The Limiting Tracking Weight of Gramophone Pickups For Negligible Groove Damage*

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It has been observed that when spherical styli are dragged over flat vinyl surfaces, scratches are produced under loads considerably exceeding the elastic limit as calculated from theory. The author, in this paper, describes the results of his experiments which bear out his argument that under load the point of yield begins below the surface; and reaches the surface, producing visible tracks, only after the calculated yield load is exceeded.

This critical value of load for styli of various radii has been measured and found to be equivalent to, for a 1-mil stylus, 0.64 gm. for a 90° record groove. No size or skin effect was found with the vinyl material tested.

INTRODUCTION

In a recent paper(1), Prof. F. V. Hunt described scratch tests in which 1 mil and 3 mil radius styli were dragged over flat vinyl surfaces. There was a critical load below which no track was observed. This limiting load was very much greater than the elastic limit, calculated from the Hertz equations for the contact of a sphere with a flat surface, and Hunt therefore suggested that the vinyl material exhibited a size effect, such that small volumes of material, like that in contact with a stylus, would have a higher elastic limit than the bulk material. The present author has argued(2) that this size effect is unlikely and is an unnecessary hypothesis, and that Hunt's results represented the expected behavior of a material under a spherical indenter. Thus, at the calculated yield load, the point of yielding is below the surface, the surface remaining elastic; as the load is increased, the yielded area spreads and will eventually reach the surface and produce visible tracks at some very much higher load, this being the limiting load which Hunt observed. The present paper describes loading tests in support of this. The practical importance of this critical load is obvious, as it represents the limiting tracking load below which damage done to the record groove wall will be negligible.

LOADING TESTS

The author has suggested(3) that the limiting load for no surface plastic deformation of a flat vinyl surface by a 1 mil radius stylus is above 0.33 gm from theoretical considerations and below 0.75 gm from Hunt's results, corresponding to 0.4 – 1 gm for a 90° record groove. The following tests were carried out to determine this load more accurately.

A 1 mm radius hardened steel Brinell ball was used as the indenter on pieces cut from vinyl records, although if large slabs of vinyl had been available, a larger radius indenter would have been used. The sphericity of the ball was checked at numerous points under the interference microscope, as a slight flat would have seriously affected results. The loads ranged from 1 gm to 15 kg, thus covering the fully plastic, intermediate, and elastic ranges. Loads of 5 kg and above were applied by means of a Vickers hardness testing machine; lower loads were applied by means of direct loading of a lever, sensitive to about 5 mg at the lower loads.

By applying a thin surface film, *e.g.*, of carbon or metal, the total contact area (plastic + elastic) under load is given by the area of film removed by the indenter. A vacuum deposited aluminum film, about 1000 A.U. thick, was found to give a readily visible track, although it is open to the possible objection that the film might be hard enough to influence results at low loads. Another possible objection to this method is that electrostatic attraction may cause particles from the film immediately adjacent to the contact area to adhere to the indenter, giving a high value for the track width; this seems unlikely and could doubtless be avoided by earthing the indenter where this is conducting. A further and more serious objection is that results will be inaccurate when the impression depth approaches the film thickness; in the present case, this only occurs below about 10 gm load on the 1 mm radius indenter, which is below the range in which the chief interest lies. It was found that by smearing a finger over the surface, a satisfactory thin film of grease was formed, on which traces could be readily detected; Fig.

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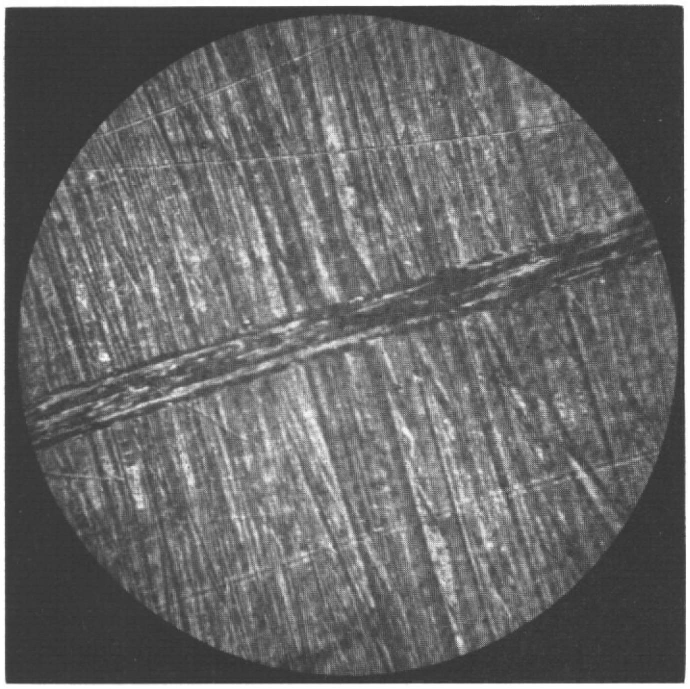

FIG. 1. Photograph of (elastic) track on vinyl left by 1 mm radius indenter under 1 gm load. Magnification × 250.

