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Friction and Abrasion of Aircraft Tire Tread Materials

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Friction and Abrasion of Elastomeric Materials

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Abstract

A description of a novel abrasion apparatus, patterned after one described by Champ, Southern and Thomas (1,2), is given. Experimental measurements are reported for four representative elastomeric materials, including a typical high-quality tire tread material (C) and a possible replacement material for aircraft tire treads (D) based on trans-polypentenamer (TPPR). Measurements have been carried out at different levels of frictional work input, corresponding to different severities of wear, and at both ambient temperature and at 100°C. Attention is drawn to several features of the results. A notable finding is the marked superiority in abrasion resistance of the material based on TPPR, especially at 100°C, in comparison with the other materials examined.

Introduction

The practical importance of the wear of rubbery materials does not need elaboration. Unfortunately, however, a detailed scientific understanding of abrasion has not yet been achieved. Tire tread materials, for example, have been developed on an empirical basis up to the present time. Although this procedure has been remarkably successful there is no way of knowing which directions will prove valuable for further improvements or on what basis to choose new polymers, fillers, crosslinking agents, etc., without expensive and protracted service tests. There is thus a clear need for understanding the mechanism or mechanisms of abrasive wear in order to be able to specify relevant test methods and to design rubber formulations in a rational way.

Recently, Champ, Southern and Thomas (1,2) have suggested that abrasive wear (at least, under particularly-simple abrasion conditions) is due to cumulative growth of cracks by tearing under repetitive loading, as in mechanical fatigue processes (3-5). They have shown that the dependence of the rate of abrasion upon the magnitude of the frictional force is broadly similar to the dependence of the rate of crack growth upon the magnitude of an intermittently-applied tearing force. Indeed, for several unfilled elastomers the two relations were found to be in good numerical agreement; a typical comparison is shown in Figure 1.

We have now carried out measurements of the rates of abrasion for a number of filled and unfilled elastomers using basically the same experimental methods as Champ, Southern and Thomas but using a somewhat wider range of experimental conditions. The results are presented here under two general headings: (i) the effects of test conditions, i.e., the magnitude of the frictional force applied to the abrading blade and the test temperature, and, (ii) the effect of the composition of the rubber.

Experimental Details

Cylindrical rubber wheels were prepared from a number of different mix formulations, given in the Appendix. The wheels were 63.5 mm in external diameter, 25.4 mm in internal diameter and 25.4 mm wide. They were cemented to aluminum hubs and abraded by rotating them against a stationary razor blade ("Schick Plus Platinum") pressed into the wheel surface. A sketch of the wear apparatus is shown in Figure 2.

The razor blade was held in a clamp at the end of a stiff cantilever beam, to which strain gauges were cemented. These gauges were so placed that independent measurements of the normal force N pressing the blade into the rubber surface and the transverse (frictional) force F were obtained simultaneously from flexure of different parts of the cantilever beam, as shown in Figure 3. It was thus possible to measure the effective sliding frictional coefficient μ at the same time as the rate of wear, although irregular fluctuations in both N and F prevented accurate determination of μ.

Measurements of wear were carried out with the frictional force F maintained approximately constant during the entire experiment. This was accomplished by adjusting the position of the cantilever support from time to time, by means of a micrometer screw. Wear measurements were carried out in this way for values of F ranging from 200 to 1600 N per m of wheel width, corresponding to frictional work expended of from 200 to 1600J per m^2 of wheel surface. Unless otherwise indicated all the experiments were carried out at room temperature, 23°C ± 3°C, and with the wheel rotating at 10 revolutions per minute, corresponding to a sliding speed of 33 mm/s. Under these conditions no significant temperature rise of the wheel surface was noted, even though up to about 2 calories of frictional work were expended per revolution.

The weight loss due to rubber abraded away per revolution of the test wheel was measured after steady-state wear conditions were attained. This took hundreds, and sometimes thousands, of revolutions, while the worn surface adopted a characteristic roughened texture, coarser at high frictional forces and finer at low ones. With a new razor blade the rate of wear was initially abnormally high but within a hundred revolutions or less this effect disappeared and the abrading power of the blade did not change subsequently during many thousands of revolutions. This initial effect is attributed to a lubricant film on new blades, which is rapidly removed under the present test conditions.

The loss in weight of the wheel per revolution was converted into a volume loss using the known density of the rubber compound (1000-1500 kg/m^3) and then by reference to the surface area of the test wheel, about 5×10^{-3} m^2, to a reduction in radial thickness per revolution.

A weight loss of 1 mg per wheel revolution corresponds to an average loss in rubber thickness of 0.2 μm, i.e., 2000Å, per revolution. The rates of wear observed ranged from less than 0.02 to 4.0 mg per revolution, i.e. from less than 40Å to 8000Å. For comparison, a normal automobile tire which loses about 5 mm in height of tread in, say, 30,000 km, suffers an average rate of wear of only about 5Å per revolution, while a typical aircraft tire may wear at a hundred times this rate.

Following Champ, Southern and Thomas,adhesive tape (3M Company Highland Brand No. 6200)was generally employed to remove particles of rubber which tended to cling to the surface of the wheel. This cleaning procedure was replaced by frequent brushing for other experiments, particularly those carried out at 100°C when cleaning with tape proved to be impractical.

