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On Stylus Wear and Surface Noise in Phonograph Playback Systems*

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A theory of rubbing wear found useful in other fields predicts that the volume of stylus (or record) material worn away is proportional to the area of "real" contact between the stylus and the groove wall. In order to evaluate the influence of system parameters on the real-contact area, the elastic-plastic regime prevailing under the stylus is first analyzed in detail. The enhancement of the effective yield strength of record materials by the so-called size effect is found to have a dominant influence on the stylus-groove contact. Application of these results to the wear problem leads to the prediction that stylus life could be extended by as much as one or two orders of magnitude if the conventional dynamic loading of the stylus contact were lowered enough to insure that no plastic yielding could ever occur even at the peak acceleration demand for either vertical or lateral motion. Avoidance of plastic yielding is also shown to remove an important component of surface noise originating in the microscale intermittency of plastic flow.

INTRODUCTION

SUBSTANTIAL progress has been made during the last ten years in almost every branch of phonograph technology except that relating to the rate at which needles and records wear out. Unfortunately for the consumer, the life expectancy of these two components of the playback process appears to have done no better than to hold its own—and perhaps not even that—during this decade.

These speculations about the fundamental nature of the wear process represent an attempt to devise a plausible explanation for three observations made by J. A. Pierce and me just shortly before the outbreak of World War II, when we were using an experimental lightweight dynamic pickup in our studies of tracing distortion. Throughout this period of prewar experimentation we were impressed by the fact that our records, even lacquers, did not seem to wear out, and we never observed any traces of wear on our sapphire styli. For example, we played one particular shellac pressing more than 700 times with no detectable increase in surface noise; also, no stylus in our experimental pickups ever developed a "flat" large enough to be detected under casual microscopic examination. As for the surface noise itself,

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this always appeared to be substantially lower than we had any right to expect in view of the passband of our playback system. We never ventured to claim publicly this apparent reduction of surface noise because we were not able then to offer any convincing explanation for it, but our belief in its validity was sustained by the occasional informal testimony of others who had also experimented with very lightweight reproducers and who had made similar observations.

The accurate measurement of needle wear rates is very difficult, and I do not know of any systematic quantitative study of this problem prior to that reported by Bauer[1] in 1951. One consequence of this lacuna was that a long time elapsed before Pierce and I realized that the wear rates we had observed were not only low but were anomalously low by as much as one to three orders of magnitude! To be sure, the mechanical constants of our 1940 pickup[2] did differ from those of the conventional pickups now available, and in the right directions to account for a somewhat lower wear rate. For example, if it be assumed for the purpose of this discussion that "conventional" loading means a bearing weight of 15 grams on a 3-mil radius stylus (or 5 grams for a 1-mil stylus), then the 5 to 7 grams that we used with a 2.85-mil stylus could, according to Bauer's analysis, account for something like a factor of 2 in the relative wear rates. At the same time, such comparisons made it very clear that some additional and more potent effect would need to be invoked in order to account for the quantitative magnitude of the observed anomaly in our wear rates—some nonlinear effect, or perhaps an abrupt load-sensitive transition of some kind in the basic nature of the stylus-groove contact.

As often happens on the frontiers of applied science, this problem had to be allowed to languish until a better understanding had been achieved in other areas concerning such fundamental questions as the nature of wear and friction, of lubrication, and of the factors that control the strength of solid materials. This understanding is still far from complete, but fortunately, the accelerated pace of basic research by metallurgists and solid-state physicists has already uncovered one phenomenon that appears to have an unsuspected relevance to the phonograph problem. To put it more specifically, the kernel of these speculations is the hypothesis that the same physical factors that give rise to a "size effect" in the strength testing of materials can account for just the kind of abrupt transition in the elastic-plastic regime prevailing under the stylus contact that is needed in order to explain the observed rates of wear, both conventional and anomalous. Before offering such an explanation, however, we will need to make a few detours in order to build a foundation for the conclusions.

THE SIZE EFFECT

The term "size effect" is used to characterize the experimental observation that many, and perhaps all, solid materials exhibit very much higher yield strength when minute specimens are examined than when the same materials are tested in bulk. For example, glass fibers that are only a few microinches in diameter are found to have a tensile strength many times higher than the handbook values,[3] and the tiny "whiskers" that appear when some metals are crystallized from the vapor phase show the ability to withstand strains many times greater than those which would produce fracture in large polycrystalline specimens of the same material.[4] An oversimplified qualitative explanation of this behavior can easily be offered: A "flaw" in such a slender fiber would occupy a substantial portion of the cross section and would lead to premature fracture. Only those without such flaws survive for testing, and these exhibit very nearly the so-called "theoretical" yield strength.

Another example of the size effect that is more closely related to the phonograph problem has been turned up recently in studies of the physical principles involved in microhardness testing. These tests turn out to be remarkably like the experiments carried out every day in millions of homes by people who think that they are just playing phonograph records! An impressed load force acting on a diamond indenter causes it to penetrate the surface of the material and produce a permanent indentation. The so-called microhardness number then expresses (in kg/mm^2) the mean pressure on the projected area of the indenter which the material supports without further yielding. Note that some plastic yielding always does occur in these tests, however, as evidenced by the permanent indentation. The importance of these techniques for our purposes stems from the fact that Tabor and others[5] have shown that the effective yield strength, V, of the material can be deduced from such measurements, and that its magnitude lies between 1.1 and 3 times the mean pressure represented by the microhardness number.

The size effect reveals itself in indentation tests as a progressive increase of the apparent microhardness as the load force on the indenter is reduced below the values that produce a depth of penetration of about one micron or less.[6]

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[1] Benjamin B. Bauer, "Wear of Phonograph Needles," *Trans. I.R.E., Professional Group on Audio* (November, 1951).

[2] F. V. Hunt and J. A. Pierce, "Phonograph Reproducer Design," *J. Acoust. Soc. Amer.*, **12**, 474 (A) (January, 1941); also U. S. Pats. No. 2,239,717 (filed August 2, 1938; issued April 29, 1941) and No. 2,369,676 (filed July 10, 1940; issued February 20, 1945).

[3] A. A. Griffith, "Phenomena of Rupture and Flow in Solids," *Phil. Trans. Roy. Soc. (London)*, **A221**, 163-198 (1920).

[4] C. Herring and J. K. Galt, "Elastic and Plastic Properties of Very Small Metal Specimens," *Phys. Rev.*, **85**, 1060-1061 (1952).

[5] For bibliography and discussion of principles of indentation tests, see D. Tabor, *The Hardness of Metals*, Chapters II and IV-VI, Clarendon Press, Oxford, 1951.

[6] Milton C. Shaw, "A Yield Criterion for Ductile Metals Based Upon Atomic Structure," *J. Franklin Inst.*, **254**, 109–126 (1952).

Experimental data illustrating this effect for phonograph record materials are lamentably meager, but I was gratified to find that the indentation tests made in 1949-1950 by Dr. F. G. Miller,[7] in connection with his study of the effects of groove-wall compliance, can indeed be interpreted in this way. I am now indebted to Dr. T. J. Schultz of our laboratory for repeating and extending these measurements. His results are exhibited in Fig. 1, which shows the width of the residual indentation track left when a 1-mil or 3-mil spherical stylus subjected to various bearing loads is drawn over an ungrooved portion of the surface of an unfilled vinylite pressing. These experimental data can also be presented in the more useful form shown in Fig. 2, where each curve has been replotted in terms of the mean pressure on the circle of contact, defined as $P_m = 4W/\pi d^2$.

Two remarks about Figs. 1 and 2 need to be made in passing. In the first place, it may come as a minor shock

[7] F. G. Miller, Doctoral Dissertation, Harvard University, 1950. Results summarized in F. V. Hunt, "Stylus-Groove Relations in the Phonograph Playback Process," *Acustica*, 4, 33-35 (1954).