1 shows the trace given by a 1 gm load on the 1 mm radius indenter. The film thickness, as measured on the interference microscope, was about 1,000 A. U. By dissolving off the film with petroleum ether, the plastic tracks only were left and could then be measured. The grease served as an adequate lubricant to prevent pickup, as it was found that without a lubricant, a frictional trace, doubtless of particles of welded-on steel, could be seen on the vinyl even at the lowest loads, so that the distinction between elastic and plastic tracks was not clear.

In carrying out the tests, loading was started from the lowest load, so that grease adhering to the indenter from wide tracks would not affect the track width seen at lower loads, although a check starting from the highest load gave similar results, showing that this effect was not serious. The record was traversed slowly at each load, and the track width measured rather than the impression diameter, thus avoiding errors due to the impact of the indenter when being loaded, a frequent source of error in micro-hardness testing. At the higher loads (5 kg and above) where the Vickers machine was used, this type of error is negligible, and the impression diameter was measured in the usual way. All measurements were taken by means of the measuring microscope of the Vickers machine, the sensitivity being 1 – 0.2 μ, according to the objective used (⅔″, ¼″, and ⅙″). The means were taken of three sets of tracks and a check on a record from a different source gave similar results. For comparison purposes, results were expressed in terms of the equivalent values for a 1 mil radius indenter. In Fig. 2, equivalent track widths, both total and plastic, are plotted against equivalent load. No plastic tracks were visible at 0.45 gm and a trace could just be observed at 0.52 gm, although as with all plastic traces at low loads, the edges are not sharp. The limiting load for a 1 mil stylus may therefore be taken as about 0.45 gm, corresponding to 0.64 gm for a 90° record groove. Fig. 3, taken under oblique illumination, shows typical plastic tracks at equivalent loads of 1.29, 0.97, 0.64 gm, disappearing at 0.45 gm. Fairly large shallow tracks such as these, are often more easily detected by the naked eye than by the microscope, and are not easily photographed. Small changes in surface contour are known to be sensitive to phase-contrast illumination, but unfortunately this was not available.

It is interesting to note in passing, that a powerful light source, *e.g.* an arc, used on a projection microscope, produces sufficient heat to cause annealing of the vinyl at low magnifications and melting at higher magnifications, in spite of the presence of the water cell, which is supposed to absorb the heat. On metal specimens, no trouble is experienced, doubtless due to the high thermal conductivity, but for vinyl, the exposure time was limited to about 10 minutes at the lower magnifications. The effect of annealing on vinyl and many other plastics is to cause the plastically deformed molecules to revert to their original positions, *i.e.* plastic tracks disappeared leaving a flat surface almost unchanged from the original. This suggests a possible method of reconditioning damaged records.

SIZE EFFECT

In order to determine if there was a size effect, loading tests were repeated on 2.5 and 1 mil radius sapphire styli, and the plastic track width results are plotted for comparison in Fig. 2. It will be seen that within the expected scatter of results, there is no size effect, although the point at which tracks dissappeared is less easy to detect on a small scale.

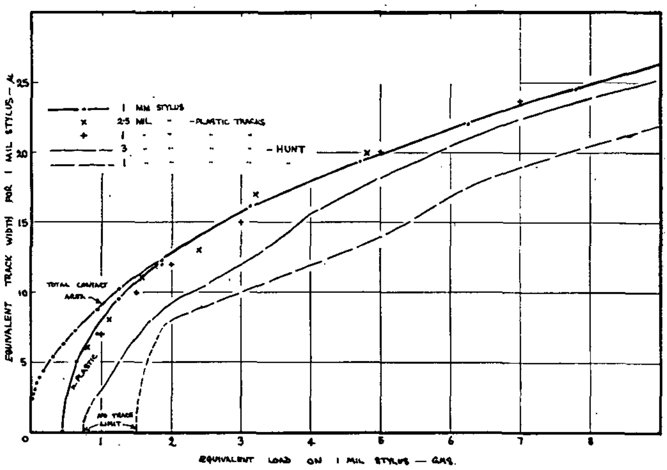

FIG. 2. Graph of equivalent track width *vs* equivalent load for 1 mil radius stylus on vinyl.