Three different types of wear product could be recognized. The first, denoted dry particulate wear, consisted of fine or coarse particles of rubber apparently formed by tearing. These particles could be readily removed from the wheel with tape or by brushing, and in some instances were swept away by the blade itself in the form of a fine spray of rubber particles. A photomicrograph of a wear particle from material A is shown in Figure 4. The second mode of wear, denoted oily debris, consisted of particles of debris which appeared to have undergone partial decomposition to yield an oily liquid-like coating. An example is shown in Figure 5. In some cases the wear product was a sticky tarry substance which adhered to the wheel with great tenacity. It coated the wheel surface and effectively prevented further wear. This product has been denoted tarry coating.

Experimental Results and Discussion

(a) Effect of frictional force on rate of wear

As would be expected, the rates of wear depended strongly upon the frictional force exerted by the blade. At low levels of frictional force the wear was light, the worn surface was relatively smooth and the debris consisted of relatively small particles. At higher frictional forces the wear was rapid, the surface was much rougher in texture and the wear particles were larger, frequently exceeding 0.1 mm in mean diameter, Figures 4 and 5. Values of the steady-state rate of wear are given in Table I for the unfilled NR material A under various frictional forces. The apparent coefficient of friction $\underline{\mu}$, i.e., the ratio F/N of the mean frictional force exerted by the blade to the mean normal force pressing the blade into the wheel is also given in Table I. It is seen to decrease somewhat, with increasing frictional (and normal) load, as is commonly observed for frictional sliding (6).

The experimentally-measured rates of wear given in Table I are plotted in Figure 6 against the frictional work input per revolution of the wheel, using logarithmic scales for both axes. In this representation the results are described rather accurately by a linear relationship. This was also found to be the case for the unfilled SBR material B and for the filled SBR material C, although in the case of the latter material (and all other filled materials examined) the rates of wear at low frictional forces were too small to measure with reasonable precision and the linear relationship is therefore less certain.

The experimentally-determined relationships between wear A and frictional work F can thus be represented by the general result

$$A\ (m) = k\ [\ F\ (j/m^2)\ ]^n\ ,$$

where the coefficient k and exponent n are characteristic of the particular material being examined. The values obtained for materials A, B and C are given in Table II. For the unfilled materials A and B, the exponent n was found to be about the same, 2.28 ± 0.1, but for the filled material C it was considerably smaller corresponding to a lesser dependence of the rate of wear upon the frictional force for this material. Values of k and n have also been read from the experimental plots presented by Champ, Southern and Thomas (1,2); they are included in Table II for comparison with the present results. The linear relations obtained by Champ, Southern and Thomas appear to be generally steeper than the present ones, i.e., the exponent n is larger, although the rates of wear at a representative value of frictional force used in their experiments are generally in the same range as those obtained by us.

A noteworthy feature of the present wear relations (given in Table II) is that they extrapolate to a common value of about 5 Å wear under a frictional work input of 50 j/m^2. The threshold tear strength of elastomers appears to be about 50 j/m^2 (7) and it is therefore particularly interesting to find that the projected wear under this energy input is of the order of a molecular dimension for all three materials, even though the dependence of wear upon input energy above this level is quite different.

(b) Effect of temperature

Measurements on four materials have been carried out at room temperature (25°C) and also at 100°C in order to examine the effect of such a temperature change on the rates of wear. A thermostatted hot-air jacket was placed around the test wheel in order to achieve a steady ambient temperature of 100°C for the high-temperature measurements. It was not feasible to clean the wheels by means of adhesive tape at 100°C, and this cleaning method was not used at 25°C either, so that the results would be fully comparable. The wear results at 25°C are therefore slightly different from those reported in the previous section, being generally somewhat smaller because the present cleaning procedure was less efficient.

Four materials were examined in this way: A, unfilled NR; B, unfilled SBR; C, carbon black filled SBR; and D, carbon black filled TPPR (trans polypentenamer). The results are presented in Table III at two levels of frictional work input for each material at each temperature. They show a relatively small effect of temperature upon the rate of wear, ranging from hardly any effect for material D to an increase by a factor of about two for the SBR materials B and C. This relatively small effect of a large temperature rise does not seem to be consistent with a mechanical fatigue mechanism of abrasion as proposed by Champ, Southern and Thomas, because the rate of growth of fatigue cracks is greatly increased by a temperature rise of this amount, by orders of magnitude for SBR materials (8).

(c) Effect of composition

The rates of wear given in Tables I-III are strikingly different for the different materials. This is made clear by considering the rates of wear at a given frictional work input, say 1.6 kj/m^2, at 25°C. Values for the unfilled materials A and B are obtained by extrapolation; the results are 1400 nm and 700 nm, approximately. For the filled materials C and D the measured rates are 80 nm and 44 nm, respectively. Thus, a range of over 30-fold is found in the rates of wear of different materials under similar wear conditions. To what degree these differences can be ascribed to differences in tensile strength, tear strength and fatigue properties, or to differences in resistance to chemical changes, remains to be established. It should be pointed out that the frictional properties are not greatly different, however. Values of the frictional coefficient $\underline{\mu}$ given in Table III show the expected reduction with increase in temperature and increase with carbon black loading, but they are otherwise rather similar for the four materials.

