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# STUDIES ON REDUCING THE SURFACE FRICTION OF ELASTOMERS

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## ABSTRACT

Methods for reducing the surface friction of elastomeric vulcanizates have been investigated, and frictional data have been obtained on polytetrafluoroethylene coatings sprayed from aqueous dispersions onto elastomeric vulcanizates.

Compounding polytetrafluoroethylene (TFE) resing with neoprene and silicone elastomers produced vulcanizates having inferior physical properties with no decrease in surface friction.

Polytetrafluoroethylene coatings on elastomer vulcanizates provided surfaces having low coefficients of friction, which adhered sufficiently well for many applications although they are not as durable as similar coatings on metal. Lower values for the coefficient of sliding friction between metal/elastomer surfaces were obtained by coating the elastomer surface with TFE than by coating the metal surface; no further decrease in the coefficient of friction was obtained by coating both surfaces.

The surface frictional characteristics of TFE coated vulcanizates were essentially independent of the hardness of the vulcanizate, in marked contrast to the behavior of uncoated elastomers. Similarly, the frictional behavior of coated elastomers was virtually independent of the thickness of the elastomer substrate.

## PROBLEM STATUS

This is an interim report on one phase of the problem; work on the problem is continuing.

## AUTHORIZATION

NRL Problem C04-03
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# STUDIES ON REDUCING THE SURFACE FRICTION OF ELASTOMERS

## INTRODUCTION

Numerous investigators in recent years have studied the frictional behavior of elastomers. The bulk of their endeavors has been directed toward understanding the influence of this behavior on the skidding characteristics of tires and toward deriving suitable mechanisms for the frictional behavior under these conditions. Interest in the frictional behavior of elastomers has been stimulated within the Defense Department in recent years because of incidences of failure of rubber components in weapons systems which were believed to be related to their surface frictional characteristics. Consequently, this Laboratory has initiated a program to develop methods for producing low-friction elastomeric surfaces. The techniques which are described in this report include: (a) the incorporation of materials into the bulk elastomer by compounding, and (b) the coating of vulcanized elastomer surfaces with an adherent thin layer of a dry lubricant.

Significant reduction of the surface friction of elastomeric vulcanizates has been attained by the latter technique using polytetrafluoroethylene (TFE), although greater adhesion of the coatings would be desirable. For some applications, however, the coating may adhere well enough to be useful. Work is being continued to improve the adhesion and cohesion of these coatings. Attempts to improve the frictional properties of the elastomers by compounding were unsuccessful.

The successful lamination of polytetrafluoroethylene fabrics to elastomer substrates to provide a tough, durable surface having a low coefficient of friction has been described in an earlier report (1).

## COMPOUNDING ELASTOMERS WITH POLYTETRAFLUOROETHYLENE RESINS

The compounding of elastomers with materials having low coefficients of friction such as oils, greases, and graphite will produce vulcanizates having reduced frictional properties. However, the amount of these additives required to affect even a marginal improvement so diminishes the physical properties of the finished product that the practical applications of these compounds are severely limited. If a material could be found which would reduce the surface frictional properties and not appreciably affect the physical quality of the vulcanizate, such an approach would be attractive. The extremely low friction properties of polytetrafluoroethylene are well known, but there is little work disclosed in the literature on compounding this material with elastomers. Consequently, this approach to producing low-surface-friction elastomers was attempted initially with neoprene and silicone compounds.

### Neoprene-Polytetrafluoroethylene Resin Compounds

Teflon 1 polytetrafluoroethylene resin, a granular molding powder having a particle size in the range of 30 mesh, was milled into a neoprene GNA masterbatch recipe shown in Table 1 in concentrations of 10 to 30 parts per hundred parts of rubber (phr) by weight and compression molded and cured in a tensile mold. Although the resin milled in readily, the cured stock had a grainy like character which was attributed to the "poor wetting" of the TFE particles by the neoprene compound. This was further evidenced by the erratic tensile strength and elongation-at-break values obtained for different specimens of the same compound. Moreover, the TFE resin-filled neoprene vulcanizates did not exhibit any observable improvement in slip characteristics over the control as determined empirically by hand-rubbing the specimens with a polished steel ball.

