Comments on the Paper, "On Stylus Wear and Surface Noise in Phonograph Playback System"*

D. A. Barlow†

When a set of conclusions is reached in a study as fundamental as this, it is certain that particular factors have been accepted as a part of the working hypothesis essential to the formulation of conclusions which are open to challenge by another student of the subject. Mr. Barlow's studies, like those of Prof. Hunt, are thorough and represent another view of the same subject.

Almost inevitably, the points of departure in such cases become the focal points for study by all concerned. The process of further investigation usually results in the collection of additional test data that removes the subject from the realm of scientific speculation, and places it within the established body of knowledge of the art. Readers wishing to offer supporting or different viewpoints of their own for publication are invited to address them to the Editor. Such comments are especially welcome.

The recent paper by F. V. Hunt, "On Stylus Wear and Surface Noise in Phonograph Playback Systems," is of great interest and importance, as are all his researches. With great ingenuity he has utilised a hypothetical size effect to explain indentation test results and the very low rate of stylus and record wear which he obtained with his pickup. I would like to suggest that there is an alternative explanation of these results.

Figure 2 of Prof. Hunt's paper (the graph presents indentation track-width measurements) gives the basic results which require explanation. Prof. Hunt considers that the upward trend in apparent hardness with decreasing load is a genuine increase in hardness of the material, following Shaw (reference 6 in the original paper‡). However, much of Shaw's evidence for a size effect operating over appreciable areas is unconvincing and will be discussed later. The alternative explanation is that the apparent increase in hardness is due to elastic springback of the material. The values of p_m in Fig. 2 represent the Load/(Area after removing load, or plastically deformed area). If there is appreciable elastic springback, hardness values will be misleading. Thus for very low loads, deformation of any material will be entirely elastic, as governed by the Hertz equations quoted by Prof. Hunt, and the apparent hardness will be infinite. With increasing load, plastic deformation begins below the surface at point 0′, Fig. 4 (original paper), surface deformation in contact with the indenter being still elastic; an apparently infinite hardness will still be obtained and no track will be visible, although slight elastic distortion of the surface might remain after removing the indenter, due to the residual stresses induced in the surface by the subsurface plastic deformation. Eventually, this subsurface deformation will reach the surface, and visual surface evidence of plastic deformation will appear; most of the area in contact with the indenter will still be elastic, and the hardness value, based on the plastic contact area, will be high. With further increase in load, plastic deformation extends until it covers the whole of the contact area (the condition described as "full plasticity" in Fig. 11 of the original paper) above which minimum load correct hardness values will be obtained. The point at which this occurs will depend on the amount of elastic recovery of the material, i.e., on the yield stress and the elastic modulus. Tabor§ (reference 5 in the original paper§) states that for work-hardened mild steel, the minimum load for full plasticity (M in Fig. 11 of the original paper) is 100 to 200 times that for the beginning of plastic deformation. However, there is no reason to suppose that this factor will be the same for other materials showing higher springback, as is assumed for vinyl in Fig. 11. The results of Fig. 11 can be explained either by assuming a 5-fold increase in yield stress over the bulk yield stress of the record material, or by a 3- to 5-fold increase in the suggested, but unknown, minimum load for full plasticity.

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* The original paper, by F. V. Hunt, appeared in the Journal of the Audio Engineering Society, 3, 2–18 (January 1955).
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† 132 Bloxham Road, Banbury, Oxon, England.
‡ Milton C. Shaw, "A Yield Criterion for Ductile Metals Based Upon Atomic Structure," *J. Franklin Inst.*, **254**, 109–126 (1952).

§ D. Tabor, *The Hardness of Metals,* Chapters II and IV–VI, Clarendon Press, Oxford, 1951.

In Fig. 1 of the original paper, for the 1-mil radius stylus, a dividing line is given at about 6 grams between tracks showing "piling up" at the edges and those showing "sinking in." The piled-up condition obviously represents the state of full plasticity, as otherwise no such rim could be formed; ordinary Brinell hardness tests confirm that at the highest loads, when full plasticity must exist (and no size effect can operate) piling up is obtained on vinyl. The sunk-in condition can occur in some materials even in the fully plastic state, but the condition depends on the shape of the stress-strain curve and both conditions could hardly occur simultaneously in the same material. However, the sunk-in condition can occur if a portion of the contact area is still in the elastic condition under load, suggesting that the minimum load for full plasticity, and hence for reliable hardness values with the 1-mil radius stylus, is at least 6 grams. This agrees with the hardness results in Fig. 2.