The wear debris from materials A, B and D were rather similar in character, consisting of dry particulate matter. For material C, however, the debris showed clear indications of chemical decomposition, Figure 5. This observation agrees with that of Boonstra, Heckman and Kabaya [illegible] They reported that under mild wear conditions a typical tire tread was converted into a sticky, apparently-degraded, surface layer. This apparent difference in wear mechanisms for different materials merits further study. We are therefore continuing with measurements on a number of other rubbery materials, involving changes in mix formulations as well as in the elastomer itself, in order to examine the role of these variables on the rate of wear under uniform wear conditions and the mechanism of wear.

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Appendix

The mix formulations in parts by weight and vulcanization conditions used for preparing test wheels are given below:

A: Unfilled NR material

SMR - 5L (NR)	100.00
Zinc Oxide	5.00
Stearic Acid	2.00
PBNA	1.00
Santocure	0.60
Sulfur	2.5

Vulcanized for 50 min at 145°C

B: Unfilled SBR material

Firestone FRS - 1502 (SBR)	100.00
Zinc Oxide	5.00
Stearic Acid	2.00
PBNA	1.00
Santocure	1.00
Sulfur	2.00

Vulcanized for 60 min at 150°C

C: Carbon black filled SBR material

FRS - 1502 (SBR)	100.00
Cabot HAF Vulcan 3 (N330 carbon black)	54.00
Zinc Oxide	5.00
Stearic Acid	2.00
PBNA	1.00
Santocure	1.00
Sulfur	2.00

Vulcanized for 60 min at 150°C

D: Carbon black filled TPPR material

Trans-polypentenamer	100.00
RPA No. 6(a)	0.07
Cabot HAF Vulcan 3, N330	50.00
Zinc Oxide	5.00
Stearic Acid	2.00
PBNA	2.00
Philrich HA5 (Oil)	7.50
Sulfur	0.50
Sulfasan R	1.50
Santocure Mor	1.00

Vulcanized for 45 min at 295°F (145.8°C)

(a) Pentachlorothiophenol (E.I. du Pont de Nemours and Co.)

Table I. Measured rates of wear A under steady-state conditions *vs* frictional work F per revolution for unfilled NR material A at room temperature.

F (kj/m^2)	A (nm/rev)	μ
0.2	14	1.55
0.3	28	1.53
0.4	75	1.35
0.6	205	1.36
0.7	290	1.36
0.8	395	1.20

Table II. Experimentally-determined relations between rate of wear A and frictional work F for various materials at room temperature

Material A (unfilled NR)

$$A\ (m) = 8.5 \times 10^{-14} [\ F\ (j/m^2)\ ]^{2.28}$$

Material B (unfilled SBR)

$$A\ (m) = 5.7 \times 10^{-14} [\ F\ (j/m^2)\ ]^{2.28}$$

Material C (filled SBR)

$$A\ (m) = 1.5 \times 10^{-12} [\ F\ (j/m^2)\ ]^{1.58}$$

Results of Champ, Southern and Thomas (1,2)

Material 1 (unfilled isomerized NR)

$$A\ (m) = 2.5 \times 10^{-17} [\ F\ (j/m^2)\ ]^{3.65}$$

Material 2 (unfilled SBR)

$$A\ (m) = 1 \times 10^{-15} [\ F\ (j/m^2)\ ]^{2.72}$$

Material 3 (unfilled ABR)

$$A\ (m) = 9.5 \times 10^{-19} [\ F\ (j/m^2)\ ]^{3.5}$$

Table III. Measured rates of wear A at 25°C and 100°C for various materials

Temp. (°C)	F (kj/m^2)	A (nm/rev)	μ
A, unfilled NR			
25	0.4	60	1.40
100	0.4	32	1.00
25	0.6	150	1.44
100	0.6	190	1.18
B, unfilled SBR			
25	0.4	24	1.78
100	0.4	68	1.62
25	0.6	82	1.58
100	0.6	195	1.37
C, filled SBR			
25	0.8	16	2.05
100	0.8	22	1.35
25	1.6	80	2.10
100	1.6	240	1.50
D, filled TPPR			
25	0.8	16	1.80
100	0.8	18	1.35
25	1.6	44	2.0
100	1.6	44	1.4