### Silicone Compounds

Considerable difficulty was experienced in the milling operation when TFE resins were added to a silicone elastomer because of the low strength of the silicone compound. In many instances the compound could not be banded on the mill prior to loading the tensile mold because the cohesive strength was so low. Addition of reinforcing silica filler (HiSil 233) tended to improve this condition slightly, but agglomeration of the TFE resin particles occurred when more than 10 phr of silica was added to Union Carbide W-97 silicone stock, and further milling resulted in the formation of TFE fibers. This phenomenon was not observed with the neoprene stocks, and no TFE fibrillation was evident in the silicone stock in the absence of silica. Apparently, without the reinforcing silica, the cohesive strength of the silicone stock was too low to hold the TFE agglomerates together long enough for the shearing action of the mill to pull the TFE out into fibers. Fibrillation occurred in the silica-filled stocks with both the Teflon #6 and #7 resins, although the latter, a very small particle size resin (ca. 35$\mu$), produced much shorter fibers than the former resin. The fibrillated TFE was distributed nonuniformly throughout the compound, and the stock had a marblelike appearance with the fibers oriented in the machine direction. The TFE was completely encapsulated in the silicone elastomer matrix with essentially none protruding from the surface, so that even where a large local concentration was evident no significant change in the frictional characteristics could be observed.

In attempts to improve the wetting of the TFE resins by the silicone elastomer, various materials were incorporated in the stock prior to the TFE resin additions. These included DC200 and DC510 silicone fluids, Kel-F 10/200 and 40 waxes, Triton X-100, and a Fluorolube heavy grease. All of these additives produced vulcanizates with poor physical properties without any improvement in slip characteristics. Intimate mixing of these "dispersing agents" with the TFE resins prior to milling them into the silicone elastomer produced essentially the same results. Neither was the surface frictional behavior changed significantly by compounding either the Kel-F waxes or the fluorocarbon grease by themselves into the silicone elastomer. This work tends to substantiate a recent study by Galwardy and Krivitsky (2) which showed that compounding materials having low coefficients of friction such as greases, waxes, graphite, and molybdenum sulfide into elastomers resulted only in marginal benefits.

Because of the lack of promising results, the compounding approach was discontinued and the effort was concentrated on developing a durable coating on the vulcanizate of a material having a low coefficient of friction.

## POLYTETRAFLUOROETHYLENE COATINGS ON ELASTOMER VULCANIZATES

The use of thin films of polytetrafluoroethylene as a dry lubricant for metal surfaces has found wide application in recent years. The Naval Research Laboratory pioneered in this field and also contributed substantially to the development of practical spray techniques for applying the coatings from aqueous dispersions of polytetrafluoroethylene resins and to improving the high temperature sintering process which provided adherent, durable, continuous films (3).

The adaptation of the dispersion spray-sintering techniques for the utilization of polytetrafluoroethylene as low-friction coatings on rubber has presented problems because of the markedly different nature of the elastomeric substrate as compared to metal substrates. Obviously the rubber substrates could not sustain the high temperatures (700° to 750°F) required to fuse the coatings to continuous films, and it is this step in the process which provides much of the cohesive strength and adhesion necessary for durable films on metals. However, coatings of polytetrafluoroethylene have been applied to elastomers to provide a low friction surface which may be sufficiently durable for many applications even though they do not match the durability of the sintered films on metals. For example, O-rings coated at this Laboratory with sprayed TFE were tested as piston seals for certain automatic devices under development at the David Taylor Model Basin and the results indicated a solution to a critical friction problem existing in these systems (4).

The sprayed TFE coatings are discontinuous (Fig. 1) but there is some evidence that the discontinuity may not be a disadvantage on a substrate having the high elasticity of rubber. It has been observed that the fine agglomerates of resin tended to adhere to the substrate when the specimen was flexed or elongated severely, whereas a thin film of Teflon cemented to a rubber substrate was permanently stretched and pulled free from the rubber whenever the specimen was similarly treated (1).