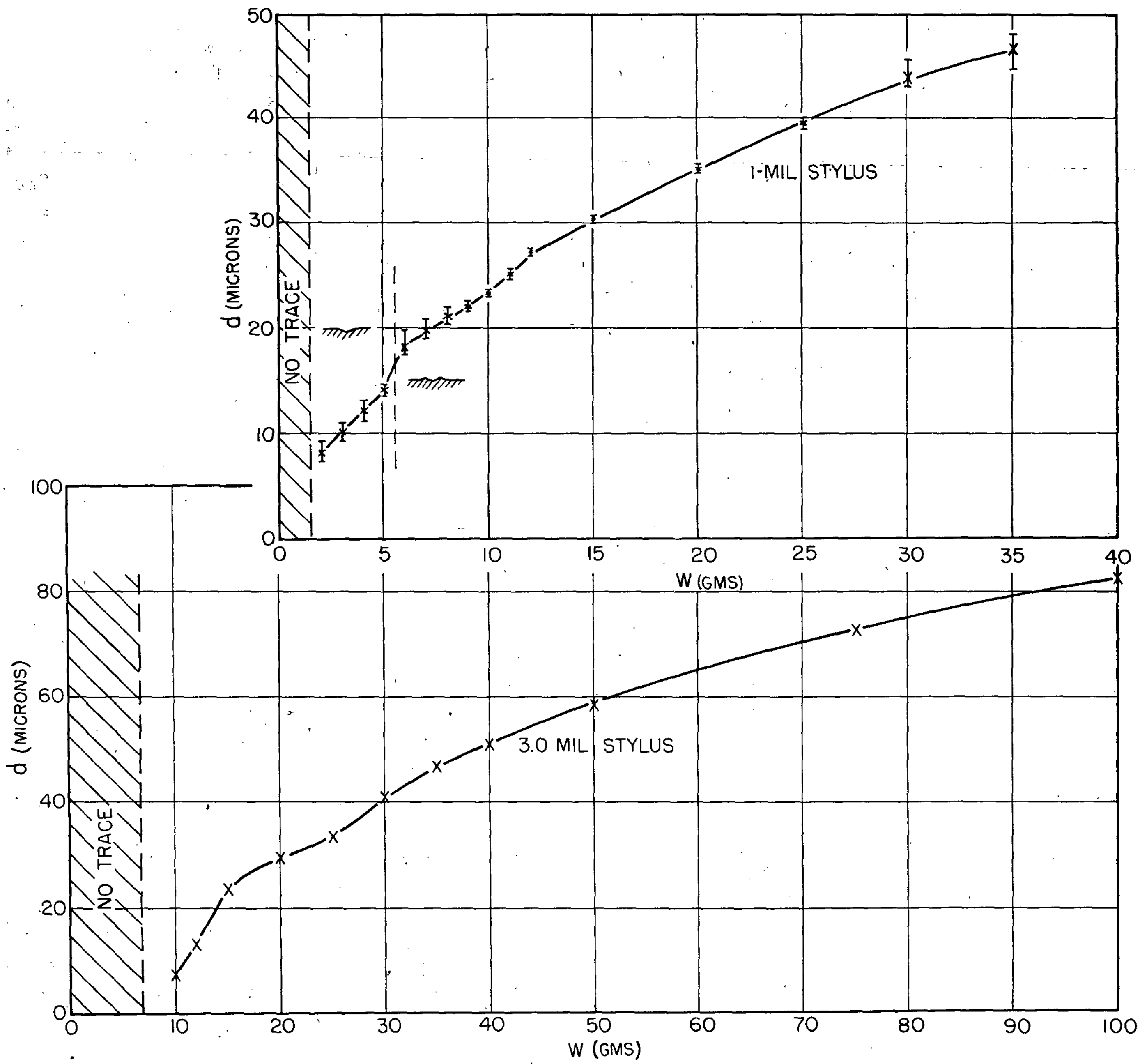

FIG. 1. Width of the residual indentation tracks made when a 3-mil or 1-mil spherical stylus subjected to various bearing loads is drawn slowly over the ungrooved surface of a clear (red) unfilled vinylite pressing.

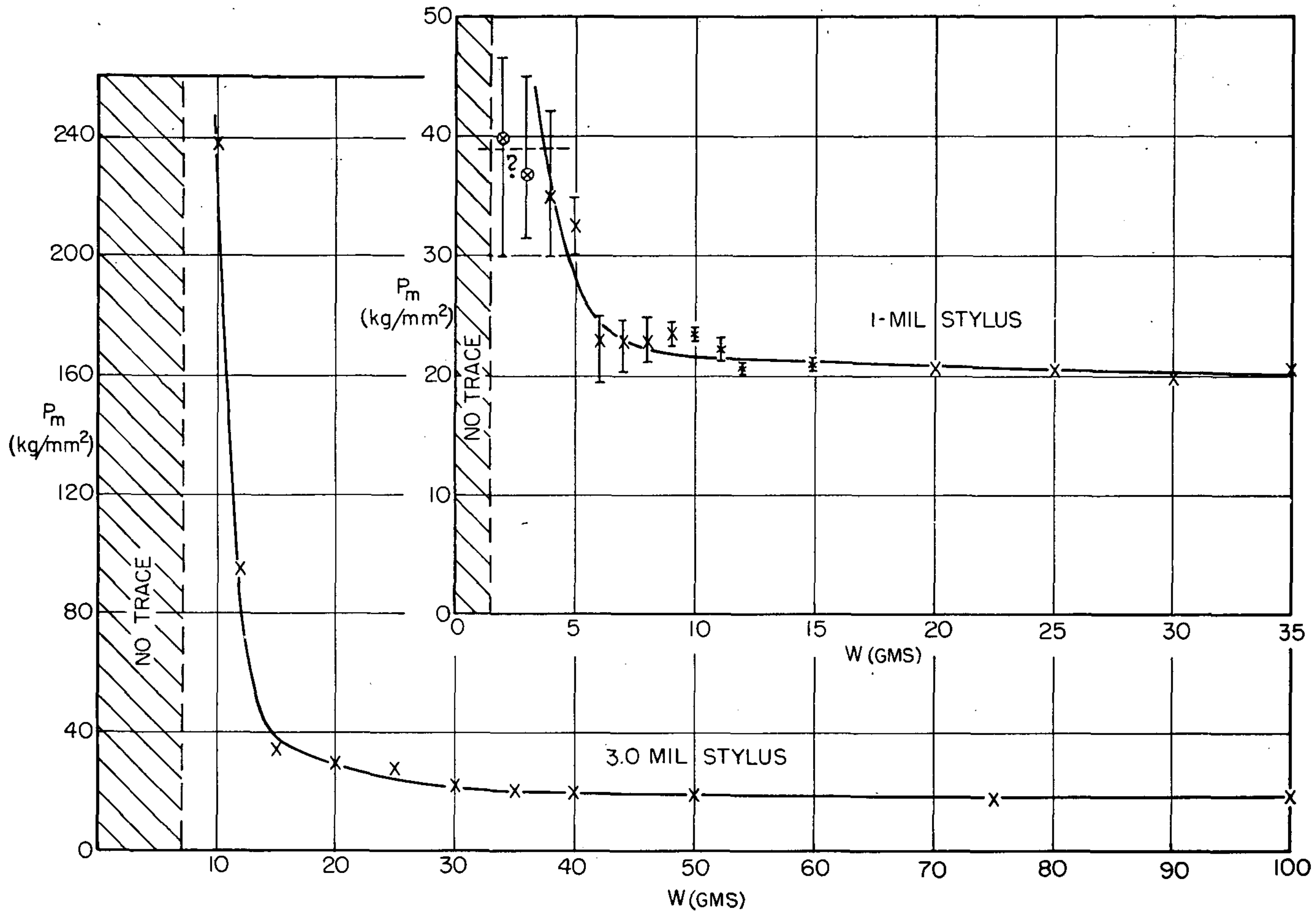

FIG. 2. The indentation track-width measurements shown in Fig. 1 replotted in terms of the apparent mean bearing pressure on the circle of contact, defined as $P_m = 4W/\pi d^2$.

to observe that conventional phonograph styli subjected to conventional bearing loads and operating on standard record materials can and do produce a permanent indentation. The residual track is narrow, to be sure, and a good bit of experimental ingenuity in arranging contrasting illumination is required in order to show the track up clearly enough to allow it to be measured. But the indentation track is certainly there, as demonstrated by the microphotograph of Fig. 3, which shows a typical example (about a third of a mil wide and 22 microinches deep) produced by a 2-gram load on a 1-mil stylus on unfilled vinylite. It is an inescapable conclusion, therefore, that, under the conditions assumed here as "conventional," the stylus-groove contact is controlled, at least to an important degree, by plastic yield considerations rather than by elasticity.

The second remark takes the form of a renewed appeal for avoidance of the term "needle pressure" in connection with the description of phonograph pickups. The bearing pressure on the stylus contact is indeed an important and useful parameter of the stylus-groove contact, but it is controlled primarily by the record material rather than by the stylus loading! If there remain any diehards who would insist that "stylus pressure" and "stylus force" are just different ways of describing the same thing, let them give heed to Fig. 2, which shows that within the range of variables arising in current phonograph practice, the stylus pressure actually increases, rather than decreases, when the stylus force is reduced.

A useful mathematical description of the size effect can be devised even without identifying (or understanding) in detail the nature of the "flaws" that control the gross yield strength of plastic record materials. What is needed is the evaluation of a weighted statistical mean, or "effective," yield strength lying somewhere between an upper limit corresponding to the "theoretical" yield strength, $Y_0 + Y_1$, that would be exhibited by a wholly flawless specimen, and a lower limit, Y_0, corresponding to the yield strength of a bulk specimen having a typical population and distribution of flaws. In formulating the effective yield strength $Y(V)$ for a particular specimen of volume V, it is plausible to assume that the two limiting values of Y should be weighted according to the probabilities of either finding or not finding

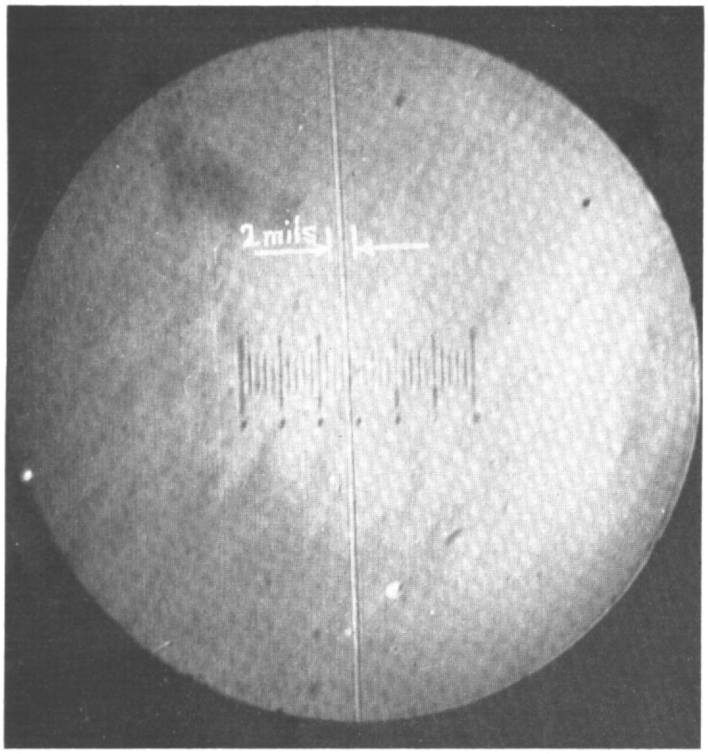

FIG. 3. Microphotograph of the indentation track made in unfilled vinylite (red) by a 1-mil stylus (spherical indenter) with a 2-gram load. Track width, 9.50 microns.

a flaw within the volume V. Thus, if there are on the average K flaws or structural imperfections per unit volume, and if the statistical distribution of these flaws throughout the material is normal, then the probability that the volume element V will *not* contain a flaw will be just e^{-KV}. It follows, of course, that the corresponding probability that V *will* contain a flaw is just $1 - e^{-KV}$. The effective yield strength can then be written at once as

$$Y(V) = (Y_0 + Y_1)\, e^{-KV} + Y_0\,(1 - e^{-KV}) = Y_0 + Y_1\, e^{-KV} \qquad (1)$$

The studies of hardness testing referred to above[5] have shown that the gross yield strength Y_0 can, with some confidence, be taken as equal to ⅓ the constant mean pressure P_m that prevails when the indenter is loaded heavily enough for the plastic state to be fully developed throughout the region of contact. Since this condition appears to be adequately satisfied for the loadings that produce the horizontal portions of the curves of Fig. 2, it follows that the value of Y_0 needed for eq. 1 is approximately 6.5 kg/mm^2 for clear (red) unfilled vinylite. Unfortunately, however, some of the secondary factors (such as elastic "recovery," increasing difficulty of measuring indentation, etc.) that contribute to the empirical nature of hardness testing begin to assume greater importance for just the conditions of light loading that produce the greatest enhancement of the yield strength. Partly for this reason, and partly on account of the size effect itself (see below), numerical values for the upper limit of the yield strength, $Y_0 + Y_1$, have remained relatively elusive, even for metals; and almost no effort has yet been devoted to establishing even the order of magnitude of the "theoretical" yield strength for the plastics used for phonograph records. Crude values for K and Y_1 can be wrung from the data presented in Fig. 2 by a process of curve fitting, but more extensive measurements, and perhaps other methods of testing, are needed in order to allow the size effect to be characterized analytically with adequate precision. In view of this state of numerical ignorance, it is comforting to observe that the qualitative conclusions to be drawn below do not depend in any critical or sensitive way on the quantitative details of the formulation expressed by eq. 1.