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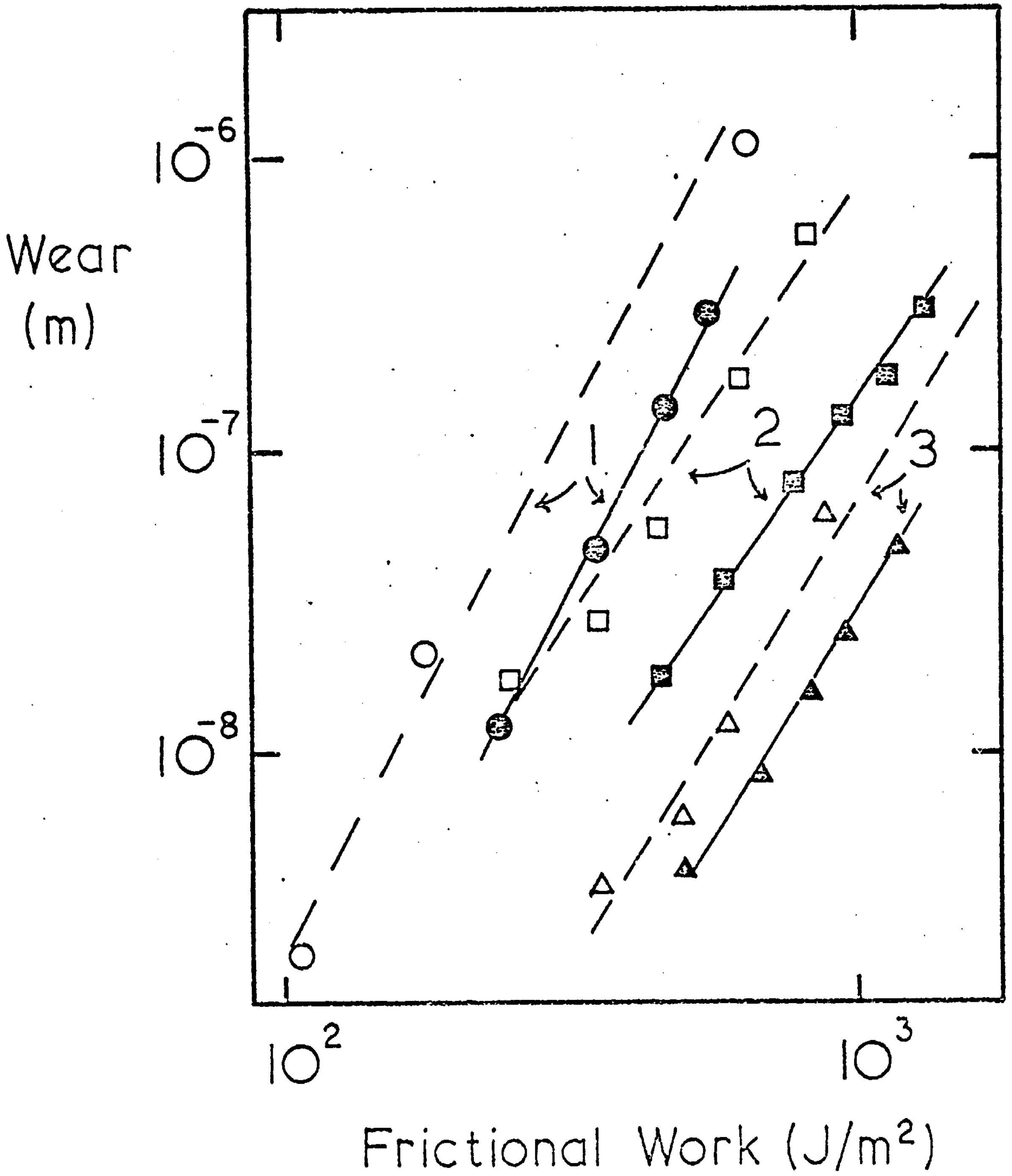


Figure 1. Rates of wear (filled-in points) plotted against frictional energy input and rates of tear propagation (open points) plotted against tear energy input for three rubbery materials: 1, isomerized NR; 2, SBR; 3, ABR (data taken from reference 1).

