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THE WEAR OF SINTERED ALUMINIUM POWDER (SAP) UNDER CONDITIONS OF VIBRATIONAL CONTACT

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S U M M A R Y

Equipment to be used in the study of wear under conditions of vibrational contact, at temperatures up to 450°C has been designed.

The following vibration patterns may be applied:

- (i) torsional vibration in the plane of contact (fretting),
- (ii) vibration normal to the plane of contact,
- (iii) a combination of i and ii.

The results concern the wear of sintered aluminium powder (SAP) against SAP in nitrogen gas and in liquid terphenyl.

It was found that adhesion and metal transfer take place, irrespective of the nature of the vibration pattern applied. When either torsional or normal vibration was applied, volume loss was low. However, a combination of both vibrations led to a very pronounced increase in wear, which can be explained in terms formation and removal of wear debris. The influences of surrounding medium, temperature and normal loading were studied.

R É S U M É

Un appareil pour l'étude de l'usure sous des conditions vibratoires et jusqu'à des températures de 450°C est construit. On peut choisir les conditions suivantes:

- (i) Vibration torsionnelle dans le plan de contact,
- (ii) Vibration normale au plan de contact,
- (iii) Une combinaison de i et ii.

Les résultats concernent l'usure de SAP (poudre d'aluminium comprimé, fritté et filé) contre SAP dans un milieu d'azote gazeux et de terphényl liquide.

On a constaté qu'il y a adhesion et transfert de metal sous toutes les conditions vibratoires. Quand seulement la vibration torsionnelle ou la vibration normale est appliquée, peu d'usure prend lieu. D'autrepart, une combinaison des vibrations cause une augmentation considérable de l'usure. Afin d'interpréter ce phénomène, un mécanisme de formation et d'enlèvement de débris d'usure est proposé. L'influence du milieu, de la température et de la force normale est étudiée.

Z U S A M M E N F A S S U N G

Es wurde eine Apparatur zur Durchführung von Verschleissprüfungen unter Vibrationsbedingungen verschiedener Art bei Temperaturen bis auf 450°C entworfen.

Die folgenden Vibrationsbedingungen können angelegt werden:

- (i) Torsionale Vibration in der Berührungsfläche (Bedingung unter welcher Passungsrost entstehen kann),
- (ii) Vibration normal zur Berührungsfläche,
- (iii) Kombination von i und ii.

Die Resultate betreffen den Verschleiss von Sinter-Aluminium-Pulver (SAP) gegen SAP im Stickstoffgas und im flüssigen Terphenyl.

Es zeigt sich, dass Adhesion und Metallübertragung unter allen Vibrationsbedingungen statt

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finden. Wenn nur torsionale oder nur normale Vibration vorliegt ist die Verschleissgeschwindigkeit niedrig. Eine Kombination beider Vibrationsbedingungen verursacht aber eine ganz erhebliche Zunahme des Verschleisses. Zur Erklärung dieser Tatsache wird ein Mechanismus für die Bildung und die Entfernung der Verschleisspartikel vorgeschlagen. Der Einfluss des Milieus, der Temperatur und der Belastung wird studiert.

INTRODUCTION

SAP (sintered aluminium powder) is a promising construction material in nuclear reactor technology, because its neutron absorption is low, while it retains its strength at elevated temperatures (for details see below). In order to obtain some indication of the wear of SAP against SAP under complex conditions of vibration in nitrogen and in terphenyl, it was found expedient to develop an apparatus in which it was possible to put an upper specimen of any chosen shape in contact with a flat lower specimen under the following conditions:

(a) The upper specimen should be capable of performing a torsional vibration of previously determined frequency and (small) amplitude in the plane of contact, under constant or, if desired, pulsating normal load. Figure 1(a) gives a diagrammatic

Fig. 1. Diagram showing possible conditions of motion.

Fig. 2. Characterization of normal vibration: (a) normal displacement of upper specimen as a function of time (idealized curve); (b) normal load as a function of time (idealized curve). t_c = part of the cycle of vibration during which contact between the specimens occurs; T = oscillation period.

presentation of this condition of motion which leads to the known phenomenon of fretting^{1,2}.