STRESS DISTRIBUTION IN THE REGION OF CONTACT

Consider now the magnitude and distribution of the elastic stresses in the record material adjacent to the stylus contact for the "wholly elastic" regime in which no plastic yielding occurs. The upper part of Fig. 4 shows the assumed geometrical situation, and the notation to be used can be summarized as follows:

- a, d = radius and diameter of the circle of contact;
- R = radius of the spherical tip of the stylus;
- h = maximum penetration, at the center of the circle of contact, measured from the plane surface;
- D = diameter of a "flat" on the spherical stylus tip;
- W = "bearing load" on the stylus (mass units);
- F = Wg = "stylus force" (force units);
- P_m = $W/\pi a^2$ = mean "bearing pressure" on the circle of contact;
- P_0 = maximum pressure (at the center of the circle of contact);
- E, ν = Young's modulus and Poisson's ratio for the record material;
- $\sigma_r, \sigma_\theta, \sigma_z$ = the three principal stresses in the radial, tangential, and normal directions;
- τ = shear stress.

The general solution given by Hertz for the elastic contact of two spheres is simplified extensively when one of the spheres expands to become the plane surface of a groove wall and when the other can be assumed to be ideally rigid (that is, when the elastic modulus of the stylus is very much larger than that of the record material). For this case, the radius of the contact circle can be expressed as

$$a^3 = \frac{3}{4}\frac{FR}{E'}, \quad a = \frac{3\pi}{4}\frac{R}{E'}P_m \qquad (2)$$

where E' is an abbreviation for $E/(1-\nu^2)$, the plane-stress or "constrained" value of Young's modulus†. If a is eliminated between the two forms of eq. 2, the mean bearing pressure can be expressed in terms of the stylus loading as follows:

$$P_m = \frac{1}{\pi}\left(\frac{16}{9}\right)^{1/3}\left(\frac{E'^2}{R^2}W\right)^{1/3} = 0.45\,\frac{E'^{2/3}}{R^{2/3}}\,W^{1/3}\,\text{kg/mm}^2 \qquad (3)$$

where the numerical factor in the second part has been adjusted to allow W to be expressed in grams, E' in kg/mm^2, and R in mils. It may be noted in passing that, for the elastic regime presumed in writing eq. 3, the stylus force must vary directly as the *square* of the stylus radius in order to

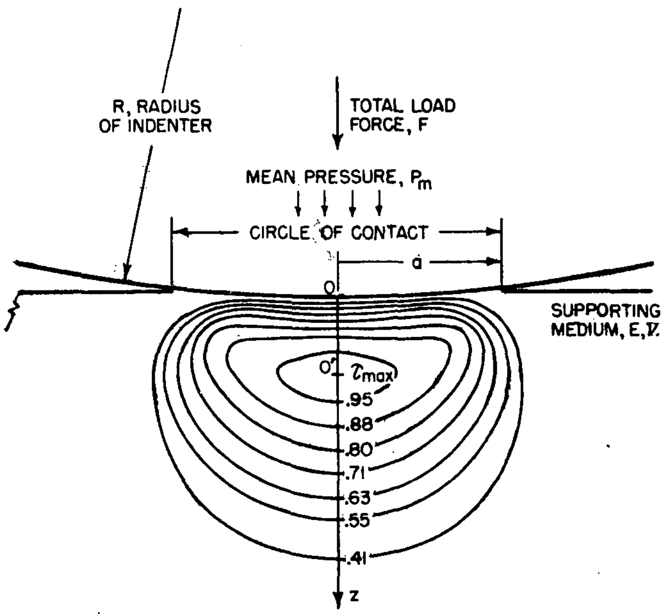

FIG. 4. The geometry of the stylus-groove contact, and a stress-contour diagram showing the distribution of the maximum difference between the principal stresses in the region underlying a spherical indenter. The number on each contour indicates its "height" in terms of the highest shear stress, which occurs at the point O' located about half a contact-circle radius below the center of contact at O. *(After Davies[9])*

maintain a constant stylus pressure. It follows that if the groove-wall deformations were to remain elastic, the current practice of reducing the stylus force by a factor of only 2 or 3 when shifting from a 3-mil to a 1-mil stylus would correspond to designing for substantially higher bearing pressures on microgroove records. On the other hand, plastic yielding actually does occur for conventional loadings in both cases, and as always, in such a way as to reduce or relieve the stresses. The designed excess of pressure on microgrooves largely disappears for this reason, as shown by Fig. 2; but the designer can draw little comfort from this, since the same yielding that relieves the pressure leads also to severe increase in the wear rate (see below).

The maximum normal stress, P_0, on the bearing surface occurs at O, the center of the contact circle, and is 3/2 the mean bearing pressure, P_m. It has been known for a long time,[8] however, that the highest shear stress in the supporting medium does not occur at the surface of contact, but rather at an interior point O' lying below the center of contact by about half the radius of the contact circle (see Fig. 4). Several investigators have computed numerically the stress distribution under a spherical indenter, in order to plot the slip-line field, and Davies[9] has exhibited the largest difference between the principal stresses in the form of the contour diagram shown in the lower part of Fig. 4. The magnitude of this stress difference at points lying on the z-axis can be expressed in closed form by integrating (with the help of a change of variable) the relations given by Timoshenko[8] for the simpler case of uniform loading over the surface of contact. The stress difference found in this way is

$$\begin{aligned} 2\tau(z) &= \sigma_\theta - \sigma_z = \sigma_r - \sigma_z \\ &= \frac{3}{2}P_m\left[\frac{3}{2}\,\frac{1}{1+z^2/a^2} - (1+\nu)\left(1-\frac{z}{a}\operatorname{ctn}^{-1}\frac{z}{a}\right)\right] \end{aligned} \qquad (4)$$

where $\tau(z)$ is the shear-stress distribution along the z-axis. Note also that two of the principal stresses, σ_r and σ_θ, are equal by virtue of symmetry. A typical graph of eq. 4 is shown in Fig. 5. Both the height and position of the maximum of this curve are weakly influenced by the value of Poisson's ratio, as may be shown by solving numerically the equation formed by setting the derivative of eq. 4 equal to zero. For values of ν lying between 0.25 and 0.40, the position of highest stress is found in this way to be

$$\left(\frac{z}{a}\right)_{\max} = 0.381 + \frac{1}{3}\nu \qquad (5)$$

† "g"-trouble rears its head at this point when one approaches eq. 2 or its descendants with numerical intent. In the literature on hardness testing, with which it seems useful to maintain numerical compatibility, it appears to be common practice to divide the "g" out of P_m with the result that pressure then has the apparent dimensions of mass loading per unit area; but since E is also expressed in the same units, consistency is maintained. I do not defend the ambivalence, but in this text all stresses (E, Y, τ, σ) are to be expressed in terms of *force* per unit area when they occur along with F, but in terms of *mass* per unit area when they are associated with P_m or W.

[8] S. Timoshenko and J. N. Goodier, *Theory of Elasticity,* 2nd ed., pp. 362-377, McGraw-Hill Book Co., New York, 1951.

[9] R. M. Davies, "The Determination of Static and Dynamic Yield Stresses Using a Steel Ball," *Proc. Roy. Soc. (London)* **A197**, 416-432 (1949).

and the corresponding maximum stress difference is

$$(\sigma_r - \sigma_z)_{\max} = \tfrac{3}{2} P_m \, (0.756 - 0.450\,\nu) \qquad (6)$$

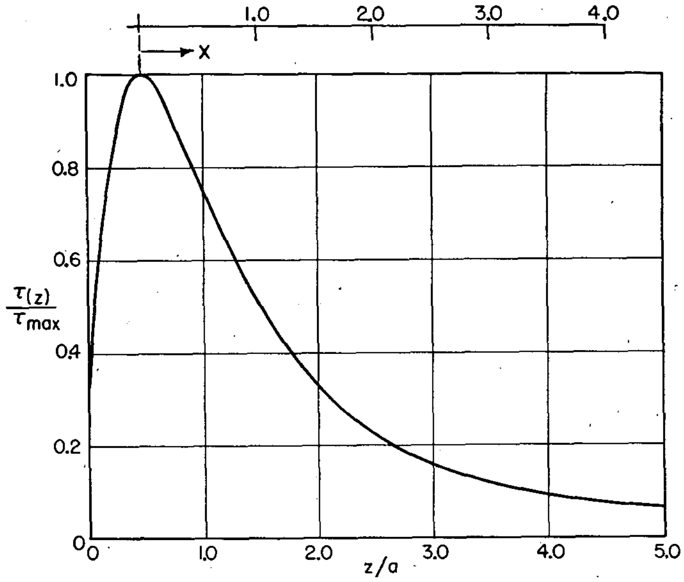

FIG. 5. Typical variation along the normal axis of the elastic shear stress under a spherical indenter.