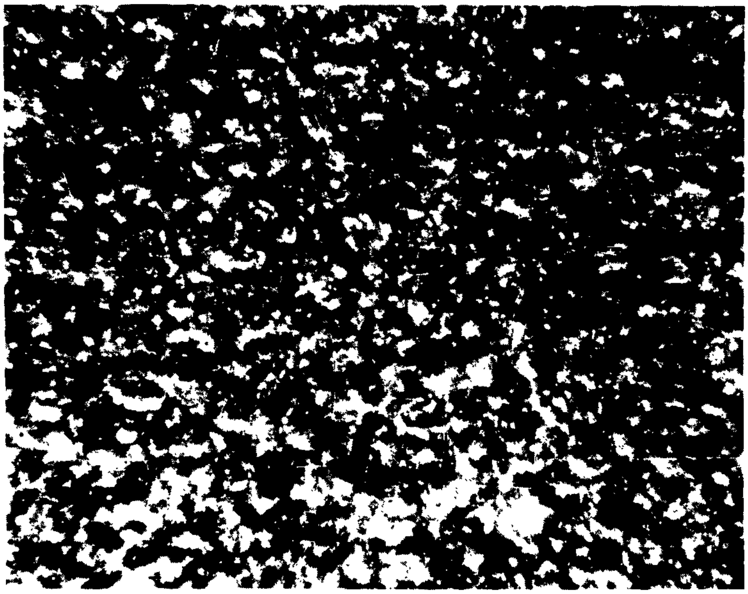

Fig. 1 - Photomicrograph of a typical TFE coating on an elastomer substrate applied from a TFE aqueous dispersion by spraying. Magnification 73X.

## Method for Measuring Surface Friction

Numerical values for the coefficient of friction of uncoated and TFE coated rubber specimens were obtained with a modified Bowden-Leben Stick-Slip apparatus. Essentially, this machine measures the frictional force generated between a steel sphere and a flat specimen surface. A description of the apparatus is contained in Appendix A. This equipment has been used successfully at this Laboratory for frictional studies on bulk plastics and on thin lubricant films on metals, but this was the first time the equipment had been used for studies with elastomers. Where the frictional forces were low, such as those generated on vulcanizates coated with TFE, the values for the coefficient of friction were reproducible on the same specimen within ±0.02 unit. However, measurements made on uncoated vulcanizates, where the frictional forces were high, were considerably less reliable because of certain design limitations of the apparatus which are explained in Appendix A. The values for the coefficients of friction reported for uncoated vulcanizates, therefore, represent at best, rough approximations which are useful only for gross comparative purposes.

From the recorded frictional force and the load normal to the two surfaces the coefficient of kinetic friction $\mu_k$ was calculated assuming, as for plastic solids, that

$$\mu_k = \frac{F}{W} \tag{1}$$

where $F$ is the tangential force and $W$ the load normal to the two surfaces.

The viscoelastic nature of elastomers in contrast to the essentially plastic character of metals introduces complexities so that the laws of friction of Amonton and Coulomb do not always apply depending on the conditions of the experiment. A number of modifications of Eq. (1) for the frictional force have been proposed in recent years for viscoelastic materials. The scope of this report, however, does not permit a discussion of the various theories propounded, and the reader is referred to a comprehensive review by Conant and Liska (5) which covers the work in this field up to 1960.

Nevertheless, the simple friction equation (Eq. 1) will be used here to give approximate values for the coefficient of friction which were found useful for comparative purposes within a single experiment.

## Experimental Coating Methods and Materials

The polytetrafluoroethylene coatings were applied from commercial aqueous dispersions to neoprene substrates compounded from the recipe in Table 1. Rubber test specimens, 1 x 2 x 0.075 inch, were die stamped from 6 x 6 inch sheets that had been formed and cured in a highly polished tensile mold. The specimens were arranged in a suitable rack and the coating applied with a DeVilbiss P-EGA-502 hand spray gun fitted with a No. 390 air cap. The coated specimens were then air dried overnight followed by heating in an oven at 50°C for two hours. At intervals on the rack a metal blank was inserted which was covered in the same spray sweep as the test specimens and this coating was assumed to be the same thickness as the coating on the rubber. The thickness of the steel blank was measured with a micrometer before and after coating. This procedure was used because of

Table 1
Neoprene GNA Masterbatch Recipe Used For Elastomer Friction Experiments (35-Minute Cure at 307°F)

| Formulation (phr) | |
|---|---|
| Neoprene GNA | 100.0 |
| Stearic acid | 0.5 |
| Magnesium oxide | 4.0 |
| Zinc oxide | 5.0 |
| Neozone A | 2.0 |
| P-33 carbon black | 50.0 |

Physical Properties
Tensile strength - 1900 psi.
Elongation at break - 800%.
Hardness - 60 (Shore A).

the inability to measure accurately the coating thicknesses on the elastic rubber. An alternative and preferred method was to weigh the rubber specimen on a balance before and after coating. The average thickness of the coating was then calculated from this data, assuming a density of 1.47 g/cc for the TFE. The values for the coating thicknesses obtained by the two methods checked within a tenth of a mil. Efforts were made to obtain a coating thickness of approximately 0.3 mil for all of the experiments.

The proprietary aqueous TFE resin dispersions which were used for coating the rubber vulcanizates had been formulated specifically for application to metals. It was understood that in addition to dispersing agents, certain chemicals were present which were intended to react with metals to provide limited adhesion to the substrate before sintering; then this adhesion was enhanced by the heating process. The chemical compositions of the dispersions were unknown and whether the additives promoted, hindered, or had no effect on the adhesion of the coatings to the rubber can only be speculated at this stage of the investigation.