(b) The upper specimen should also be capable of performing a vibration normal to the plane of contact, independent of the torsional vibration specified in (a). Figure 1(b) gives a diagrammatic view of this condition.

Taking the moment at which both specimens are still just in contact with each other as the beginning of a cycle of vibration, this vibration can be represented by Fig. 2.

For a part of the cycle of vibration, the upper specimen should be lifted to a previously adjusted height and subsequently lowered again according to the curve shown in Fig. 2(a). For the remaining part of the cycle both specimens should be in touch with each other and a normal load should be built up according to the curve shown in Fig. 2(b). If desired, it should be possible to apply both normal and torsional motion in combination. By choosing appropriate frequencies, it should be ensured that for consecutive cycles of normal vibration the upper specimen is always in another phase of torsional vibration.

The environment of the specimens should be gas or liquid, the temperature being adjustable from ambient to 450°C and the pressure up to 10 atm.

In this article a concise description of the equipment is given with some actual performance characteristics. Finally, some experimental data concerning the wear of SAP in nitrogen and terphenyl are given and discussed.

DESCRIPTION OF EQUIPMENT

A difficulty was to obtain displacement-time and force-time diagrams as shown in Fig. 2. The principle of the system which was designed, is shown in Fig. 3.

Vessel A contains the specimens. Cylinder B, which is completely filled with oil, is connected to an oil supply vessel C, *via* an orifice D. Vessels A and C are kept under gas pressure, the pressure in C exceeding that in A. *Sinusoidal* vibration of the driving piston E causes the driven piston F to perform the *forced* normal vibration, shown

Fig. 3. Driving system for the normal vibration. (For description see text.)

in Fig. 2(a). During contact of the specimens, excess oil pressure is built up between the pistons because of the continued downward motion of the driving piston. This causes the normal load between the specimens to vary approximately as shown in Fig. 2(b). (The actual diagrams, recorded during performance, are shown and discussed below.)

A feature of the system is that the average distance between upper and lower specimens remains constant, irrespective of the amount of specimen wear.

The general arrangement (Fig. 4) shows the implementation of the ideas outlined above. The lower specimen 1 is mounted in a cage which is fitted to the upper part of the machine by a screw connection. The upper specimen 2 is mounted on a vertical shaft, which transmits the desired movements. The vertical vibration of this shaft

Fig. 4. General arrangement of equipment.

is effected by means of a hydraulic system the principle of which has been described above (Fig. 3). The elements of the hydraulic system are: lower piston 3 (F in Fig. 3), upper piston 4 (E in Fig. 3), coupled *via* an adjustable eccentric 5 to driving motor 6, by-pass with an orifice 7 and an oil supply vessel that is not shown in the drawing. The surface area of both pistons is 1 cm^2 . Pressure is applied to the oil supply vessel *via* a membrane in order to avoid contamination of the oil. De-aeration of the system takes place through air release valves 8 and 9.

The shaft has an extension in the form of a thin rod, which moves within an inductive measuring coil 10. The output of this coil is a measure of the displacement of the shaft *vs.* time (*cf.* Fig. 2(a)). Moreover, when this output signal is fed into a slow recorder with integrating function, information about changes in the average position of the shaft, and thus about any specimen wear which may occur, is obtained.

The torsional vibration of the shaft is effected by means of a flat spring 11, mechanically driven by motor 12. Again, frequency and amplitude can be measured with an inductive measuring coil 13.

The axis of the shaft is fixed by the use of three thin rods 14, which can tilt over in the pivot bearings 15 and 16. The bearings 16 are set in flexible supports 17. The inner vessel 18 contains the gaseous or liquid medium that surrounds the specimens.

Stirring takes place by means of a magnetic stirring device, the components of which are clearly shown in the drawing. The medium is heated up through the wall of the inner vessel by means of "Pyrothenax"* heating cable 19. In order to keep

Fig. 5. Upper specimen mounted on a vertical shaft and lower specimen mounted in a cage.