THE CRITERION FOR YIELDING

A further consequence of the symmetry that makes two of the principal stresses equal on the z-axis is that the Huber-von Mises, the Tresca-Mohr, and the Haar-von Karman criteria for the onset of plastic yielding all agree in predicting that yielding will begin at the critical load that just satisfies the limiting equality expressed by

$$\sigma_r - \sigma_z \leq Y(V) \qquad (7)$$

The physical significance of this yield criterion must now be interpreted with due regard for the distribution of elastic stresses represented by the contours of Fig. 4, and for the influence of the size effect represented by the functional dependence of yield strength on the volume of the stressed specimen. One may observe qualitatively that the stress decreases from one contour to the next in moving away from the point of highest stress, in a manner governed by eq. 4 and that, as the volume of stressed material contained within successive contours increases, there will be a corresponding reduction of yield strength governed by eq. 1. Whether the stress difference will first exceed the yield strength at the point of highest stress, O', or at some other point along the z-axis, will obviously depend on the respective rates at which these quantities vary along the z-axis.

One preliminary conclusion can be drawn at once by inspection of the stress-contour diagram. The increments of volume are smaller between O and O' than on the other side of O'; from which it follows that, while yielding may commence either at the highest-stress point or beyond, it can never begin in the region between O' and the center of contact. As a consequence, only the portion of the stress-distribution curve lying beyond the maximum needs to be considered in exploring the conditions for the onset of yielding. It also follows that this controlling portion of the stress curve can be expressed most usefully in terms of a new dimensionless position variable, x, whose origin is placed at O', as indicated by the x-scale annexed to Fig. 5. Thus, by incorporating eq. 5 to make the definition explicit,

$$x \equiv \left(\frac{z}{a}\right) - \left(\frac{z}{a}\right)_{\max} = \left(\frac{z}{a}\right) - \left(0.381 + \frac{1}{3}\nu\right) \qquad (8)$$

In terms of this variable, the yield-controlling stress difference can be described very simply as

$$\sigma_r - \sigma_z = \tfrac{3}{2} P_m \, f_1(x), \qquad x \geq 0 \qquad (9)$$

in which the stress-distribution function $f_1(x)$ stands as an abbreviation for the bracketed terms in eq. 4 modified by the change of variable. Finally, since the bearing pressure P_m can only be controlled indirectly, it is useful to go one step further and use eq. 3 to replace P_m with the variables that are experimentally accessible. This step leads to the convenient working relation for the stress-difference, or shear-stress distribution,

$$2\tau = \sigma_r - \sigma_z = 0.578 \frac{F^{1/3} E'^{2/3}}{R^{2/3}} f_1(x) \qquad (10)$$

Consider next the yield strength given by eq. 1. To put this in a form better adapted for the specified comparison of stress and yield strength, let us first express the volume of material enclosed within any stress-difference contour in terms of the value of x at which the contour cuts the z-axis. Such a relation might be written arbitrarily in the form

$$V = \frac{4}{3} a^3 f_2(x) = \frac{FR}{E'} f_2(x) \qquad (11)$$

where the factor a^3 is first introduced in order to normalize the dimensions and is then eliminated (by substitution from eq. 2) in order to put in evidence again the experimental variables. The function $f_2(x)$ is defined arbitrarily to include any leftover numerical factors as well as the volume distribution function. It would not be easy (to say the least) to derive a closed-form analytical expression for $f_2(x)$, owing to the complex nature of the three-dimensional stress field. On the other hand, it is not difficult—just tedious—to compute by numerical integration the volumes corresponding to the seven particular contours shown in Fig. 4. A log-log graph of these results, as shown by Fig. 6, then reveals that the enclosed volume begins to increase as x^3 for small values of x less than about 0.3, and then increases less rapidly, approximately as $x^{1.7}$, for larger values of x. Usable values of $f_2(x)$ can be read directly from such a graph, but it is somewhat more convenient numerically to represent this function by the empirical equations

$$f_2(x) \doteq 13.6\,x^3, \quad \text{for } x < 0.3 \qquad (12)$$
$$\doteq 3.2\,x^{1.7} \quad \text{for } x > 0.3$$

With the volume distribution function thus in hand, we can proceed to put eq. 11 in eq. 1, whereupon the working relation for the effective yield strength takes the form

$$Y = Y_0 + Y_1 \exp\left[-\frac{FRK}{E'} f_2(x)\right] \qquad (13)$$

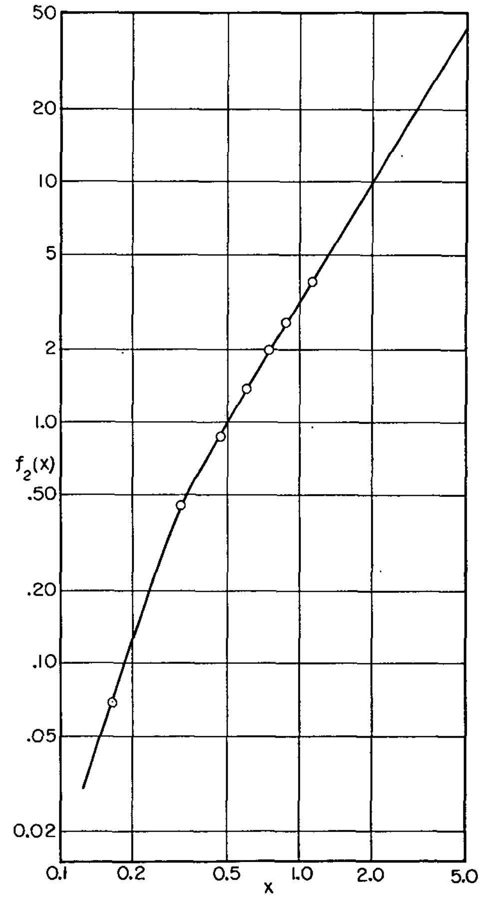

FIG. 6. Log-log graph of the function $f_2(x) = 3V/4a^3$, where V is the volume of material enclosed by the stress-difference contour passing through x.

CONDITIONS FOR THE ONSET OF PLASTIC YIELDING

The physical significance of the criterion for plastic yielding expressed by eq. 7 can be restated as follows. Any combination of the experimental variables F and R and of the material constants E', Y_0, Y_1, and K which produces stress differences (eq. 10) that are less than the yield strength (eq. 13), for *all* values of x, will produce deformations that are wholly elastic. Recovery will be complete in these cases after the stylus has moved on and thereby removed the load. On the other hand, when any combination of these six parameters first allows equality to be achieved between stress difference and yield strength, at *any* value of x most favorable for such equality, then plastic yielding will begin at the point on the z-axis corresponding to this most-favorable value of x.

What happens *after* yielding has commenced is another question, and one on which the yield criterion itself is mute. Energy considerations require that yielding always proceed in such a way as to relieve, and hence to reduce, the causal stresses; and it is safe to add that the rate of plastic flow will increase with the excess of the stresses over those that can be supported by elastic strains. Our state of ignorance about the *rates* of plastic flow under a phonograph stylus would be downright embarrassing, were it not for the fact that in what follows it will be argued that any plastic flow at all is highly undesirable on grounds of both wear and noise, and that the pickup designer dare not rest until he achieves the safe quiet haven of the fully elastic regime!

One important feature of eqs. 10 and 13 can be pointed out that makes it possible to draw useful generalizations about the threshold of plastic yielding in spite of the large number of disposable parameters. For example, the variables F, R, and E' enter only as multipliers in eq. 10, and hence will influence the *scale* but not the *form* of the functional relation between the stress difference and x. As a consequence, the log-log graph of $(\sigma_r - \sigma_z)$ versus x will have a constant shape and will be merely translated upward or downward by changes in these multiplying factors. This behavior is indicated by the direction arrows superposed on the typical stress-difference curve shown in Fig. 7.

The functional relation between the yield strength and x also reveals the influence of the experimental variables in a no less useful, but different, way. It can be seen, either by inspection of eq. 13 or by plotting a few typical curves, that the *shape* of a log-log graph of Y versus x will consist of two horizontal segments, corresponding to the limiting values Y_0 and $Y_0 + Y_1$, joined by an S-shaped transition curve that rises steeply at a value of x that will depend on the multiplying factors that appear along with $f_2(x)$ in the exponent. Thus in this case it is the *lateral* position of the steeply rising portion of the yield curve that shifts with F, R, E', and the flaw constant K, as indicated by the direction arrows superposed on the yield-strength curve shown in Fig. 7.

The two curves of Fig. 7 thus provide an objective representation of the stress differences and the yield strengths that must be in balance at the threshold of yielding, and these can readily be manipulated in hypothetical experiments, thanks to the fact that each curve can be regarded as if it were a plane bent-wire figure—rigid, but freely movable in the coordinate plane. The various conditions attending the onset of plastic yielding can then be surveyed by observing where these two curves first become tangent as each is shifted at the rate and in the direction called for by changes in the several parameters. Four cases of particular interest can be identified.

(*a*) *Large-radius indenter.* Large values of the radius R tend to depress the "starting" position of the stress curve (since $R^{2/3}$ appears in the denominator of eq. 10), and to displace the initial position of the transition segment of the yield curve relatively far to the left on the log x-axis. As a consequence, when the load force F is progressively increased, the stress curve shifts upward and the transition segment of the yield curve moves still farther toward the left, until first tangency occurs at the vanishingly small values of x corresponding to O', the interior point of highest shear stress, as shown at T_a in Fig. 8a. Note that the size effect enhancement of the yield strength plays no part in controlling the onset or course of plastic yielding in this case, and that the maximum elastic stress which can be sustained at the threshold of yield corresponds to $P_m \doteq 1.1\ Y_0$. This is the typical situation that prevails in all conventional

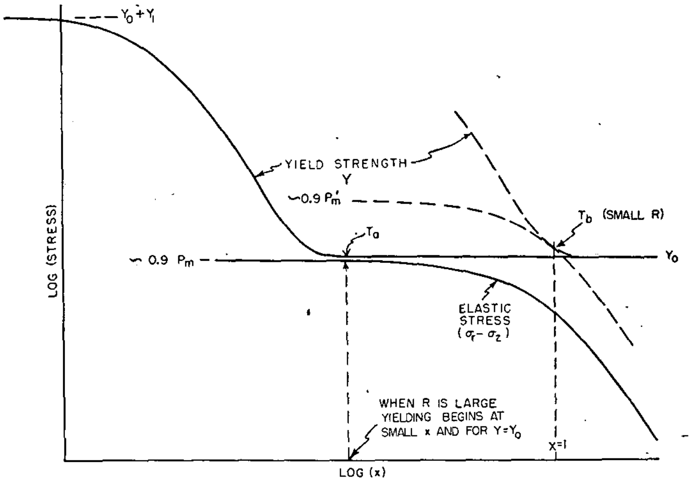

FIG. 8a. The solid curves show that the "bulk" value of yield strength controls the onset of plastic yielding for a large-radius indenter. The dashed curves show how the point of tangency can occur beyond the knee of the yield curve, with a corresponding enhancement of the yield pressure, when the indenter radius is small.

hardness tests that make use of spherical indenters 1 mm or more in diameter.