From their physical appearance and some difficulties experienced in the spraying operation, it seemed that the dispersions varied appreciably in composition from one batch to another. This necessitated experimentation with each batch to obtain optimum coating conditions and reproducible results. The dispersions also had a relatively short shelf-life of about three to four months before the TFE particles agglomerated into aggregates which clogged the spray gun. The useful life of the dispersions could be extended somewhat by storing them in a refrigerator. It was discovered also that less clogging of the gun occurred, and the coatings were more uniform, if spraying was continued without stopping until all the specimens were covered. All of the coating friction data described in this report were obtained with duPont 851-204 TFE-Fluorocarbon Resin One-Coat Enamel.

The elastomer specimens were cemented to 1 x 4 x 0.250 inch steel plates for measurement of the frictional forces. The specimen surfaces were cleaned thoroughly with n-hexane (99 mole percent minimum purity), and stored in a desiccator prior to the measurements. The 1/2-inch-diameter, 440C stainless steel balls used with Bowden-Leben apparatus were cleaned by refluxing in thiophene-free C.P. benzene in a Soxhlet Extractor. The spheres thereafter were handled only with platinum-tipped tongs.

### Comparison of Coated and Uncoated Surfaces in an Elastomer/Metal System

It has been suggested that since TFE coatings on rubber cannot be sintered without destroying the rubber substrate, the same results would be achieved by utilizing a sintered coating of TFE on the metal component of the system in contact with the rubber part. Mitigating against this is the fact that the metal parts are often machined to precision tolerances and it is doubtful that they would sustain the high sintering temperatures without permanent changes in their dimensions or temper. In an attempt to ascertain the relative advantages of coating either the elastomers or the metal surface, a series of frictional measurements were made with the Bowden-Leben apparatus between sintered TFE-coated and uncoated metal spheres and unsintered TFE-coated flat rubber vulcanizates. The TFE coating on the steel ball was sintered by heating in an oven at 400°C for 25 minutes and quenching in cold water. A load of 800 grams was applied normal to the two surfaces and the coefficient of friction was measured for 50 cycles (one cycle is equal to two slides, one in each direction) at a sliding speed of 0.1 cm/sec over a track 1 cm in length.

The results of these measurements are shown in Table 2; within the conditions of the experiment, it would appear that substantially better lubrication results from coating the rubber component than by coating the metal part. Neither does it appear that

Table 2
Comparison of Coated and Uncoated Surfaces in an Elastomer/Metal System

| Number of Slides | Coefficient of Kinetic Friction | | | |
|---|---|---|---|---|
| | System A<br>Uncoated Steel Ball<br>Uncoated Rubber Flat | System B<br>Uncoated Steel Ball<br>Coated Rubber Flat | System C<br>Coated Steel Ball<br>Uncoated Rubber Flat | System D<br>Coated Steel Ball<br>Coated Rubber Flat |
| 1 | 2.0 | 0.30 | 0.44 | 0.33 |
| 5 | 2.5 | 0.25 | 0.44 | 0.30 |
| 25 | 2.2 | 0.22 | 0.44 | 0.28 |
| 50 | 2.0 | 0.25 | 0.44 | 0.28 |
| 75 | 1.9 | 0.28 | 0.47 | 0.25 |
| 100 | 1.8 | 0.28 | 0.50 | 0.25 |

*Test Conditions
Normal load - 800 g.
Speed of slide - 0.1 cm/sec.
Length of slide - 1 cm.

any advantage is gained by coating both surfaces, since the measured $\mu_k$ of System B and D are essentially the same. Examination of the TFE-coated ball (System C) after 50 cycles showed only slight wear of the dry lubricant film. Little if any wear could be observed when the uncoated steel sphere was cycled on the TFE-coated vulcanizate. As well as could be ascertained, a polishing action is the only manifestation of wear after 50 cycles. No transfer of TFE from the coated rubber to the uncoated ball was observed, even under microscopic examination. To verify this observation further, a fresh steel ball was cycled 15 times in both directions (30 slides) on the TFE-coated rubber specimen. The coated rubber specimen was then replaced with a polished steel flat and the coefficients of friction determined; first, using the same area on the ball that had been in contact with the TFE surface in the previous run and secondly, between fresh clean areas on the ball and the steel flat. A lower value for the coefficient of friction in the first case as compared to the second should have been a manifestation of the transfer of TFE from the coated specimen to the steel ball; however, the values were practically the same in both instances, indicating no transfer of TFE to the ball or transfer of so little that it was immediately removed on contact with the steel flat.