In using the size-effect hypothesis, a 5-fold increase in yield stress is required with the 1-mil-radius stylus; for the 3-mil stylus, a 35-fold increase would be required, i.e., a yield stress of 250 kgs per square millimeter. This is greater than that obtained on the very finest vinyl fibers, finer than the track widths being considered, and this strength increase in fibers is known to be due to preferred orientation of the molecules. A further objection to the size-effect explanation is that, for a given track width, e.g., 8 microns, when any size effect should be similar for both stylus radii, the 3-mil stylus is required to give a yield stress about 6 times greater than the 1-mil stylus. Elastic springback is a more likely explanation, as it is known to be greater for larger-radius indenters (for a given load or plastic track width). Also, in the case of a size effect based on the presence or absence of flaws, the results obtained for small sizes will be very variable, according to whether the area contains a flaw or not. Presumably the tracks obtained for a given load did not vary appreciably in width.

The calculation of the minimum load for full plasticity and the hardness values to be expected at lower loads is impossible at present, and results can only be obtained by large-scale tests. It would be very interesting to carry out an indentation test, using an indenter radius of, say, 10 in. or more, to give appreciable contact areas at very low loads in the elastic range, to see if results are obtained similar to those set forth in Fig. 2 of the original paper for plastic contact areas, and decreasing hardness with decreasing load for (plastic + elastic) contact areas. In this way, the influence of elastic springback could be determined with reasonable accuracy without the hypothecated presence of any size effect and decisive evidence would be obtained for or against a size effect. If large slabs of transparent vinyl could be obtained for the tests, the area of impression while under load could be visually determined very easily, and the development of surface and subsurface deformation could be followed, using photo-elastic methods. An alternative method of measuring total contact areas would be by means of radioactive-tracer technique.

It is just conceivable that the results of Fig. 2 could be explained by the "skin" of the vinyl's being harder than the core, due to moulding conditions. Doubtless this possibility has already been considered.

DETECTION OF TRACKS

Prof. Hunt has apparently detected no tracks narrower than about 8 microns. Figure 3 of the original paper shows one of these tracks near the "no trace" limit, having a width of 9.5 microns. The magnification of this microphotograph is about 60 diameters. This is a very low power, and tracks of this width can be seen with the naked eye; it would be interesting to know if higher powers of magnification have been used to detect tracks at lower loads. The limit of resolution of the light microscope is about 0.2 micron and that of the electron microscope 0.002 to 0.02 micron, depending on the particular technique employed; tracks of that order of width might be detected. X-rays might also be used. In this way, the curves of Fig. 1 might be extended beyond their present limits, perhaps into the "no trace" region.

In order to avoid all plastic deformation of vinyl (in the absence of any size effect) a load of only 11 milligrams must be used on a 1-mil radius stylus, or 99 milligrams for a 3-mil radius stylus. Now, the maximum shear stress at the surface of contact with the indenter at the moment of subsurface yielding is only about 0.37 of the shear yield stress. Just to obtain plastic deformation at the surface, the load must be raised by some considerable factor, probably greater than $\left(\frac{1}{0.37}\right)^3$ times, i.e., greater than 0.22 gram for the 1-mil radius stylus and greater than 2 grams for the 3-mil radius stylus. It is quite possible that Prof. Hunt's pre-war pickup, with a 2.85-mil-radius stylus and 5- to 7-gram load was near the critical point, and would give appreciable subsurface plastic deformation but no surface damage. A more usual pickup, with 15-gram load, would give a trace of about 30 microns width, which represents a considerable amount of damage.

PLASTIC DEFORMATION

During the initial playing of a record, the stylus will plastically deform the groove until it has sufficient area and has been sufficiently work hardened to support the stylus without further deformation. On further playing, following exactly the same track, there would normally be no further plastic deformation and no component of surface noise due to slip or discontinuous plastic deformation. The damage is done on the first playing and there is no means of telling what the virgin record would sound like. It would therefore be possible, as in manufacturers' claims, to have a record which, after 1000 playings, sounds similar to the first playing, although, in fact, it may be horribly mutilated (on the first playing only). On repeated playing there may be very slight further deformation for several reasons:

1. *Plastic recovery.* After playing, the material may plastically recover slightly towards its original shape, and will be deformed again on playing. This effect will be very small and will disappear after a few playings.