(*b*) *Small-radius indenter—marginal case.* As the radius of the indenter is made progressively smaller, the transition segment of the yield curve will shift to the right on the log-x scale and there will turn up eventually some small value of R for which the yield curve will occupy a position such as shown by the dash-line curve of Fig. 8a. For this case the point of tangency T_b will begin to occur "just around the corner" of the lower bend of the transition segment and at a point near the knee of the stress curve at which $x \approx 1$. Since x is a measure of the distance from O', in units of a, it follows that plastic yielding would begin in this case at a point about $3a/2$ below the surface. This does not mean that the point of highest shear stress has retreated farther from the surface, but rather that the small volume of material in the immediate neighborhood of the point of highest stress is being protected against yielding, as it were, by the size effect. What is most important for our purposes, however, is that the mean bearing pressure P_m' that can be sustained elastically without yielding is substantially higher than would be predicted in the absence of a size effect.

It will be apparent that the magnitude of this enhancement of the supportable pre-yield elastic stress will depend on how far up on the yield curve the point of first tangency occurs, and that this will in turn depend on the radius R and on the material parameters E', K, and Y_1/Y_0. The illustrative curves of Fig. 8a show a 2.5-fold elevation of the elastic stress, with the critical yield point (i.e., tangency) at $x = 1$, for an assumed value of $Y_1/Y_0 = 19$. It can then

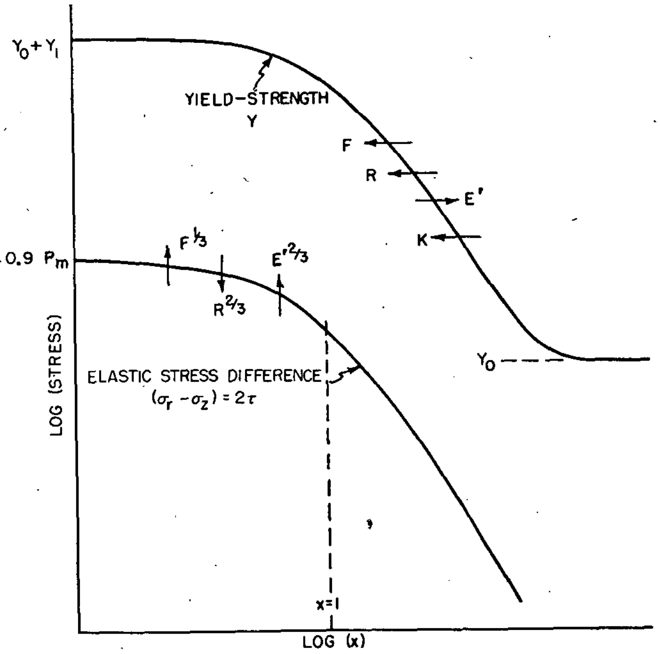

FIG. 7. Typical log-log graphs showing, as a function of x, the elastic stress difference and the effective yield strength for a hard spherical indenter penetrating the plane surface of an extended medium. The arrows show how the indicated parameters act to translate the curves without change of shape. An assumed value of $(Y_0 + Y_1)/Y_0 = 20$ was used in computing the yield curve.

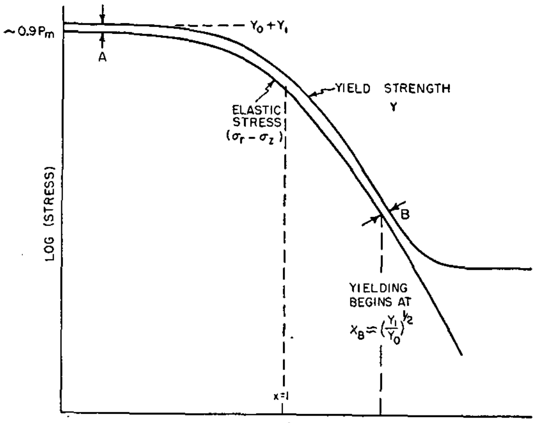

FIG. 8b. The critical case of elastic-plastic instability for which plastic yielding may start simultaneously throughout an extended region underlying the circle of contact.

be shown, by numerical manipulations with eqs. 13, 6, and 3, that these assumptions require, for consistency, that $R \doteq 0.16\ E'Y_0^{-1}K^{-1/3}$; but none of these parameters is known with enough precision to allow the quantitative relevance of this case to the phonograph stylus problem to be argued conclusively. On other grounds, however—notably on the basis of the data for Fig. 2—there is reason to believe that this case does embrace the situations that prevail in current phonograph practice. In particular, it seems likely that it is just such an enhancement of the pre-yield elastic stress that prevents the designed excess of bearing pressure on microgrooves from causing even more trouble than it does.

A speculative gleam may well appear in the designer's eye at this juncture. It might be that vulnerability to plastic yielding could actually be reduced by still further reduction of the stylus-tip radius to half a mil or less. Unfortunately, the quantitative information about record materials in general, and about the parameters Y_1 and K in particular, is still too sketchy to allow such a proposal to be assessed. The potential advantages of such a change of system parameters would suggest, however, that it may be worthwhile to pursue the needed data with some vigor.

(*c*) *Small-radius indenter—the critical case of elastic-plastic instability*. It can be seen that as the radius is made slightly smaller than assumed for case *b*, or when any changes in the other parameters combine to produce an equivalent displacement of the stress and yield curves, there will always arise one critical juxtaposition of these curves for which tangency will occur—and hence for which plastic yielding will be initiated—simultaneously at both a large and small value of x.

For example, suppose that the parameters are such that the stress and yield curves have the relative positions shown in Fig. 8b. When first tangency almost—but not quite—occurs in the region A of Fig. 8b, the deformation remains wholly elastic and enjoys the "protection" of a yield strength nearly equal to the "theoretical" upper limit $Y_0 + Y_1$. A slight further increase of load force, however, will bring the stress curve into contact with the yield curve not only at A, but also at B, and plastic yielding will at once be precipitated throughout the volume of material bounded by the stress contour passing through x_B. The region so affected may extend into the underlying medium by as much as several times the diameter of the contact circle, depending on the relative magnitudes of Y_0 and Y_1. In a static indentation test, this type of instability could only manifest itself for increasing loads inasmuch as plastic yielding is not reversible. For the *sliding* contact of stylus on groove wall, however, new material is constantly being presented to the stylus, the situation can be regarded as statistical, and a relatively abrupt transition from the plastic to the elastic regime can equally well appear on reduction of the load. This is, therefore, just the kind of "abrupt load-sensitive transition in the basic nature of the stylus-groove contact" that was referred to above in the introduction.

(*d*). *Very-small-radius indenter*. For all values of the indenter radius smaller than the one that gives rise to the critical instability of Case (*c*), the whole transition segment of the yield curve will have been displaced to the right beyond the stress curve, as shown in Fig. 8c. Tangency can only occur then at vanishingly small values of x, and for a controlling value of the yield strength near the upper limit $Y_0 + Y_1$. In effect, the volume of material "protected" against yielding by the size effect includes all the region within which the elastic stress difference is higher than Y_0. As a consequence, yielding will begin only when the stress difference exceeds the upper limiting yield strength, and it

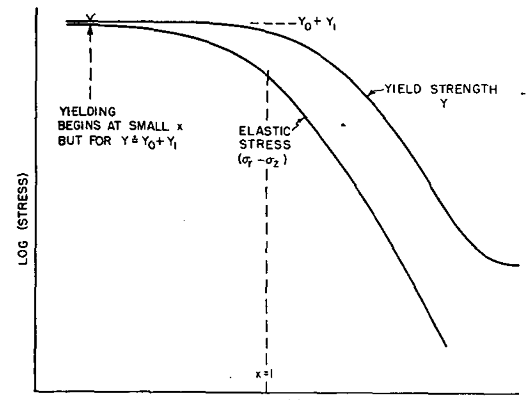

FIG. 8c. For a very-small-radius indenter, such as a submicroscopic "high" point on a "smooth" surface, the deformation may remain elastic for stresses nearly equal to the theoretical yield strength.

will do this first at O'. This is the typical situation that prevails in the localized areas, or asperities, at which a solid material makes "real" contact with its load. It can also be said that the conventional stylus-groove contact appears to come just close enough to falling within this category to make the eventual attainment of its high-stress, elastic regime a realistic design objective for phonograph playback systems.

THE AREA OF REAL CONTACT AND RUBBING WEAR

The mysteries of sliding friction and wear have challenged the intellectual curiosity of scientists since antiquity. A clear understanding of the facts behind the facts is still far from complete, but recent studies[10] have evolved a plausible model of the mechanism of mechanical interaction that has at least the virtue of simplicity and perhaps that of adequacy. Many of the details of this model are still controversial, of course; and there is, as usual, a lamentable scarcity of quantitative data relating to the materials and circumstances of phonographic interest. Nevertheless, the basic conceptions that have been advanced to explain the behavior of dry metals in sliding contact will serve as a useful framework for these speculations about stylus wear.