## Effect of Elastomer Hardness on the Frictional Properties of Uncoated and TFE-Coated Elastomers

The frictional forces between a hard solid and a flat rubber surface are influenced by the hardness of the rubber since this determines to a large extent the area of contact between the two surfaces. There is also less deformation, and therefore less dissipation of energy in elastic hysteresis, when a solid rides on a hard rubber than on one which is softer. It was of interest to determine the effect of this property on the frictional forces between a spherical slider and rubber surfaces coated with a dry lubricant such as polytetrafluoroethylene.

Two neoprene GNA compound formulations were selected which gave a wide spread in hardness. The recipes and physical properties of the cured rubbers are listed in Table 3. The standard procedure was used to coat and to mount the specimens for the friction measurements with the Bowden-Leben apparatus. Measurements were made with an 800-gram load, a sliding speed of 0.1 cm/sec, and for 50 cycles over a 1-cm-length track.

Table 3
Formulations and Physical Properties of Compounds for the Determination of the Effect of Elastomer Hardness on Frictional Properties (35-Minute Cure at 307°F)

| Formulation | A(phr) | B(phr) |
|---|---|---|
| Neoprene GNA | 100.0 | 100.0 |
| Stearic acid | 0.5 | 0.5 |
| Magnesium oxide | 4.0 | 4.0 |
| Zinc oxide | 5.0 | 5.0 |
| Neozone A | 2.0 | 2.0 |
| Carbon black E.P.C. | 14.6 | 87.7 |

Physical Properties - A
Tensile strength - 4750 psi
Elongation at break - 760%
Hardness - 51 (Shore A)

Physical Properties - B
Tensile strength - 3892 psi
Elongation at break - 150%
Hardness - 94 (Shore A)

Table 4 lists the values for the coefficients of friction obtained on specimens 85 mils thick. Although the Shore A hardness of compound B was almost twice that of compound A the values for the coefficients of friction of the TFE-coated specimens were essentially the same. Uncoated vulcanizates of these two compounds, however, displayed a pronounced difference in frictional properties with the coefficients of friction of compound A, the softer specimen, being approximately two times greater than those of compound B. This indicates, at least under the conditions of this experiment, that hardness influences substantially the frictional

Table 4
Effect of Elastomer Hardness on the Coefficient of Kinetic Friction of TFE-Coated and Uncoated Vulcanizates*

| Number of slides | Coefficient of Kinetic Friction | | | |
|---|---|---|---|---|
| | Compound A (Low Durometer) | | Compound B (High Durometer) | |
| | Coated | Uncoated | Coated | Uncoated |
| 1 | 0.13 | 2.5 | 0.10 | 1.1 |
| 5 | 0.13 | 2.1 | 0.09 | 1.1 |
| 25 | 0.17 | 2.1 | 0.15 | 1.1 |
| 50 | 0.18 | 2.1 | 0.17 | 1.1 |
| 75 | 0.19 | 2.2 | 0.16 | 1.0 |
| 100 | 0.19 | 2.1 | 0.15 | 1.0 |

*Test Conditions:
Normal load - 800 grams.
Speed of slide - 0.1 cm/sec.
Length of slide - 1 cm.

characteristics of vulcanized elastomers as expected, but the frictional coefficient becomes essentially independent of this property when an elastomer is coated with a dry lubricant such as TFE.

### Effect of Elastomer Thickness on the Frictional Properties of Uncoated and TFE-Coated Elastomers

A related variable which probably influences the frictional forces between a hard solid and an elastomer mounted on a hard substrate is the thickness of the elastomer layer. The deformation and hysteretic losses of the elastomer may contribute a substantial part of the total frictional force and these factors, as well as the area of contact, in turn are governed in a large part by the relative amounts of pressure sustained by the elastomer and the hard substrate. Bowers, Clinton, and Zisman (6) have shown with thin plastic films on metals that the thin films are able to withstand high pressures because the metal substrate bears the greatest part of the load. Thus the thickness of the elastomer layer should influence its frictional behavior. This thickness-friction relationship may be altered by a lubricant layer interposed between the two sliding surfaces. In order to determine these effects, a series of frictional measurements were made on TFE-coated and uncoated elastomer specimens mounted on steel blocks. Film thicknesses ranged from 25 to 150 mils.