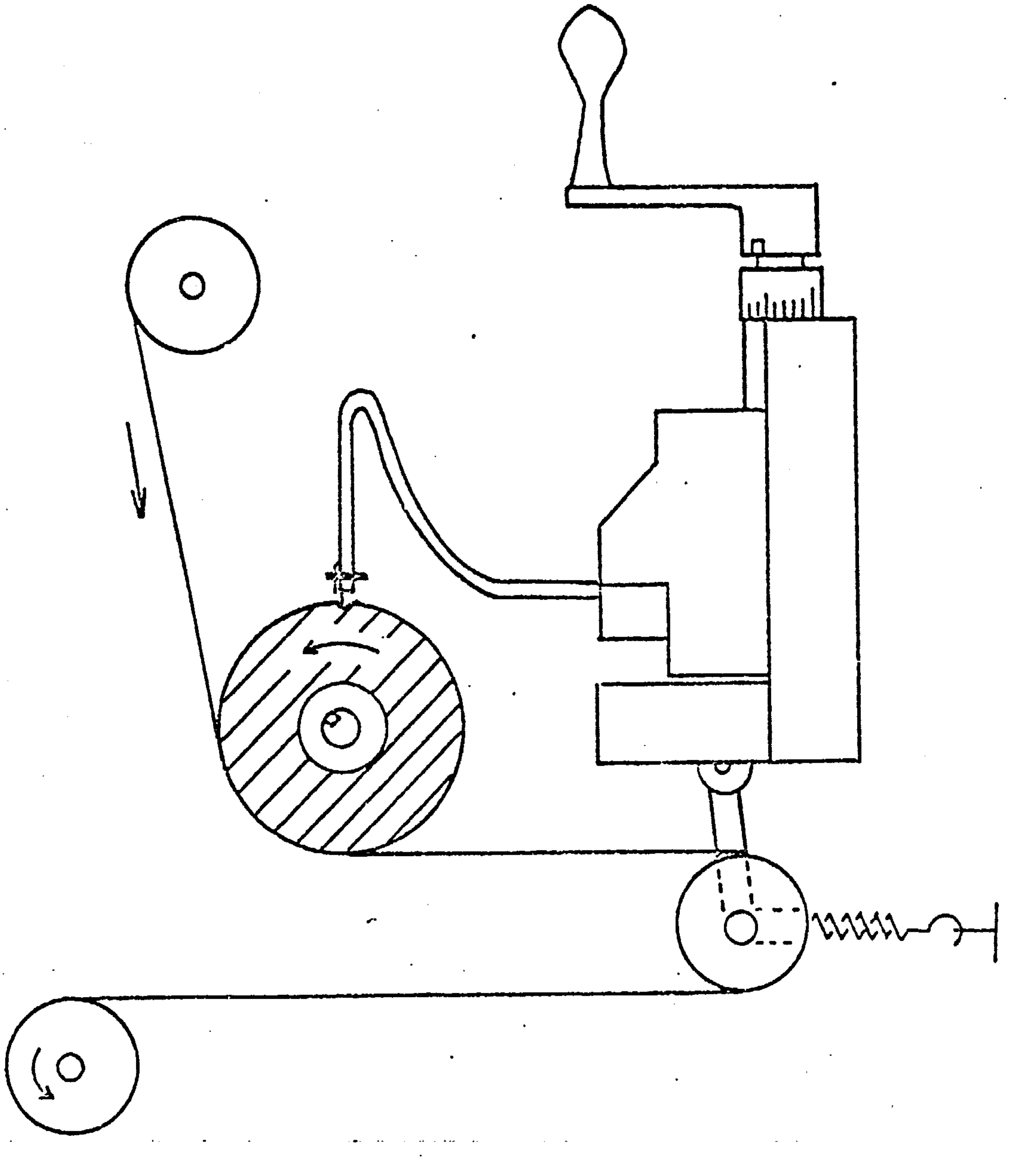


Figure 2. Sketch of wear apparatus (after Champ, Southern and Thomas (1,2)).