* Trade-mark of Pyrothenax Ltd., Hebburn, U.K.

the temperature of the upper part of the machine, which contains the hydraulic system and the measuring coils, below 100°C , water at about 90°C is circulated through the cooling jacket 20 and cooler 21 which separates the upper and lower parts of the machine. The inner vessel is completely surrounded by an outer vessel 22, filled with heating oil. This outer vessel is provided with a jacket 23, into which cold water can be introduced. Occasionally experiments must be performed in terphenyl mixtures which melt at about 80°C or even higher. In these cases, the terphenyl is melted and pumped under nitrogen pressure into the previously de-aerated and preheated inner vessel through the siphon 24, before the outer vessel is connected.

Fig. 6. General view of equipment consisting of 3 identical units.

With the equipment thus designed a frequency range of 10–50 c/sec can be applied for both oscillations. The stroke of the vertical movement can be varied between 0.2 and 2.0 mm and the rotational amplitude between 0.5 and 2 degrees.

Figure 5 shows the actual specimen assembly mounted in the cage. In this case a spherical upper specimen is chosen.

Figure 6 shows three identical testing units, as described. In the unit in the foreground the pressure vessel has been removed; the specimen assembly A can be seen. The second unit is provided with a pressure vessel B and the third unit is completely assembled, including the outer vessel C.

At ambient temperatures the normal force between the specimens is measured with a pick-up, consisting of a piezo-electric barium-titanate crystal (Fig. 7). This pick-up has the same shape and dimensions as a lower specimen and can thus be mounted

Fig. 7. Piezo-electric barium titanate crystal pick-up.

Fig. 8. Arrangement for calibration of barium titanate pick-up.

Fig. 9. Pick-up output vs. time diagram, obtained by a sudden change in normal force of 8 kg. Oscilloscope deflection, 2 V/cm; Oscilloscope sweep rate, 10 msec/cm.

Fig. 10. Simultaneously recorded diagrams: (a) torsional amplitude as a function of time; (b) normal amplitude as a function of time; (c) normal load as a function of time. Oscilloscope deflection, 2 V/cm; Oscilloscope sweep rate, 10 msec/cm.

in the cage, which normally contains the lower specimens. Therefore, the force-time diagram can be obtained under working conditions. The piezo-electric crystal responds to a sudden change in normal load (compression or decompression of the crystal) by building up an electric charge. The potential difference involved is proportional to the *absolute* value of the change in normal load. This enables calibration to be carried out by pressing an upper specimen against the pick-up by means of a loaded lever (Fig. 8). Cutting of the thread, which carries the load, results in a sudden decompression of the crystal. This, in turn, causes a potential difference, which can be observed on an oscilloscope. Figure 9 shows the result of a calibration experiment involving a change in normal load of 8 kg.

DIAGRAMS RECORDED DURING EXPERIMENTS

During experiments performed at temperatures from ambient to 450°C the following quantities can be measured as a function of time:

- (i) the amplitude of torsional vibration of the upper specimen,
- (ii) the amplitude of normal vibration (stroke) of the upper specimen, and, in addition, at ambient temperatures only:
- (iii) the normal load on the specimens.

These three different variables, recorded during the same experiment, are shown in Fig. 10. The experiment was performed at ambient temperature under combined torsional and normal vibration. A spherical upper specimen with a radius of curvature of 10 mm vibrated against the barium titanate pick-up. The specimens were surrounded by nitrogen, the pressure inside the inner vessel being 3 kg/cm² and the oil supply pressure 5 kg/cm². The pressure difference, Δp , which controls the load pattern, was, therefore, 2 kg/cm².

The vibration conditions were:

frequency of torsional vibration 36 c/s;

amplitude of torsional vibration 45 minutes of arc;

frequency of normal vibration 42 c/s.