The specimens for determining the effect of the elastomer thickness on the coefficient of friction were vulcanized and molded in place on the steel blocks using the standard neoprene compound recipe given in Table 1 and Ty-Ply S cement. The TFE-coated specimens were prepared in the usual way and the conditions for the frictional measurements followed those previously used.

The values for the coefficient of kinetic friction listed in Table 5 indicate that the thickness of the vulcanizate does influence the sliding frictional forces between a steel sphere and uncoated rubber surfaces in a manner similar to that of increasing the elastomer hardness; i.e., an elastomer layer has its "apparent" hardness increased by a hard backing, the effect increasing, within limits, as the elastomer thickness decreases. Significantly lower values were obtained on the 25 mil specimen than those obtained on the 85 and 150 mil specimens. However, this effect is manifested only over a limited range of thicknesses, since the frictional coefficients for the last two specimens were essentially the same.

Table 5
The Effect of Elastomer Specimen Thickness on the Coefficient of Kinetic Friction of Uncoated and TFE-Coated Neoprene GNA Vulcanizates*

| Number of Slides | Coefficient of Kinetic Friction | | | | | |
|---|---|---|---|---|---|---|
| | 25 mils | | 85 mils | | 150 mils | |
| | Run 1† | Run 2† | Run 1† | Run 2† | Run 1† | Run 2† |
| Uncoated Neoprene Vulcanizates | | | | | | |
| 1 | 1.7 | 1.6 | 2.6 | 2.4 | 2.4 | – |
| 5 | 1.5 | 1.5 | 2.1 | 2.1 | 2.1 | – |
| 25 | 1.5 | 1.3 | 2.1 | 2.1 | 2.1 | – |
| 50 | 1.5 | 1.3 | 2.1 | 2.1 | 2.1 | – |
| 75 | 1.4 | 1.3 | 2.1 | 2.2 | 2.2 | – |
| 100 | 1.5 | 1.3 | 2.0 | 2.3 | 2.2 | – |
| TFE-Coated Neoprene Vulcanizates | | | | | | |
| 1 | 0.15 | 0.13 | 0.14 | 0.13 | 0.13 | 0.13 |
| 5 | 0.14 | 0.12 | 0.16 | 0.13 | 0.15 | 0.14 |
| 25 | 0.15 | 0.17 | 0.18 | 0.16 | 0.18 | 0.16 |
| 50 | 0.13 | 0.16 | 0.19 | 0.15 | 0.16 | 0.16 |
| 75 | 0.14 | 0.15 | 0.19 | 0.15 | 0.16 | 0.16 |
| 100 | 0.14 | 0.16 | 0.20 | 0.15 | 0.17 | 0.17 |

*Test Conditions
Normal load - 800 g.
Speed of slide - 0.1 cm/sec.
Length of slide - 1 cm.
†Duplicate runs were made on separate areas of the same specimen.

The values obtained with the TFE-coated vulcanizates were approximately the same for all three of the thicknesses as shown in Table 5. There is evidence in the literature (7-10) that in lubricated sliding any adhesion between the two surfaces is reduced to a very low value and the principal sources of friction are the work required to deform the rubber and the hysteretic losses sustained during sliding. Although these factors possibly were influenced somewhat by the different substrate thicknesses, the deformation and hysteretic effects apparently were not great enough over the range of substrate thicknesses, the load, and velocity of slide included in the experiment to produce a significant difference in the frictional behavior of the coated elastomers.

## CONCLUSIONS

Data obtained in a study of the surface frictional behavior of elastomers and techniques for improving the slip-characteristics of elastomeric vulcanizates have demonstrated that:

1. Compounding elastomers with polytetrafluoroethylene resins produces vulcanizates having inferior physical properties with no significant decrease in surface friction.

2. Polytetrafluoroethylene coatings applied to vulcanizate surfaces from aqueous dispersions by spray techniques provide surfaces having low coefficients of sliding friction which, while not as durable as similar coatings on metal, adhere sufficiently well for many applications.

3. Lower values for the coefficient of sliding friction are obtained between metal/elastomer surfaces by coating the elastomer surface with TFE than by coating the metal surfaces; no further decrease in the coefficient of friction was obtained by coating both surfaces.

4. Hardness of the elastomer substrate of TFE-coated vulcanizates over a range of 50-90 durometer (Shore A) does not appear to significantly affect the surface frictional characteristics, whereas, hardness substantially influences the frictional behavior of uncoated elastomeric vulcanizates.