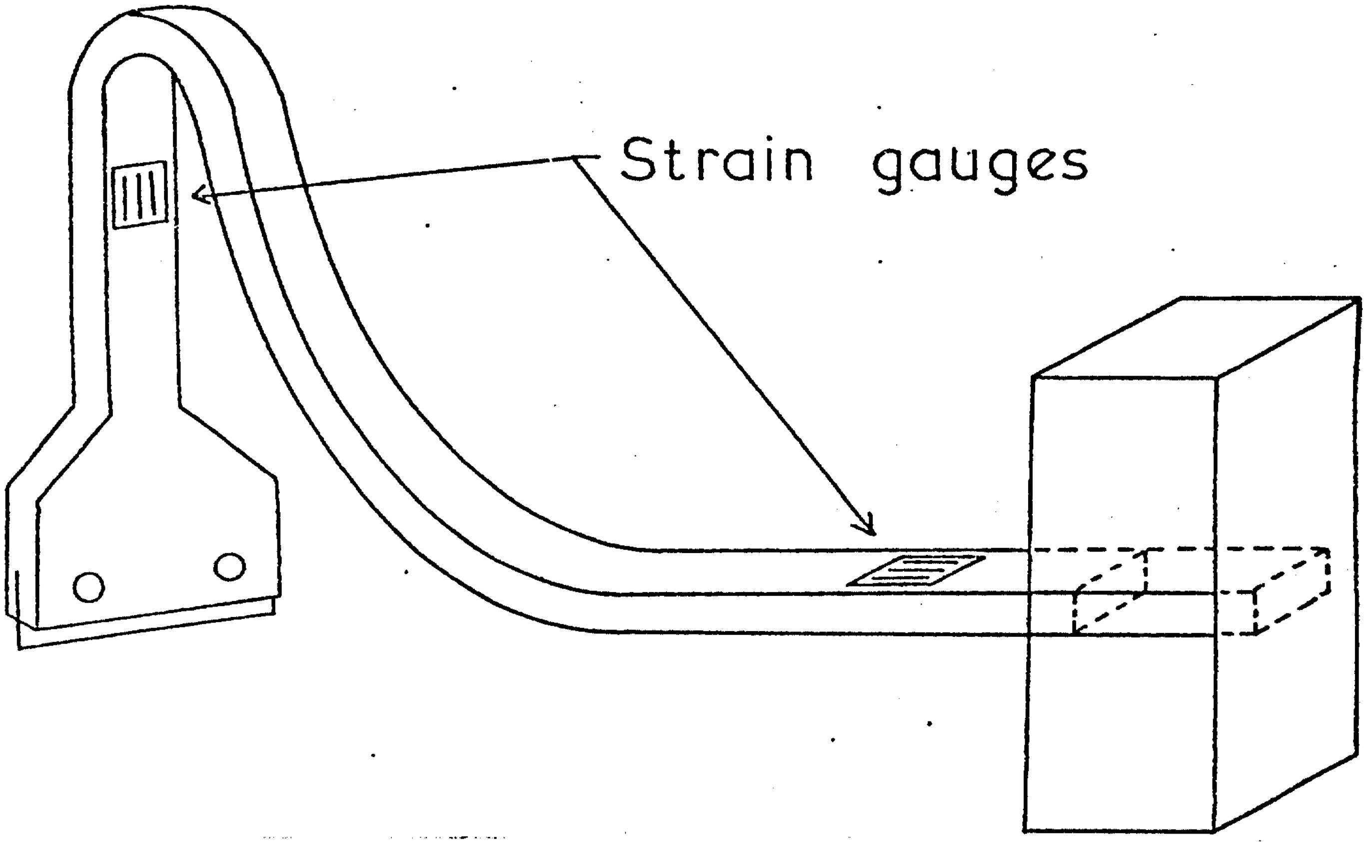
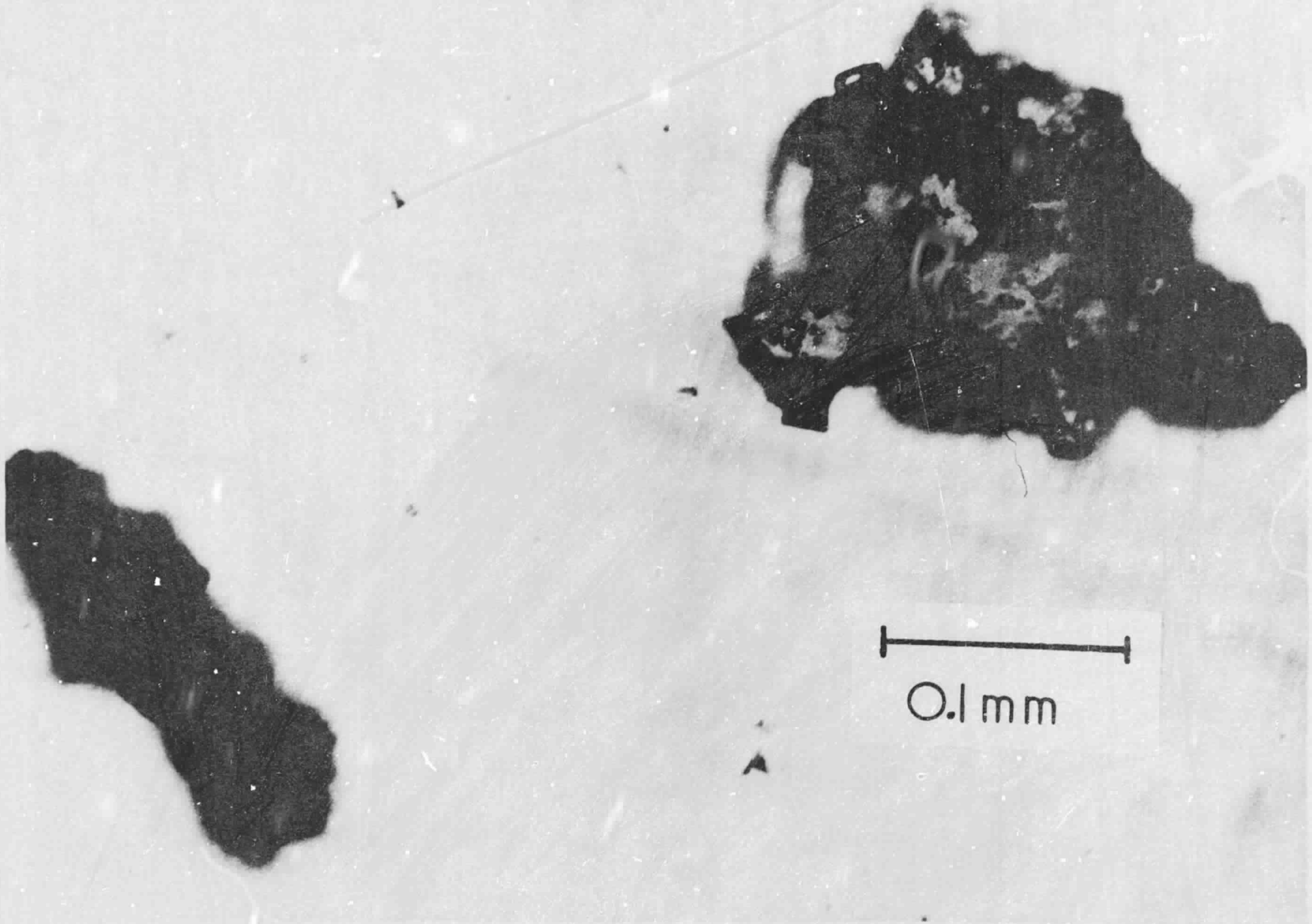


Figure 3. Cantilever beam blade-holder with strain gauges for measuring normal and frictional forces.