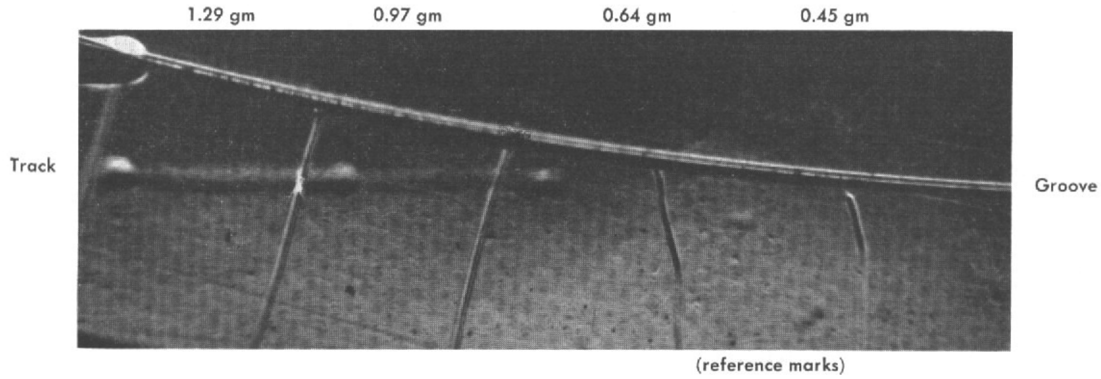

FIG. 3. Photograph of plastic tracks on vinyl, left by 1 mm radius indenter under equivalent loads on 1 mil radius stylus of 1.29 gm, 0.97 gm, 0.64 gm, disappearing at 0.45 gm. Magnification × 10.

The contact pressure, calculated as $\dfrac{4 \times \text{load}}{\pi \times (\text{track width})^2}$ kg/mm^2, versus the load is plotted in Fig. 4 for both total and plastic track widths. It will be seen that if the total contact area under load is taken, the curve passes through the origin, as would be expected. However, if the plastic track width only is taken, the curve takes a sharp upward turn with decreasing load; this again is to be expected, as, if the load is low enough, the stresses will be entirely within the elastic range, there will be no plastic track and a meaningless value of infinity will be obtained for the contact pressure or hardness. It seems that this apparent increase in hardness or contact pressure with decreasing load led Hunt to suggest the size effect theory.

Hunt's results are plotted for comparison in Figs. 2 and 4, and are appreciably different from the present values. This may be due to the materials being from different sources, Hunt's material being generally harder. However, although there is no size effect in the present material, and although the apparent increase in hardness at low loads is seen to be a bogus one, the fact remains that under the 1 mil stylus, Hunt's vinyl is harder than under the 3 mil indenter. This might be a skin effect. Thus if the skin of the vinyl is harder than the interior, the shallow impressions of the 1 mil stylus will give a greater hardness than the deeper impressions of the 3 mil stylus. For a comparison between impressions of different widths and depths, an indenter giving geometrically similar impressions at all loads must be used. The Vickers diamond pyramid is one such indenter (this consists of a square pyramid with an included angle of 136° between opposite faces). This was used on the present material with loads of 1–50 gm, the diagonals of the pyramid being at 0° and 90° to the track, Fig. 5. The contact pressure was calculated as $\dfrac{2 \times \text{load}}{(\text{track width})^2}$ and values are plotted in Fig. 6. This shows that there is no skin (or size) effect in the present material. As the Vickers diamond is sharp, impressions at all loads are in the fully plastic range, where all the material in contact with the indenter is plastic, and

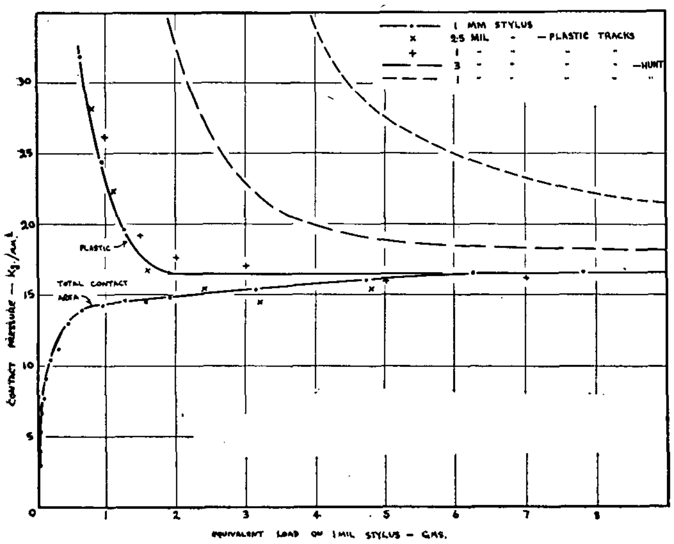

FIG. 4. Graph of contact pressure *vs* equivalent load for 1 mil radius stylus on vinyl.