2. *Creep, or cold flow.* Under high stresses in the plastic range, slight creep of the material may take place at each playing and may eventually become serious after a very large number of playings.

3. *Fatigue.* Repeated stressing of a material below its fracture stress may lead to eventual fracture. For very low stresses, fracture will never occur; at intermediate stresses, millions of repetitions (i.e., millions of playings) will be required to give failure; at high stresses, few repetitions only may be required. Failure will take place by cracking or flaking, giving a pitted surface; as pitting develops, surface noise will increase.

Factors 2 and 3 would partly explain the progressive deterioration of records which occurs with heavy pickups. It should be noted that there is radial tension in the material under an indenter, and although this is lower than the compressive stresses present, the fatigue strength in tension may be lower than that in compression.

When operating in the range of subsurface deformation only, subsurface fatigue may eventually take place, if a sufficient number of repetitions are ever reached. Ball races frequently fail in this manner.

WEAR

In frictional wear, due to welding, shearing and ploughing of asperities, high local temperatures are often reached; thus, melting of the asperities may occur, giving a burnishing action like the facets of the groove cutter. Under heavy loads the stylus will cause serious melting and damage; the material adjoining the contact surface may become hot and thus weaker, further increasing wear.

In the fully plastic range, as in normal indentation hardness testing, the maximum possible coefficient of friction between the contacting surfaces is about $\frac{0.5}{3} = 0.167$. The normal pressure is about three times the yield stress and the real contact area closely approaches the apparent area; in the worst case, the whole of the contact area would be welded, so that any attempt to slide the indenter over the surface would involve shearing of the whole contact area of the specimen, which would require a stress of about 0.5 times the yield stress. Most commercial pickups operate in this range, and although the value of the coefficient of friction may not seem high, considerable frictional wear will take place. Even with a polytetrafluorethylene record (in the fully plastic range) with a coefficient of friction of about 0.04, 25% of the surface of contact is welded. Polytetrafluorethylene is the obvious choice for records, except for its cost; if it were used, its low yield stress would be a disadvantage, although this could be increased by cold rolling; also, the modulus might be rather low, leading to excessive elastic deformation, giving distortion, even if wear were low.

It seems that for low loads on most materials, diamond generally gives a coefficient of friction of around 0.1, sapphire, 0.2. On this basis, diamond might be expected to give lower wear than sapphire, depending on whether shearing of welds takes place at the junctions or in the record material. Since the rate of wear of the diamond is so low, there may also be less wear of the grooves by stylus attritus. In this connection, it is known that serious wear by stylus particles takes place when a steel stylus is used.

SIZE EFFECT

As already indicated, the size effect is unlikely to operate over the relatively large apparent area of contact with the stylus, but the effect may exist over smaller areas, e.g., those asperities which do not contain flaws. In this way, a light pickup which avoids plastic deformation of the surface will have a comparatively small area of real contact, giving a very low rate of frictional wear. A small increase in load, just exceeding the increased yield stress of the asperities, will cause flattening, giving a large area of real contact and a sudden increase in wear rate. This, together, perhaps, with lower friction or less perfect welds at lower loads, could explain the low rate of stylus and record wear observed by Prof. Hunt. Low surface noise would also result.

The size effect could also operate for the asperities of highly finished metal surfaces. The bulk strength of a metal is lower than the theoretical strength because of the presence of dislocations or imperfect spacings of the atoms forming the lattice structure. The high strength of the whiskers referred to by Prof. Hunt is due to the special mode of formation which results in the absence of dislocations (apart from a particular longitudinal one which does not affect the longitudinal properties). The presence of even a few dislocations in a large metal crystal will cause yielding in the same manner as for large numbers of dislocations, so that there will be no statistical size effect as for Griffith cracks in glass. However, the spacing of dislocations is of the order of 150 Å.U. and it is possible that, if an asperity were sufficiently small so as not to contain a dislocation, its strength would be the theoretical value. It is just conceivable that the hills and hollows of a highly finished metal surface are due to the local absence, or presence, respectively, of a dislocation.