Solid surfaces are never ideally smooth and flat. It is not widely appreciated, however, that the surface of a freshly-cut groove in a lacquer record is one of the smoothest surfaces known to exist. For example, if it is safe to assume that a 10-kcs sine wave can be reproduced at a level 40 db above the overall background noise in a 12-kcs playback channel, then it can be shown that the root-mean-square "roughness" of the groove surface must be of the order of magnitude 50 Å, or about 1/100 of a wavelength of visible light. In spite of this remarkable degree of smoothness, it must be conceded that even such a surface will have a statistical distribution of irregularities that represent departures from ideal smoothness many times larger than the average spacing between neighboring atoms of the surface material. These surface irregularities will, in fact, be larger than the interatomic spacing by several orders of magnitude in all but the most ideal cases.

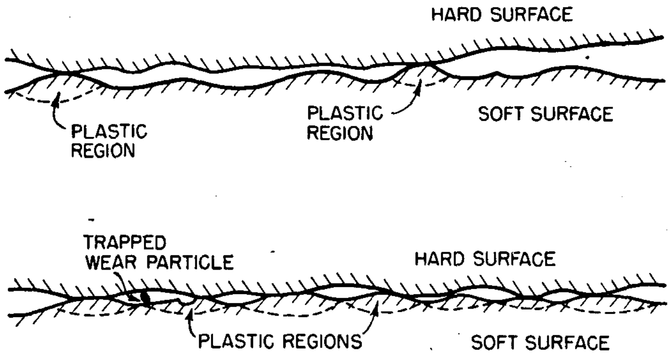

FIG. 9. Diagrammatic representation of two contacting surfaces that make "real" contact only in localized areas. The upper part shows how light loads are carried by only a few points of real contact; the lower part shows the spreading area of real contact under heavier loads and illustrates the entrapment of an abraded wear particle. *(After Burwell and Strang[13])*

[10] F. P. Bowden and D. Tabor, *The Friction and Lubrication of Solids,* Clarendon Press, Oxford, 1950; J. T. Burwell, ed., *Mechanical Wear,* American Society for Metals, 1950; also, many additional references cited in each of the foregoing.

It must follow then, that even when two very smooth surfaces are brought lightly together, "real" contact will be made only at the tips of the high points, or asperities, of the mating surfaces. The area of real contact between each asperity and its mating surface will increase as the load force increases, moreover, in much the same way that the surface of contact increases in area when the load is increased on a spherical indenter of macroscopic size. In addition, progressive deformation of the highest asperities will allow other high points to come into real contact. Increasing loads serve, therefore, to increase both the number and the size of the local areas in real contact. It can be seen that the total area of real contact, A_{re}, will be directly related to the total force acting, and that this area of real contact is not related in any essential way to the apparent area of the contacting surfaces.

The physical situation thus assumed to exist in the region of contact between two surfaces is illustrated diagrammatically in the upper half of Fig. 9, which shows two typical asperities making "real" contact. The actual size of typical asperities, even for very smooth surfaces like those of the stylus and groove, is almost surely small enough to qualify under case d discussed above, and hence the micro-yield strength Y_μ, that would be effective throughout the volume of the small asperity will be

$$Y_\mu \doteq Y_0 + Y_1 \qquad (14)$$

Case d teaches that plastic yielding will begin at the tip of the asperity when the local mean bearing pressure reaches about $1.1Y_\mu$. The studies of hardness testing[5] go further, however, and say that as the plastic state becomes fully developed under an indenter (represented by the asperity in this case), the local mean pressure gradually rises to about $3Y_\mu$.

The existence of supra-yield stresses throughout the volume of a local asperity does not imply necessarily that the underlying material is also in the plastic state. These high stresses will diminish toward the base of the asperity where it broadens at its junction with the basal plane, and may—in fact, had better—become small enough in that region to produce only elastic deformation of the base material. Of course, the regime that does prevail at any point in the base material will be determined by the resultant of all the stresses transmitted from all the nearby asperities. The net effect of these considerations is to leave unaffected the conclusions drawn above in cases *a–d* regarding the onset of plastic yielding in the base material. Only in dealing with wear and friction is it necessary to notice the difference between the real and apparent area of contact, but for these two problems the difference is crucial.

The circumstances described above are illustrated schematically by the profilometer traces[11] shown in Fig. 10. The actual scale of these original traces was macroscopic, rather than submicroscopic as in the case discussed here, but the descriptive analogy is complete. Traces *A* and *B* show that the tips of these "asperities" experienced plastic deformation from which they did not recover, but that the deformation of the base material was elastic and its recovery essentially complete. Under the loading for trace *C*, the base material also was deformed plastically and a permanent indentation of the "mean surface" remained after the load was removed.

Conceiving the mechanism of contact between solids to consist of a myriad of small local areas in intimate real contact provides the framework for a phenomenological theory of the wear process. First assume that a typical "wear particle" can be identified, and that the average distance between such particles is a. Then the total number of such particles lying in each surface of all the areas of real contact will be A_{re}/a^2. Moreover, since the average inter-particle spacing is a, a sliding motion of the stylus through the distance L will bring each single particle lying in the stylus surface into intimate juxtaposition with L/a particles of the groove surface. It follows that when the stylus has travelled a distance L, there will have occurred, on the average, $L\,A_{re}/a^3$ encounters or near-approaches between particles of the two surfaces. We now make the crucial assumption that in every such encounter there is a fixed probability, Z, that one of the stylus particles will be removed, or abraded from its parent surface either by adhering to the groove surface or by acquiring from the encounter a sufficient surplus of vibrational energy. According to this notion, the total number of particles liberated from the stylus surface will be ZLA_{re}/a^3; and since the number of particles contained in a volume V is just V/a^3, the total volume of stylus material abraded or worn away in travelling a distance L will be given by the simple relation

$$V = ZA_{re}L \tag{15}$$

When this elegantly simple theory of rubbing wear was proposed originally by Holm,[12] he assumed that the abrasive attrition would be atomic in character. Burwell[13] has pointed out, however, that the theory is not impaired if Holm's atoms are replaced (as in the foregoing discussion) by small "wear particles," and he supports this substitution by showing that typical wear particles removed from hardened steel surfaces fall within the size range 50 to 100 Å. Although it may be only coincidental, one cannot fail to be

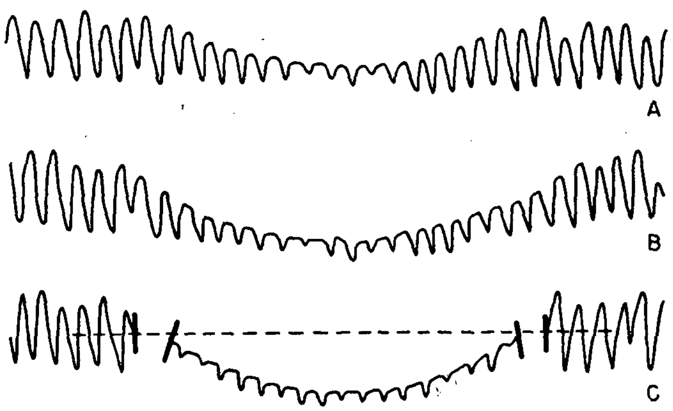

FIG. 10. Profilometer traces of the deformation of a finely grooved metallic surface. These macroscopic profiles illustrate schematically the assumed behavior of submicroscopic asperities at the stylus-groove interface. *(After Moore[11])*

impressed by the inviting similarity between the size of Burwell's steel wear particles, the residual roughness of a very quiet groove, and the typical dimensions of the large molecular aggregates that characterize plastic polymers. Has anybody studied size distribution in the sapphire dust embedded in tired groove walls?

The volume rate of removal of stylus material per unit distance of travel along the groove is given, with disarming simplicity, by eq. 15. It is usually more convenient, however, to measure stylus wear in terms of the diameter of the "flat" that gradually appears on the flanks of the spherical tip. This conversion can be made readily by noting that

$$V = \frac{\pi}{64}\frac{D^4}{R}\left(1 + \frac{D^2}{12R^2} + \ldots\right) \doteq \frac{\pi}{64}\frac{D^4}{R} \tag{16}$$

When the approximate form of eq. 16 is introduced in eq. 15, the controlling relation for stylus wear can be written in the form

[11] A. J. W. Moore, "Deformation of Metals in Static and in Sliding Contact," *Proc. Roy. Soc. (London)* **A195**, 231–244 (1948).

[12] R. Holm, *Electrical Contacts*, pp. 214-221, H. Geber, Stockholm, 1946; also "Hardness and Its Influence on Wear," pp. 317-329, in *Mechanical Wear*. (See footnote 10.)

[13] J. T. Burwell and C. D. Strang, "On the Empirical Law of Adhesive Wear," *J. Appl. Phys.*, **23**, 18–28 (1952).

$$\frac{0.049}{RZ}\,\frac{D^4}{L} = A_{\rm re} \qquad (17)$$

The problem of analyzing stylus wear now becomes one of studying the behavior of the area of real contact $A_{\rm re}$ under various conditions of operation. So long as the deformation of the underlying record material supporting the asperities remains wholly elastic (as for the A and B traces of Fig. 10), we can infer from the remarks following eq. 14 that

$$A_{\rm re} = W/3Y_\mu \qquad \text{(elastic)} \qquad (18)$$

On the other hand, if the base material itself is stressed highly enough to flow plastically, the asperities will tend to be thrust into the base material; or, to put it another way, in the underlying medium becomes progressively more fully developed. It is to be noted that the apparent area of contact is itself directly proportional to the load in this case, since these are the conditions for which the mean pressure P_m remains essentially constant at the value $3Y_0$. A companion expression similar to eq. 18 can, therefore, be written as

$$A_{\rm re} = 0.8\,A_{\rm app} = 0.8\,\frac{W}{P_m} = 0.8\,\frac{W}{3Y_0} \quad \text{(fully plastic)} \qquad (19)$$

The areas of contact, both real and apparent, cannot be described in such simple mathematical form for the transition condition that is not wholly elastic nor yet fully plastic. The course of variation of these areas can be deduced, however, from a study of Fig. 11, which shows the typical variation of mean pressure with applied load for two sets of circumstances.