The stroke of the upper specimen was fixed at 0.6 mm by adjustment of the stroke of the driving eccentric (5 in Fig. 4). It is seen that the recorded diagrams meet the requirements mentioned in the introduction. The diagram of the torsional vibration is sinusoidal (Fig. 10(a)) and those of the normal vibration and loading cycle

Fig. 11. Influence of frequency of normal vibration on the force-time diagram: (a) 42 c/sec; (b) 23 c/sec. Oscilloscope deflection, 2 V/cm; oscilloscope sweep rate, 0.5 msec/cm.

(Figs. 10(b) and (c)) have approximately the shape of the idealized curves shown in Fig. 2. From Fig. 10(c) it appears that at a pressure difference, Δp , of 2 kg/cm² the normal load upon the specimens reaches a maximum value of 9.7 kg. As was to be expected, some impact peaks are superimposed upon the gradually increasing load,

the highest peaks reaching a value of about 14 kg. The beginning of a loading cycle is shown in Fig. 11 (a), this time recorded at a higher sweep rate (extended time base). The pattern of impact vibration can now be studied in detail. The upper specimen appears to bounce once.

The influence of Δp on the normal amplitude and the normal load, keeping all other independent variables at the values given above, appears from Table I in which

TABLE I
INFLUENCE OF PRESSURE DIFFERENCE (Δp) ON LOADING CHARACTERISTIC

Δp (kg/cm ²)	S (mm)	L_{max} (kg)	t_c (sec · 10 ⁻³)	F_{imp} (kg)	$1/T \int_0^{t_c} L dt$ (kg)
0.5	0.77	4.0	6.3	12.0	0.7
1.0	0.72	5.7	8.0	13.0	1.2
1.5	0.65	7.5	8.7	13.6	1.7
2.0	0.60	9.7	10.0	13.6	2.6
2.5	0.55	11.6	11.4	13.6	3.5
3.0	0.50	12.5	12.0	13.6	4.0
3.5	0.45	14.2	12.7	13.6	4.8
4.0	0.40	15.4	13.7	13.6	5.6

the relevant figures are given. For the range of Δp values involved, the stroke S of the upper specimen decreases linearly with increasing Δp , while both the maximum value of the load upon the specimens, L_{max} , and that part of the cycle of vibration during which contact between the specimens takes place, t_c , increase linearly. The maximum force due to impact appears to remain roughly constant, which means that the average velocity of the upper specimen remains constant, a smaller distance being covered in a shorter time at increasing Δp . From results not given here it was shown that, as could be expected, the impact force increases appreciably when the stroke of the upper specimen is kept constant by adjusting the driving eccentric.

Excluding the impulse due to impact and assuming that the load-time diagram is sinusoidal, the impulse imparted per second is

$$\frac{1}{T} \int_0^{t_c} L dt = 2L_{max}t_c/\pi T \quad (1)$$

in which T is the oscillation period.

Table I shows that the impulse imparted per second is proportional to Δp , the proportionality constant being about 1.3. Results, not given here, prove that this value remains constant for the entire frequency range from 10–50 c/s. This means that

Fig. 12. Influence of viscosity of surrounding medium on the force-time diagram: (a) nitrogen, kinematic viscosity 17 cstokes; (b) oil, kinematic viscosity 45 cstokes.

for two experiments performed at different frequencies, but both lasting the same time, the total of the impulses imparted is the same.

Of course, at a lower normal frequency the effects due to impact are much smaller. This is seen from Fig. 11, in which the load-time diagrams for 42 c/s and 23 c/s are shown. They were recorded at a high sweep rate of the oscilloscope. Finally, Fig. 12 shows that a change from nitrogen to a viscous oil as the medium surrounding the specimen diminishes the height of the first impact peak by only 15%. This facilitates the comparison of experiments performed in different media.

RESULTS OF THE WEAR OF SAP AGAINST SAP

Experiments were performed with commercially available SAP 895. It is made by sintering preoxidized aluminium powder, the final product containing about 10.5% aluminium oxide in a finely dispersed condition. A feature of the material is that it retains its strength at elevated temperatures because recrystallization is inhibited by the inclusions of oxide.