Glass is about the only material in which a statistical size effect operating over large areas of the order postulated by Prof. Hunt is definitely established; thus, commercial glass fibers as large as several mils diameter show a strength increase of up to 50 times that of the bulk material, due largely to the absence of surface flaws (which have been detected) by virtue of the drawing process. Glass records might thus be very interesting, particularly if produced in such a manner as to avoid surface flaws, although the very act of playing would probably produce flaws.

The objection to the notion of a size effect operating over appreciable areas is that such an effect would be noticeable in fine fibers, quite apart from preferred orientation. Most of the results quoted by Prof. Shaw as evidence of a size effect, such as microhardness tests, strength of brazing metal, fatigue test results etc., are more readily explained by other means or are definitely known to be due to other causes. Moreover, Shaw's own evidence on the nature of plastic flow in metals shows that a size effect could be operative only over areas smaller than about 0.8 micro-in., to quote his own figures; yet he apparently obtains a size effect only by assuming that the surface layer is free from flaws and by ignoring the known behavior of the imperfections or dislocations which he invokes. Further, in Morrison's work, on which Shaw's yield criterion is largely based, the size effect was not due to a stronger surface layer (it was, in fact, weaker than the bulk material) but was a characteristic of the steel used, due to the presence of an upper and lower yield point. Very few other materials show this type of yield—certainly not plastics—and, in any case, it could account only for a very small increase in apparent yield strength with decreasing size; also, this effect does not operate for all stress conditions and may not operate in the case of the stress conditions obtaining under an indenter.

SHELLAC RECORDS

No mention has been made so far of shellac records. Their high hardness will tend to reduce damage, but the high modulus may offset this by giving very small areas of contact. A few tests suggest that visible tracks are formed by a 2.5-mil sapphire stylus at loads appreciably less than 3 grams, i.e., at low loads the material is subject to more serious damage than vinyl; at high loads, say 20 grams, the track width is no greater than it is for vinyl and will be less for higher loads. Also, the rate of frictional wear may be less for shellac than for vinyl by reason of the hard filler used in the case of the former. This would account for conflicting reports concerning the relative damage and wear of shellac and vinyl records.

LUBRICATION

This may not be quite as ludicrous as it would seem. The shortest wavelength likely to be recorded would be 20 kc at a diameter of 4¾ in. and a speed of 33⅓ rpm, equivalent to ½ mil (if it could be traced). The thickness of an adsorbed lubricant film for thin film lubrication can be as low as 1 to 2 molecules, so that the groove would be traced without appreciable distortion, due to the lubricant film. With a sufficiently viscous hydrodynamic lubricant, the high frequencies might be obscured; however, a thinner lubricant could be chosen to give a hydrodynamic film of suitable thickness, but this would be rather messy. Graphite has been used as a lubricant by the fiber-needle school, but it would probably not be adsorbed onto the record and therefore would be useless; any large particles trapped under the stylus would give noise. An adsorbed surface film would thus be most suitable. By using a suitable volatile carrier, the very small amount of liquid which it would be necessary to wipe onto the record before each playing would quickly dry off. A suitable carrier might be a light petroleum fraction and the lubricant could be a small percentage of soap, or better, a calcium-petroleum-sulphonate compound, as a strongly polar lubricant is required to give adequate adsorption. Some detergents used as anti-static agents are somewhat akin to the latter compound, so that limited lubrication is perhaps already being used unconsciously.

CONCLUSIONS

The main comments may be summarized as follows:

1. The apparent increase in hardness at low loads may be explained by elastic recovery, rather than by a size effect, especially since, for a given size, the strength would have to be much greater for a 3-mil stylus than for a 1-mil stylus. Prof. Hunt's results are exactly of the type to be expected from the known mode of deformation of a material under a spherical indenter.
2. Results of indentation tests could be extended by examining tracks under a high-power microscope, the electron microscope, and perhaps by X-rays.
3. Between the fully elastic condition and the appearance of surface tracks there is a region where all plastic deformation of the record is subsurface. This is a practical range for pickup design, with the obvious advantage of negligible plastic deformation of the groove surface.
4. The size effect is unlikely to operate over large areas but could apply to asperities, thus explaining the low wear and noise of Prof. Hunt's pickup.