Figure 4. Wear particle from unfilled SBR material B, under frictional force of 0.8 kN/m (= 0.8 kj/m^2).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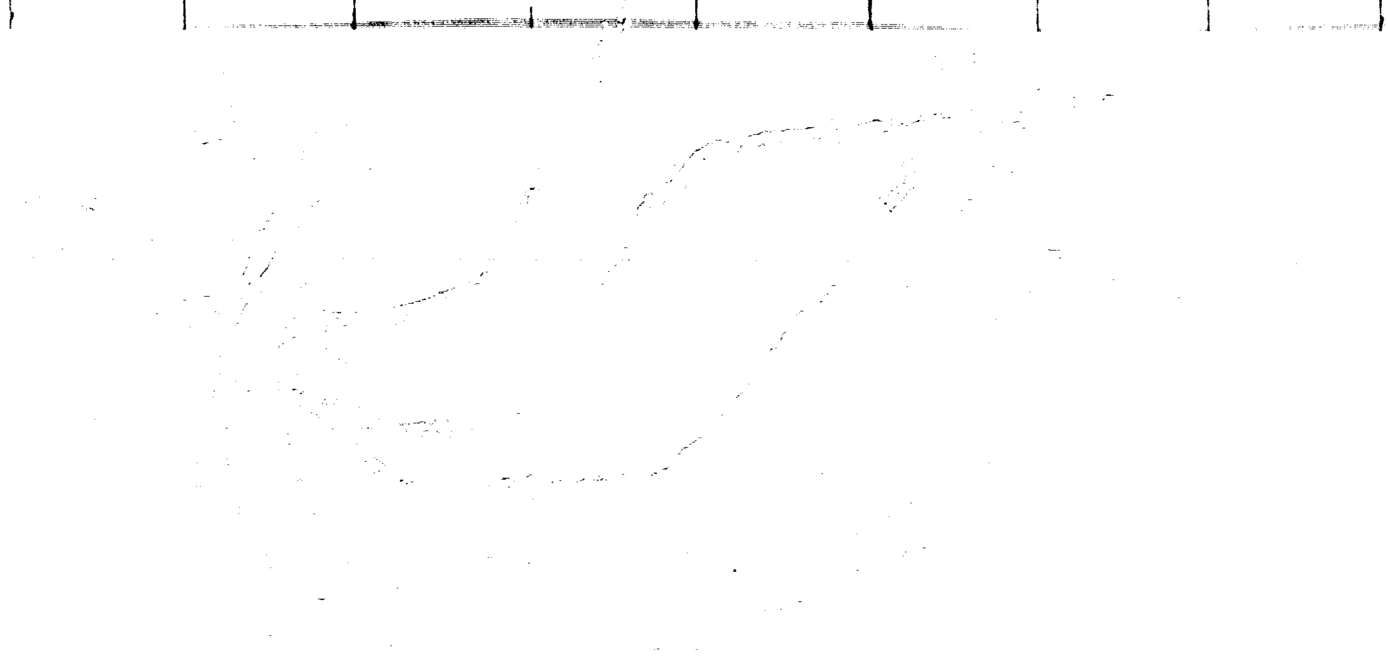
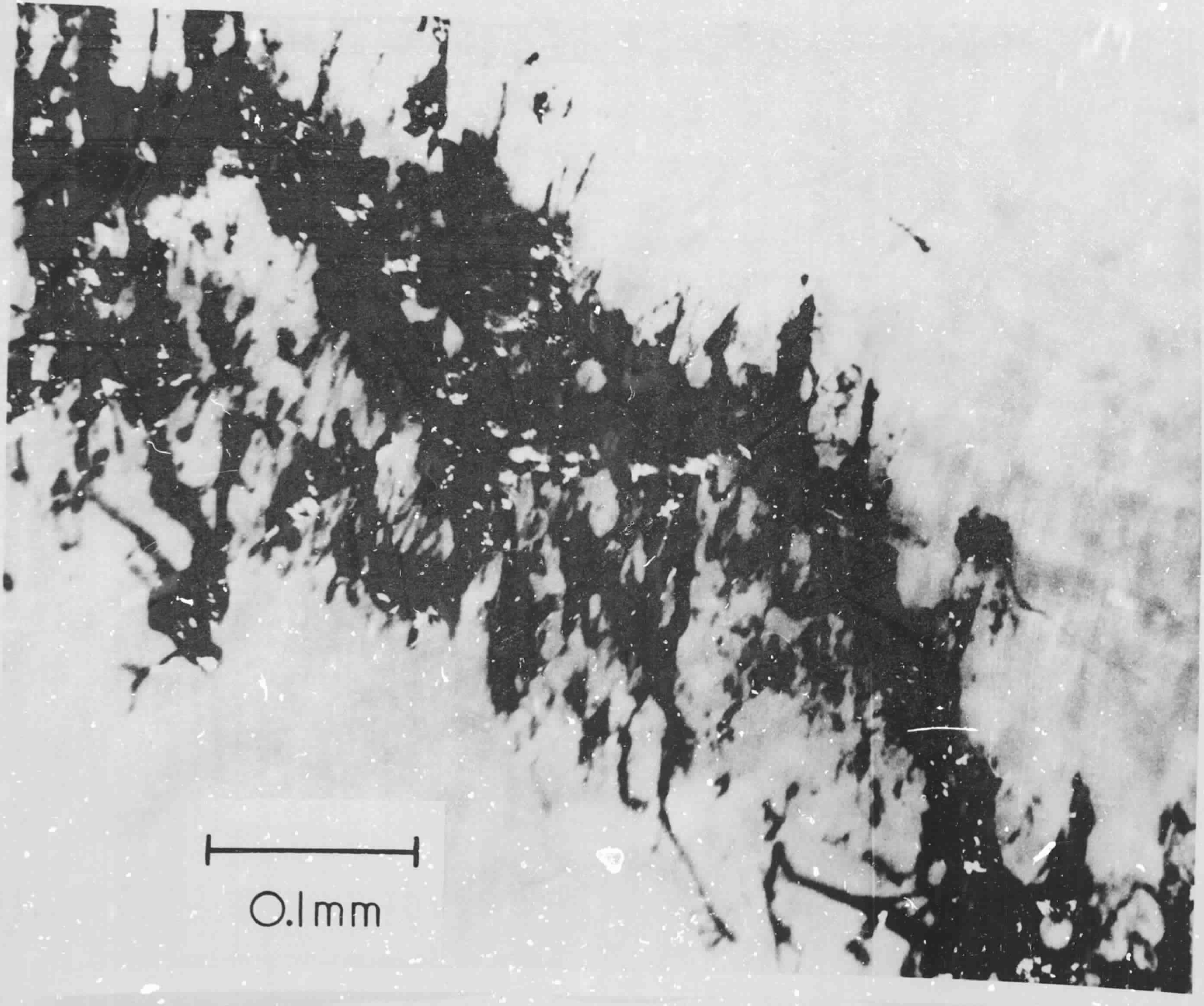


