of friction, the block would simply move with the slab from O to B and stay there. Because the static coefficient is greater than the kinetic, the block moves with the slab to A and then slips back to C. If the movement of the slab were continued at the same speed, the block would oscillate between A and C.

down, in other cases speeding up. For example, a car's tires squeal if it rounds a corner rapidly but not if the turn is slow; on the other hand, a door that creaks when opened slowly may be silent when swung rapidly. Secondly, we may reduce the stored energy (*e.g.*, in the spring) whose intermittent release is responsible for stick-slip. Stiffening the spring will accomplish this end; similarly, stiffening a toolholder will make the tool cut more smoothly. Or we may damp the stored energy by immersing some part of the vibrating system in a bath of viscous oil.

The third and most common method is to lubricate the sliding surfaces. A lubricant forms a soft film which has far less frictional resistance than a metal's surface. The problem here is to maintain the film over the whole interface. As the surfaces slide, the lubricant is gradually worn off, so that parts of the metal surfaces come into contact with each other. So long as the lubricant coverage is 90 per cent or better, stick-slip cannot occur. But when coverage has fallen to 75 per cent, stick-slip becomes very possible [*see chart below*]. At this stage its squeaky protest is a boon, for it serves as a warning that the lubricant must be replenished. The quality of the lubricant is important; some poor lubricants never give even 90 per cent coverage, no matter how much is applied.

External factors, such as humidity, also may play a part. Squeaks in an automobile are apt to be silenced on a wet day—and, perversely, almost invariably when the car is taken to a garage to have the squeaks located and removed. Demonstrations of stick-slip during public lectures are likewise hazardous undertakings.

Friction in a machine brings a train of unhappy events. The sliding surfaces



LUBRICATED SURFACES may be subject to stick-slip. This chart represents one piece of steel slid over another with a film of lubricant between them. When the lubricant is first applied, it covers 100 per cent of the area between the two surfaces. This area is steadily reduced as the surfaces are rubbed together. When 90 per cent of the film remains, the curve is still almost horizontal and no stick-slip occurs. When only 75 per cent remains, the slope of curve is down (*see curve at lower right on page 112*) and stick-slip can begin.

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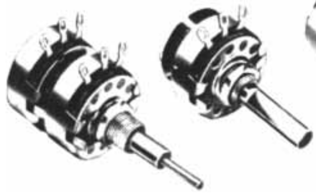

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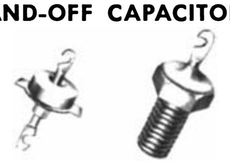

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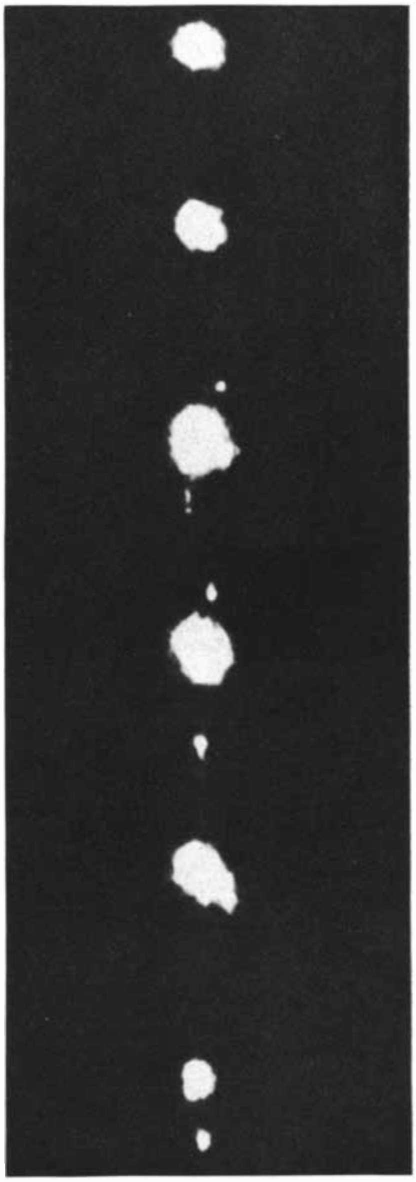
are scarred; the loose particles worn off them act as abrasives and produce more wear; the increasing friction generates heat and robs the machine's mechanical energy. Expensive systems are sometimes installed to warn when more lubricant is needed. But stick-slip itself supplies its own admonitory voice, without which our machine age would soon grind to a shuddering breakdown. It performs the warning function automatically, cheaply and effectively.



RADIOAUTOGRAPH shows stick-slip between two pieces of copper. One piece had been made artificially radioactive in a nuclear reactor. When it was slid over the other piece, some of it was transferred. When the second piece was placed in contact with a sheet of photographic film, the radioactive copper was made visible. Most of the transfer had occurred at the "stick." Only a few fragments were transferred in "slip."