When SAP is used for 2 years at 200 °C the proofstress measured at 200 °C is about 20 kg/mm² and the elongation 6–9%. For comparison: at 200 °C the proofstress of the precipitation hardened alloy AlCu 4 Mg 0.4 Si 0.8 is 10 kg/mm² and the elongation 35%. After use for 2 years at 500°C the proofstress of SAP measured at 500°C is about 10 kg/mm² and the elongation about 2%. Full details about SAP are given by BLOCH³.

The results of experiments performed in nitrogen and in terphenyl under the conditions of vibration described in the preceding section (*viz.* those relevant to Fig. 10), are given first. The influence of changes in the conditions of vibration is then illustrated.

The influence of the surrounding medium and temperature

The experimental conditions were:

shape of the upper specimen	spherical ($r = 10$ mm)
shape of the lower specimen	flat
surface finish	turned to 40 microinch c.l.a.
torsional vibration	frequency 36 c/s
	amplitude 45 minutes of arc
normal vibration	frequency 42 c/s
	amplitude 0.6 mm
pressure in inner vessel	3 kg/cm ²
pressure in outer vessel	5 kg/cm ²
maximum load	9.7 kg
maximum impact force	13.9 kg
loading period $((t_e/T) \cdot 100)$	42 %
impulse imparted per second	2.6 kg

Experiments were performed in nitrogen at 135°C, in terphenyl at 135°C and in terphenyl at 400°C. The duration of each experiment was 24 h.

Unloaded specimens were initially in point contact. Owing to the fact that deformation took place under the normal load, the torsional vibration caused slip in the contact region. The amplitude of torsional slip increased from zero at the centre of rotation to the maximum value at the outer diameter of the circular contact region.

Numerical results are given in Table II. The values of the total volume loss given in Table II were calculated from the diameters of the circular wear scars formed. Surface profile measurements, not given here, indicated that the volume loss was always about equally divided between the two specimens.

It was found that the amount of wear is dependent on whether nitrogen or terphenyl surrounds the specimens, the wear in terphenyl being somewhat greater than the wear in nitrogen. However, when the temperature of the terphenyl is increased from 135°C to 400°C wear increases by a factor of 15.

TABLE II

EXPERIMENTS PERFORMED UNDER CONDITIONS OF COMBINED NORMAL AND TORSIONAL VIBRATION

<i>Environment</i>	<i>Diameter of circular wear scar (mm)</i>	<i>Total volume loss after 24 h (mm³)</i>
Nitrogen 135°C	2.6; 2.7	0.23; 0.26
terphenyl 135°C	3.3; 3.3	0.59; 0.59
terphenyl 400°C	6.7; 6.1	10.4 ; 7.0

Figure 13 shows the circular contact area of a lower specimen worn against a spherical upper specimen in nitrogen. The surface of the SAP is considerably roughened due to mutual metal transfer (see below).

Wear debris is ultimately generated in the form of a fine grey powder which is seen in Fig. 13 as an "embankment", completely surrounding the contact region. X-ray analysis proved that this powder has exactly the same chemical composition as

Fig. 13. Contact region on the surface of a lower specimen worn against an originally spherical upper specimen in nitrogen under combined vibration conditions ($\Delta p = 2 \text{ kg/cm}^2$). The circular wear scar is completely surrounded by fine grey wear debris. The greatest depth of the scar is about $15 \mu\text{m}$; its surface is roughened considerably due to adhesion and metal transfer.

Fig. 14. Contact region on the surface of a lower specimen worn against an originally spherical upper specimen in terphenyl under combined vibration conditions ($\Delta p = 2 \text{ kg/cm}^2$). The circular wear scar is surrounded by a light zone, probably formed by an erosive action of the terphenyl.

the original SAP. This generation of fine wear debris is characteristic of a fretting process¹.