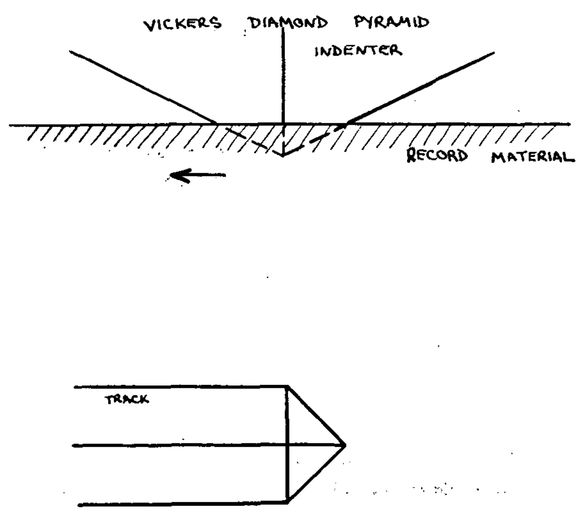

FIG. 5. Mode of producing tracks with Vickers diamond pyramid indenter.

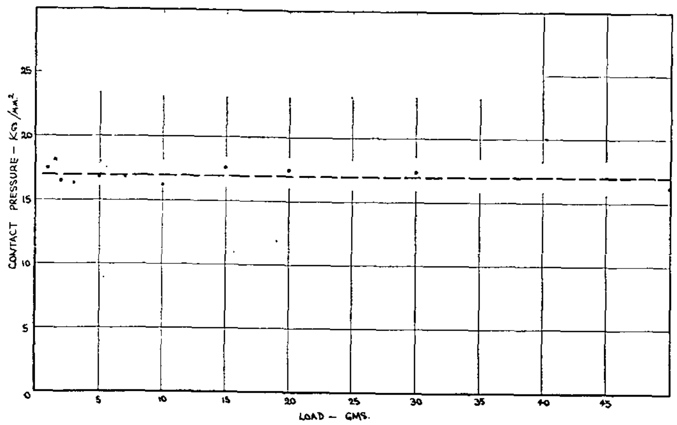

FIG. 6. Graph of contact pressure *vs* load on Vickers diamond pyramid indenter on vinyl.

reliable and comparable hardness values are obtained at all loads; values are always slightly higher with a pyramid than with a spherical indenter.

A harder skin on vinyl could arise in two possible ways. Thus, mechanically polishing the surface might give a work-hardened or oriented layer. Alternatively, in molding, the different conditions at the surface of the mold might give rise to an oriented or more highly polymerised skin; where a plasticizer is used, it is known that under some conditions, a hard skin can be obtained due to the plasticizer at the surface being depleted or rendered ineffective, although the grades of vinyl used for records do not usually contain a plasticizer.

MECHANICAL TESTS

The mechanical properties of the material used in these tests were determined from tensile and bend tests on small test pieces cut from the record. The yield stress coincided with the ultimate tensile stress, after which the material necked down considerably before fracture. The neck formed at one point and then travelled along the test piece at constant load until fracture. The sudden yield and the fibrous appearance of the fracture were doubtless due to the orientation of the previous random molecules, as occurs with some other plastics. The elastic modulus was obtained from a bend test, using a simple cantilever and measuring the deflection with a travelling microscope. This was much more accurate than direct measurement on a tensile test piece, where the accuracy is limited by the short gauge-length and the lack of reliable small extensometers. Values of 300 kg/mm^2 for the modulus and 4.75 kg/mm^2 for the yield stress were obtained, which agree with the plastic manufacturers data, giving the calculated limiting elastic load for a 1 mil stylus on a flat surface of 12.6 mg, compared with Hunt's value of 11 mg.

CONCLUSIONS

1. The increase in hardness with decreasing load reported by Hunt is an apparent one only, due to using the plastic instead of the total contact area in calculating the hardness.
2. The elastic limit of the present material is about 13 mg with a 1 mil radius stylus on a flat surface; the limiting load for all plastic deformation to remain subsurface is about 0.45 gm, corresponding to 0.64 gm for a 1 mil stylus in a 90° record groove.
3. A size effect hypothesis is unnecessary, as the vinyl behaves as would be expected under a spherical indenter.
4. Loading tests with 1 mil, 2.5 mil, 1 mm radius, and pyramid indenters show that there is no size or skin effect on the present material.
5. The differences between Hunt's results for the 1 mil and 3 mil radius styli might be due to the skin of his material being harder than the interior.

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