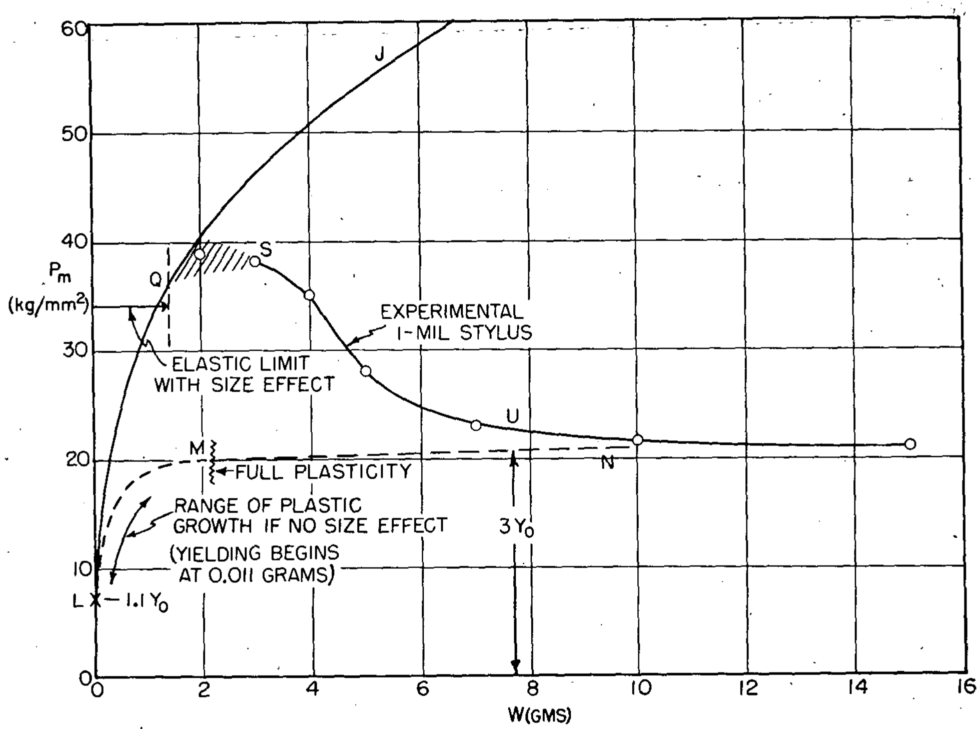

FIG. 11. The dashed curve *OLMN* shows the archetype behavior of P_m versus W for the relatively large spherical indenters used in hardness testing (*Tabor*[5]); the curve *OLQSU* shows how the size effect influences this behavior for a 1-mil stylus.

the underlying material will flow plastically until it engulfs the asperities and establishes real contact over nearly all the apparent surface of contact. An intermediate stage in the establishment of this situation is shown in the lower part of Fig. 9. Note, however, that the size effect (now working in reverse, as it were) prevents the spaces between the asperities from disappearing entirely (compare trace C of Fig. 10). It will be assumed, then, in the absence of more precise information, that the ratio of the real to the apparent area of contact will vary from about 0.5 to 0.8 as the plastic state

If it were possible for the deformations of the groove wall to remain completely elastic, P_m would follow the ⅓-power curve *OLQJ*. Plastic yielding always will begin at some point along this curve, however, and in the absence of any size effect—or what is equivalent, for a large-radius indenter, as in case *a* above—it will do so at L. It is of interest to note that the value of W at the onset of yielding is so small (only 11 milligrams for a 1-mil stylus!) that the "elastic" segment *OL* appears to be almost vertical when a linear scale is used for W.

As yielding begins, the P_m curve breaks away from the elastic curve along the dashed line *LM*, but full plasticity is not established until the load *W* has increased to about 100 to 200 times its value at the onset of yielding (a factor of 20 comes from the cube of 3/1.1, and the rest from the decreased slope of *LM*).[5] The apparent area of the surface of contact can then be found for each point along *OLMN*, merely by dividing *W* by P_m. The way this area varies with *W* is shown by the upper curve (correspondingly lettered) of Fig. 12.

An example of the profound influence of the size effect on the stylus-groove contact can now be exhibited by adding to Fig. 11 the experimental curve *QSU*, which is a replot of the indentation data of Fig. 2. The situation represented by this curve seems clearly to fall within case *b* discussed above, since the value of P_m at which yielding begins appears to have been raised by a factor of nearly 5. What is even more important, so far as wear and noise are concerned, such an enhancement of the yield value of P_m increases the bearing load that can be supported with full elasticity by the cube of the enhancement ratio (P'_m/P_m in Fig. 8a).

The apparent area of contact for points along *OLQSU* is now computed as before and the results are represented in Fig. 12 by the correspondingly lettered curve. Note that the apparent area follows the "elastic" ⅔-power curve *OLQJ* as far as *Q*, at which point yielding begins and the area curve breaks upward along the dashed line *QSU*. The area of real contact, whose delineation is the objective of this graphical maneuvering, can now be pinned down with the help of eqs. 18 and 19. For loads that do not transgress the elastic boundary at *Q*, the real area increases along the slowly rising straight line *OHP*, whose slope is the reciprocal of $3Y_\mu$. Note that this segment of the real-area curve does not depend at all on the apparent area of contact. Beyond the break in this curve at *P*, however, the apparent area takes over control in accordance with the remarks preceding eq. 19. Thus the *PSGU* portion of the real-area curve is to be constructed by assuming that the ratio of the real-to-apparent area will have reached the value 0.5 at *S*, and that this ratio increases smoothly to 0.8 at *U*.

The real-area curve of Fig. 12 *can now be identified as the relative stylus wear rate* (see eq. 15 or eq. 17). The existence of a sharp break in this curve at *P* suggests—in fact, it fairly shouts—that substantial reductions in the rate of stylus wear can be achieved by operating exclusively along the low-slope *HP* portion of such a rate curve. Thus, for example, the rate curve of Fig. 12 predicts that a reduction of the load from 4 grams to 2 grams would lower the wear rate by a factor of 14; that a change from 5 grams to 2 grams would yield a factor of 25; and that a change from 7 grams to 1 gram would reduce wear by a factor of 100. It must be quickly pointed out, however, that the wear reduction is strongly influenced by the micro-yield strength, and that these numerical estimates merely indicate the improvement to be expected *if* Y_μ has the value $20Y_0$ assumed in drawing Fig. 12.

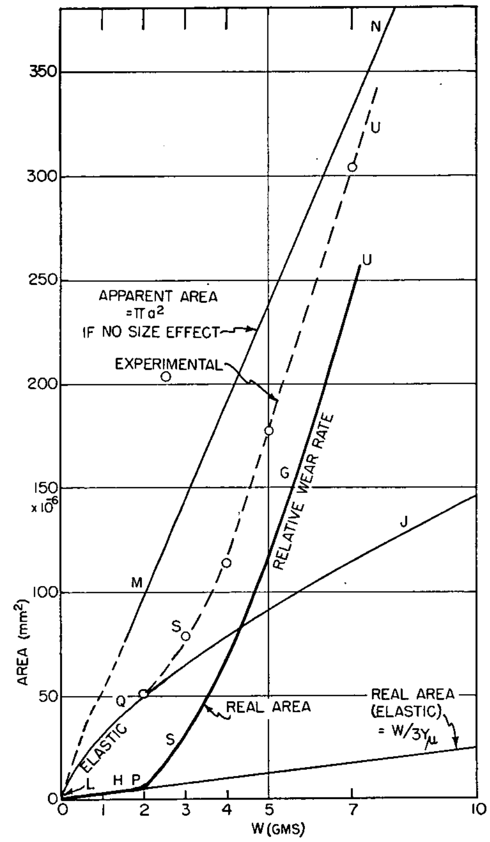

FIG. 12. Real and apparent areas of contact derived in part from the P_m versus *W* curves of Fig. 11, with corresponding curves similarly lettered. The heavy-line curve shows the variation of relative stylus wear rate with load.

It is fortunate that even though reliable estimates of the microyield strength are not yet available, the break point in the real-area curve can be located, at least with enough precision to furnish useful design guidance, by following the experimental and graphical routines described above. The inability to precalculate accurately the *amount* of wear-rate improvement need not, therefore, inhibit—and should not be allowed to delay—the redesign of conventional pickups for substantially extended stylus life.

A quantitative assessment of the exchange probability *Z* is needed if eqs. 15 and 17 are to be made numerically as well as functionally useful. Both Bauer[1] and Weiler[14] have reported stylus wear tests from which *Z* can be deduced. A novel consideration needs to be allowed for, however, in making use of their results. Neither of these experimenters

14 Harold D. Weiler, *The Wear and Care of Records and Styli*, pp. 32, 43, Climax Publishing Company, New York, 1954.

attempted to measure the "flat" until it had attained a diameter of 0.75 mil; but such a flat already exceeds the diameter of the "elastic" circle of contact. As a matter of fact, as Bauer points out, it is unlikely that a so-called "flat" is really very flat until it does reach the stage at which its diameter is at least equal to that of the elastic circle of contact. In using these reported wear data, therefore, the apparent area of contact must be taken as that of the flat itself. The effective mean pressure will be lowered somewhat by this enhancement of the bearing area, but a few trial computations indicate that only a flat of intolerable size could lower the pressure enough to remit the condition of plasticity. As before, then, the real area will be controlled by the apparent area and will be given in this case by

$$A_{re} = 0.8\,A_{app} = 0.8\,\frac{\pi D^2}{4} \tag{20}$$

When this equation is combined with eq. 19, the wear relation becomes

$$D^2 = 12.8\,ZRL, \qquad D > (6R\,W/E')^{1/3} \tag{21}$$

Since this relation only holds *after* the flat has reached the indicated minimum size, it is the rate at which the flat is predicted to grow thereafter that must be used in coordinating experimental data. This is found by differentiating eq. 21 to give

$$\frac{\triangle D}{\triangle L} = 6.4\,\frac{RZ}{D} \tag{22}$$

The exchange probability Z can now be evaluated by substituting the reported wear data in eq. 22. Weiler's wear rates are somewhat higher than Bauer's, but in conjunction they can be used to define a probable range of values for the exchange probability for sapphire and diamond as follows:

$$Z_{\text{sapphire}} = \begin{matrix} 0.24 \times 10^{-10}\ \text{(Bauer)} \\ 1.7\ \times 10^{-10}\ \text{(Weiler)} \end{matrix} \tag{23}$$

$$Z_{\text{diamond}} = 3.9\ \times 10^{-12}\ \text{(Weiler)}$$

Relatively few numerical values of Z are available for comparison with these estimates. It is interesting, however, and perhaps useful, to notice that the Z-value for the harder of two materials in sliding contact appears to vary approximately as the inverse cube of the hardness number. No theoretical explanation of this relation can be offered. Neither can it be said with any certainty that such a relation would hold over a sufficiently wide range to allow the values of Z given by eq. 23 to be used as a basis for predicting *record* wear. Nevertheless, it can be expected that there will be some pertinent value of Z for the record material, since the exchange theory of rubbing wear advanced here can be applied equally well to the abrasion of either stylus or record material. In short, rubbing wear is always bilateral and mutual, and both stylus and record groove "grow old together," each wearing away at the rate corresponding to its own particle-exchange probability.