Figure 14 shows the contact region of a lower specimen worn in terphenyl. The general appearance of the worn surface resembles that of the surface worn in nitrogen. In this case no wear debris can be found, because the debris which was undoubtedly generated during the experiment, was washed away by the terphenyl. The contact region is completely surrounded by a light zone, probably formed by erosive action of the terphenyl, pressed out from between the specimens at each successive down-

Fig. 15. Cross-section of lower specimen worn in terphenyl under combined vibration conditions ($\Delta p = 2 \text{ kg/cm}^2$). The picture shows heavily work-hardened transferred material. The figures shown give local Vickers hardness values in kg/mm^2 , measured at a normal load of 15 g.

ward stroke of the upper specimen. The centre of torsional vibration is distinctly marked by a little "mountain" of SAP, transferred from the upper specimen which shows a corresponding hollow. Clear proof of metal transfer is given by the cross section of the lower specimen which shows transferred material (Fig. 15). Microhardness measurements show that the transferred SAP is considerably work-hardened.

The influence of the vibration pattern on the wear of SAP against SAP in terphenyl at 135°C

In order to establish the influence of the vibration pattern chosen, three series of experiments were performed. In the first normal and torsional vibration were combined. Vibration conditions were the same as those given in the preceding section but experiments were performed at pressure differences ranging from 0.5–3.0 kg/cm^2 . As the amplitude of the driving piston was adjusted so that the stroke of the upper specimen was 0.6 mm at $\Delta p = 2 \text{ kg/cm}^2$, the actual conditions under which loading took place follow from Table I. Thus the maximum normal load ranged from 4.0–12.5 kg, the loading period from 6.3–12.0 msec and the impulse imparted per sec from 0.7–4.0 kg. In the second series only normal vibration was applied with pressure differences ranging from 0.5–3.0 kg/cm^2 . Finally, in the third series only torsional vibration was applied. Experiments were performed at $\Delta p = 2$ and 5 kg/cm^2 . Because the cross section of the lower piston is 1 cm^2 this corresponds to constant normal loads of respectively 2 and 5 kg. The duration of each experiment was 24 h.

Results are summarized in Tables III, IV and V. Table III shows that under conditions of combined normal and torsional vibration, volume loss increases roughly quadratically with increasing Δp , and therefore with increasing values of maximum normal load, loading period and impulse imparted per sec. As was to be expected, excessive metal transfer occurred at each value of Δp . From Table IV it is seen that when only normal vibration is applied, volume loss is very low in comparison with the values observed under conditions of combined vibration. However, metal transfer still took place, resulting in roughening of the contact area (Fig. 16). Table V shows that when only torsional vibration is applied volume loss is again very low. Figure 17 shows the contact region of a lower specimen. It is seen that towards the centre of the contact circle the original surface of the specimen is still relatively undamaged. This middle section is surrounded by a roughened zone in which mutual transfer took place. The sequence of events which occurred during the process, must have been, firstly, a deformation of the surfaces under the influence of the constant normal load, followed by torsional slip in the region of contact as a result of the torsional vibration.

TABLE III

EXPERIMENTS PERFORMED IN TERPHENYL AT 135°C UNDER CONDITIONS OF COMBINED NORMAL AND TORSIONAL VIBRATION

Δp (kg/cm ²)	Maximum normal load (kg)	Maximum impact force (kg)	Loading period (t_c/T) · 100 (%)	Impulse per second (kg)	Scar diameter (mm)	Total volume loss after 24 h (mm ³)
0.5	4.0	12.0	26	0.7	2.7; 2.1	0.26; 0.10
1.0	5.7	13.0	33	1.2	2.9; 2.9	0.36; 0.36
2.0	9.7	13.6	42	2.6	3.3; 3.5	0.58; 0.73
3.0	12.5	13.6	50	4.0	4.1 ⁵ ; 4.0	1.45; 1.26

TABLE IV

EXPERIMENTS PERFORMED IN TERPHENYL AT 135°C UNDER CONDITIONS OF NORMAL VIBRATION

Δp (kg/cm ²)	Maximum normal load (kg)	Maximum impact force (kg)	Loading period (t_c/T) · 100 (%)	Impulse per second (kg)	Scar diameter (mm)	Total volume loss after 24 h (mm ³)
0.5	4.0	12.0	26	0.7	0.8; 0.8	0.002; 0.002
1.0	5.7	13.0	33	1.2	1.0; 0.9 ⁵	0.005; 0.004
2.0	9.7	13.6	42	2.6	1.2; 1.3 ⁵	0.010; 0.016
3.0	12.5	13.6	50	4.0	1.5 ⁵ ; 1.5	0.028; 0.025