Figure 5. Wear debris from filled SBR material C, under frictional force of 1.2 kN/m (= 1.2 kj/m^2).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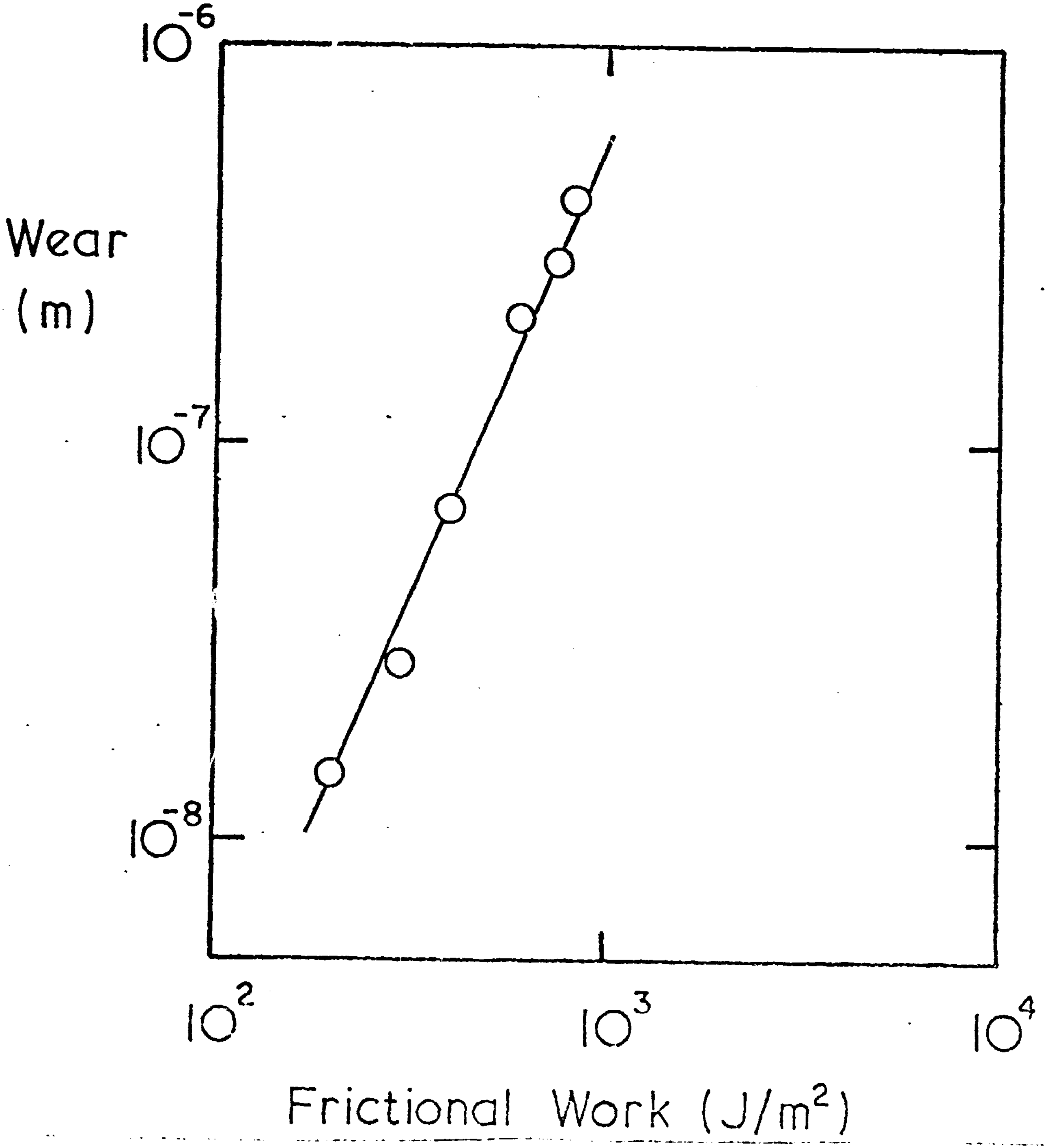

Figure 6. Rate of wear for unfilled NR material A *vs* frictional work (data taken from Table I).