5. Varying the thickness of the TFE-coated-elastomer substrate mounted on a hard support from 25 to 150 mils does not influence significantly the surface frictional characteristics. The thickness of the rubber specimen does affect the frictional properties of thin uncoated rubber surfaces, but this effect decreases rapidly as the elastomer thickness increases.

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## Appendix A

## THE NRL MODIFIED BOWDEN-LEBEN STICK-SLIP APPARATUS

An adaptation of the well-known Bowden-Leben Stick-Slip apparatus (A1) was constructed at this Laboratory and has been used extensively for studying the frictional behavior of bulk plastics and thin lubricant films on metal surfaces (A2-A4).

The apparatus is shown in Fig. A1 and consists of a Brown and Sharp No. 5 surface grinder modified so that the flat test specimen (A) is held in a jig mounted on the reciprocating table of the grinder. The spherical rider, a 1/2-inch-diameter 440C stainless steel ball, is attached to the end of a cantilever beam (B) which is secured in a steel housing (C) replacing the head of the grinder. An enlargement of the test specimen and cantilever arrangement is shown in Fig. A2. The load normal to the two

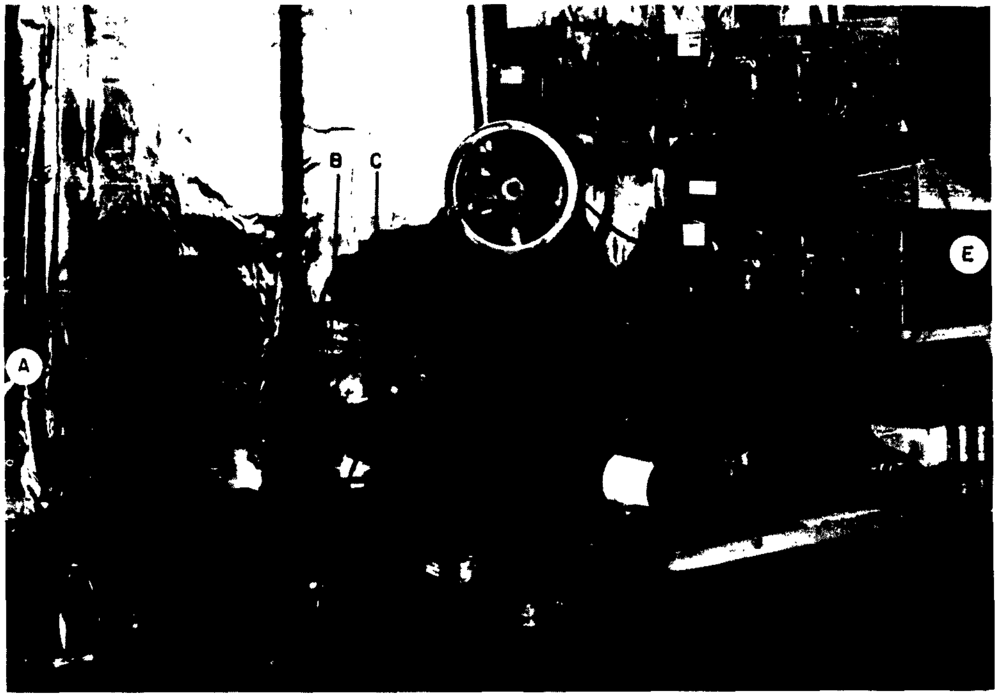

Fig. A1 - The NRL constructed Bowden-Leben Stick-Slip apparatus: (A) test specimen; (B) cantilever beam holding stainless steel ball slider; (C) steel housing replacing grinder head; (D) strain gauges; (E) Brush amplifiers and two-channel recorder.

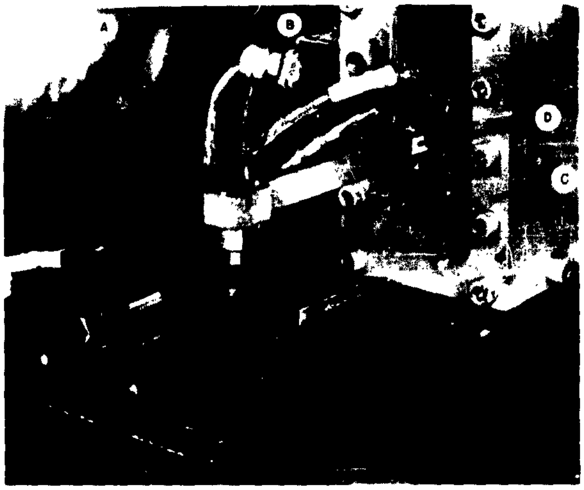

Fig. A2 - The test specimen and cantilever beam arrangement of Bowden-Leben Stick-Slip apparatus

surfaces is controlled by lowering and raising the housing so as to apply a bending moment to the cantilever beam. Strain gauges (D) attached to the cantilever beam and connected electrically through two Brush amplifiers to a two-channel recorder (E) continuously measure the frictional forces and the load normal to the two surfaces. A typical record of the kinetic frictional forces obtained with a steel ball sliding on TFE-coated rubber is shown in Fig. A3.