TABLE V

EXPERIMENTS PERFORMED IN TERPHENYL AT 135°C UNDER CONDITIONS OF TORSIONAL VIBRATION

Δp (kg/cm ²)	Constant normal load (kg)	Scar diameter (mm)	Total volume loss after 24 h (mm ³)
2.0	2.0	0.8; 0.8	0.002; 0.002
5.0	5.0	1.1; 0.9 ⁵	0.007; 0.004

Fig. 16. Contact region on the surface of a lower specimen worn against an originally spherical upper specimen in terphenyl under normal vibration conditions ($\Delta p = 2 \text{ kg/cm}^2$).

Fig. 17. Contact region on the surface of a lower specimen worn against an originally spherical upper specimen in terphenyl under torsional vibration conditions ($\Delta p = 2 \text{ kg/cm}^2$). Towards the middle of the contact circle a relatively undamaged part of the original surface of the specimen can be noticed.

At a certain distance from the centre of rotation this torsional slip reached a value large enough to initiate mutual transfer between the surfaces.

Tables IV and V show that under normal as well as under torsional vibration conditions, volume loss increases exponentially with increasing Δp .

DISCUSSION

From the preceding sections it can be concluded that the equipment gives reproducible and consistent results under a wide variety of conditions.

The observed dramatic increase in wear when torsional and normal vibration are superimposed, is once more illustrated in Fig. 18, in which wear is expanded on a logarithmic scale.

Interpretation in terms of a wear mechanism is possible on the following assumptions:

(i) adhesion and metal transfer can only occur when surface films which inhibit adhesion, are largely damaged

(ii) for appreciable wear (removal of wear debris) to occur, welds which may form between the surfaces, must be subjected to shear in the plane of contact. Moreover, the removal of loose wear debris must be stimulated.

In the present case, when either normal or torsional vibration is applied, conditions are favourable for the destruction of surface films. When only normal vibration is applied, the loosening of brittle films easily occurs under the combined influence of initially occurring plastic microslip, followed by repeated elastic compression and decompression and the cleaning action of the fluid which is pressed out from between the surfaces at each successive downward stroke of the upper specimen. When only torsional vibration is applied, the torsional slip causes destruction of the surface films, provided that the amplitude of slip is large enough (*cf.* Fig. 17). Thus adhesion and metal transfer occur under normal as well as under torsional vibration con-

ditions. However, only little wear occurs in either case, because when only normal vibration is applied, no shear occurs and when only torsional vibration is applied, the removal of wear debris is hampered.

In contrast, when both vibrations are superimposed, shear in the plane of contact and intense removal of wear debris occur, so that the wear rate is high. Under conditions of combined vibration, a change-over from nitrogen to terphenyl causes the amount of wear to be approximately doubled. This is probably due to the fact that a liquid carries away wear debris more easily than a gas.

Fig. 18. Volume loss after 24 h as a function of normal load for various conditions of vibration.

The observed pronounced influence of temperature is somewhat unexpected, as the properties of SAP are usually found to be relatively independent of temperature (although the proofstress decreases from 20 kg/mm² at 200°C to 10 kg/mm² at 500°C). Probably the explanation lies mainly in the adhesive character of the wear process, adhesion generally increasing considerably with increasing temperature.

It was observed that wear increases exponentially with increasing values of the sinusoidally changing normal load (*viz.* with maximum normal load, loading period and impulse imparted per sec), irrespective of the nature of the vibration conditions applied. Consequently, it is this normal load and not the almost constant superimposed impact force which determines the amount of wear. This is probably due to the fact that the energy, imparted during impact, is very small in comparison with the total energy involved (*cf.* Fig. 10).

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