One further comment needs to be added concerning the interpretation of these exchange probabilities. It was tacitly assumed in defining Z that the probability of removing a single particle was not influenced by anything that might be happening to, or might already have happened to, any other particle. Such an assumption is probably justified for the lightly loaded condition in which the area of real contact is only a small fraction of the apparent area of contact. On the other hand, when the fully plastic condition prevails and the real area becomes nearly as large as the apparent area of contact, there may be literally no place for the abraded wear particles to hide. Wear particles may thus become trapped between the two surfaces, as illustrated diagrammatically in Fig. 9, where their abrasive and gouging action can serve to dislodge many more wear particles than would be expected on the basis of a constant exchange probability. When the rubbing orbit is a closed circuit, as in a journal bearing, this effect can cascade and precipitate seizure,[13] and even for the open orbits represented by a record groove, it can presumably explain Weiler's observation that wear particles themselves are important accelerants of wear. Whether large or small, however, the contribution that such interference makes to the wear rate will already have made itself felt in the wear tests relied on above in estimating Z. As a consequence, substantially smaller values of Z than those given by eq. 23 should probably be used in predicting wear rates for loadings that are light enough to confine operation to the *HP*, or elastic, portion of the wear-rate curve.

STATIC VERSUS DYNAMIC LOADING OF THE STYLUS CONTACT

It is a measure, perhaps, of progress in the phonograph arts that it is now taken for granted that proper tracking of a lateral-cut groove demands that the stylus be supported in continuous contact with both sidewalls without bottoming in the groove. Most pickups now in use can meet this requirement (at least until the stylus becomes badly worn), although as recently as fifteen years ago, when the basic requirements for proper tracking were first enunciated,[15] there were no pickups available that were free from the sin of bottoming in the groove both on account of stylus shape and because the bearing weights were always high enough to deform the groove walls until contact was established on the tip as well as on the flanks of the stylus. All the analysis presented above, however, has been couched in terms of the loading of a single stylus-groove contact, from

[15] J. A. Pierce and F. V. Hunt, "On Distortion in Sound Reproduction from Phonograph Records," *J. Acoust. Soc. Amer.*, **10**, 14–28 (1938); U. S. Pat. No. 2,239,717. (See footnote 2.)

which it follows that all the bearing loads mentioned must be multiplied by 1.4 when they are to be interpreted as representing the total weight carried by the stylus.

Another quantitative feature of the stylus-contact loading resides in the fact that it is the instantaneous or dynamic stylus force that controls the groove wall deformation, *not* alone the static or average value of the bearing load. The importance of this consideration in pickup design is paramount. Although the average of the instantaneous stylus force cannot exceed the static value, high momentary peak values of groove-wall reaction force can and do occur, both as a result of high peak factors in the recorded signal and as a consequence of the vertical motion required to "track" the pinch effect. The effect of these high momentary force reactions on stylus wear will *not* average out in a linear fashion owing to the sharp break in the slope of the wear-rate curve at P. It follows that if the low wear rates promised by the HP portion of the rate curve are to be achieved in practice, the peak loading must not exceed the value corresponding to the knee of the curve. This is equivalent to saying that the pickup stylus must be able to follow both the lateral groove modulation *and* the vertical pinch-effect excursions without arousing even momentary peak values of groove-wall reaction in excess of those imposed by the static bearing load.

It is easy to show that peak stylus accelerations of the order of magnitude 1000"g" may be demanded in both horizontal and vertical directions for proper tracking at typical recorded levels. This numerical boundary condition, in conjunction with the foregoing, leads to the convenient specification that the equivalent vibratory mass of the stylus measured in milligrams should be no larger than the static value of the bearing load in grams. Moreover, it is not sufficient merely to provide "compliance" for the vertical motion of the stylus demanded by the pinch effect; it is also necessary that the equivalent vibratory mass of the stylus for vertical motion be kept almost as low as for lateral, since the vertical acceleration demand becomes nearly as large as the lateral for high-level, high-frequency groove modulation.

SURFACE NOISE

Two, at least, of the factors that contribute to "surface noise" have their origin in the playback process itself. One stems from the stick-slip nature of sliding friction, the other from the microscale intermittency of plastic flow. To single these out for discussion is not, of course, to deny the importance of such troublesome sources of noise as dust lodged in the record groove, thermal agitation of the cutting stylus, lead-screw vibration transmitted to the cutting head, turntable bearing noise, and so on. The control or elimination of these troubles must be accomplished *before* playback, however, since the pickup, if it is to be honest, must reproduce these unwanted groove modulations just as faithfully as it does the signal modulation.

Vibration of the pickup stylus induced by frictional drag *ought* not to be transduced into an electrical output signal, but few pickups are proof against this kind of vibrational stimulus to an adequate degree. The effective coefficient of friction for a sapphire stylus on unfilled vinylite, at conventional loadings, may lie in the range between 0.2 and 0.5, and hence very small departures due to tangency and other alignment errors can produce lateral force components that are far from negligible. According to modern theories, the tangential force of friction has its origin in the shearing stresses required to break the bonds of adhesion established across the interfacial areas of real contact. These bonds can sometimes be as strong as the cohesive forces that hold the material itself together, as in the contact of similar dry, clean metals; or they may be extremely weak, as in the case of contact between Teflon and almost anything else. The adhesion can never vanish entirely, however, even for materials as dissimilar as sapphire and vinylite, since there is bound to be some interpenetration, on the atomic scale at least, in the regions of real contact.

One consequence of the foregoing is that the contribution of each local true-contact area to the friction force will always be of the stick-slip variety. That is to say, each asperity will first "stick," then progressively experience elastic deformation in shear produced by the gross sliding motion, until finally the shear stress becomes high enough to produce another "slip" either by rupturing the asperity or by causing the adhering surfaces to separate. The total force of friction will thus represent a statistical summation of the stick-slip contributions from all the local areas of real contact. This inherent "graininess" of the force of friction is closely analogous to the "graininess" of the electron current in temperature-limited thermionic emission. In view of this analogy, the surface noise arising from this cause might be called a frictional "shot effect"; and like the electronic shot effect, it will have a "white," or uniform, spectral distribution whose spectrum level will be directly proportional to the total "current"—in this case the total number of "slips" per second. It follows that this component of noise will be abated by anything that reduces the net frictional drag, such as lubrication(!) or a choice of materials having lower interfacial adhesion. Who will be the first to produce a pressing (or a stylus) with a Teflon surface? More immediate relief from this cause of surface noise is to be found, however, in a mere reduction of the stylus loading. The coefficient of friction appears to drop to substantially lower values when the medium underlying the surface asperities is not stressed beyond its elastic limit, and this effect combines with the reduced normal force to yield a compound reduction of the tangential force of friction.

What is probably the most important residual factor contributing to surface noise is that originating in the mechanism of plastic yielding. Even materials as nearly amorphous as record plastics must be conceived to "flow" by a process involving the slipping of molecular aggregates from one position of equilibrium with their neighbors to another. In elastic deformation, to point up the contrast, no atom is strained to move beyond the continuing influence of its neighbors and each returns to its original equilibrium site when external stress is removed; in fact such complete recovery is the essence of *elastic* strain. At the atomic, molecular, or macromolecular size level, however, the mechanism of plastic yielding takes the form of a volumetric version of stick-slip behavior, and must be regarded as inherently discontinuous in microscopic detail even though it appears in statistical summation to be continuous. A homely illustration of this type of behavior is available to anyone who can recall how it feels to thrust a stick slowly into wet sand—a revealing analogy suggested to me in 1941 by R. M. Morris during our naive discussion of what we promptly dubbed the "crunch-crunch theory of surface noise."

A good bit of study has been devoted to the slip phenomena occurring in metals but, as usual, information bearing on phonographic materials is conspicuously missing. As a matter of fact, it may well be that the techniques of phonograph playback applied to metal molds made of materials that have already been studied theoretically would yield new and useful grist for the solid-state physicists' mill. Pending further enlightenment from that quarter, however, it seems safe to presume that the energy of the noise arising from this source must vary in some way with the cohesive forces of the record material (its hardness, perhaps?) and with the total volume of material deformed plastically by the stylus. Moreover, two components of this "crunch" noise can be identified: one that varies with the static loading of the stylus and is always present even in the absence of groove modulation, and one that corresponds to the periodic plastic flow induced by the dynamic force reactions arising from groove modulation. The latter component constitutes a modulation noise, or "noise behind the signal," of the type whose elimination yields a welcome improvement in the so-called "cleanness" of reproduction. Fortunately, both of these noise components can be eliminated completely by the straightforward expedient of avoiding the conditions of static and dynamic stylus loading that induce plastic flow.

CONCLUSIONS

The simple moral of this tale is that plastic yielding of the record material under the conventionally loaded stylus is primarily responsible for a deplorably high rate of stylus wear and record wear, and for at least three identifiable components of playback surface noise. Quantitative estimates of shaky precision but undeniable trend suggest that a five-to-one reduction of pickup bearing weights and a ten-to-one reduction of dynamic stylus loading will yield a relatively spectacular extension of both stylus life and record life, and a substantial reduction of surface noise; and that these benefits will yield a secondary improvement of average distortion levels that now soar due to the complacent retention in service of styli long since worn flat. Scattered, but reassuring, experimental evidence confirms the feasibility of achieving these predicted improvements.

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