This investigation utilized for the first time the modified Bowden-Leben apparatus for studying the frictional phenomena of elastomeric surfaces. Where the frictional forces were low, as on lubricated surfaces, reproducible results were obtained. However, where high frictional forces exist, as on uncoated rubber, the results tend to be erratic as shown in Fig. A4. This is attributed to a slight torsional moment being produced in the cantilever arm which results in an apparent variation in load as the ball slides over the elastomer surface. Unsuccessful attempts were made in various experiments through use of static weights, etc., to obtain a correction factor for the cantilever arm action. Since such a correction factor was unobtainable, the values of the coefficient of friction were calculated from load data obtained by averaging the load values recorded for the particular slides from which data was being taken. Although the reliability of the frictional data obtained on uncoated rubber was not as great as that obtained on TFE-coated rubber, the values fell within the range ($\mu_k = 1$ to 4) cited in the literature for elastomers by investigators using other means of measurement.

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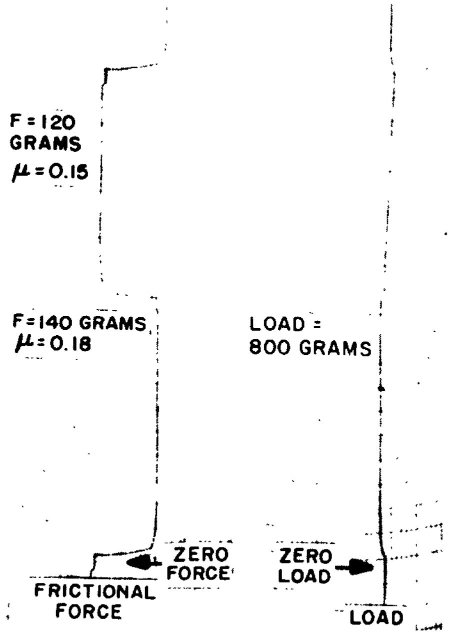

Fig. A3 - Typical recorder traces of the frictional force and normal load obtained with the NRL Bowden-Leben Stick-Slip apparatus on TFE-coated rubber vulcanizate

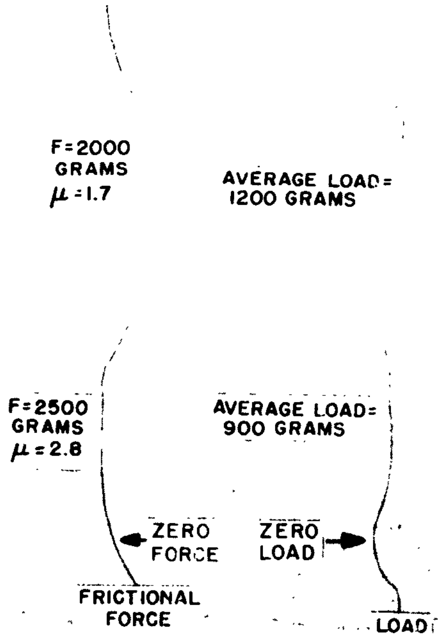

Fig. A4 - Typical recorder traces of the frictional force and normal load obtained with the NRL Bowden-Leben Stick-Slip apparatus on uncoated rubber vulcanizate

A3. FitzSimmons, V. G., and Zisman, W. A., "Thin Films of Polytetrafluoroethylene Resin (Teflon) as Lubricants and Preservative Coatings for Metals," NRL Report 4753, June 15, 1956

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Naval Research Laboratory. Report 5911.
**STUDIES ON REDUCING THE SURFACE FRICTION OF ELASTOMERS** by H. C. Nash and E. J. Kohn.
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Compounding polytetrafluoroethylene (TFE) resins with neoprene and silicone elastomers produced vulcanizates having inferior physical properties with no decrease in surface friction.

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The surface frictional characteristics of TFE coated vulcanizates were essentially independent of the hardness of the vulcanizate, in marked contrast to the behavior of uncoated elastomers. Similarly, the frictional behavior of coated elastomers was virtually independent of the thickness of the elastomer substrate.

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