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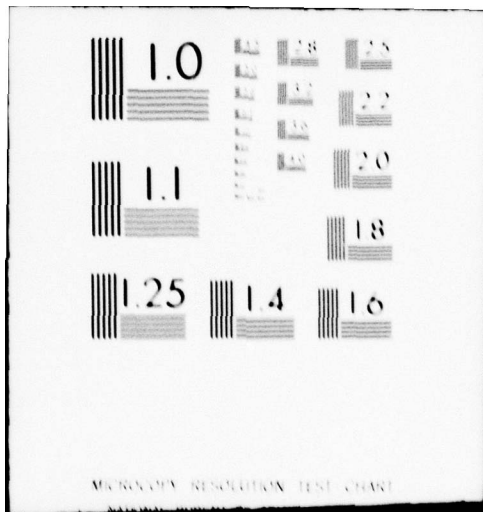
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ROYAL AIRCRAFT ESTABLISHMENT

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Technical Report 78061

June 1978

**THE WEAR OF PLASTICS MATERIALS  
IN WATER AND AQUEOUS SOLUTIONS**

by

D.C. Evans

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### SUMMARY

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Wear rates of some thermoplastic polymers have also been measured in oil-in-water emulsions. The results show that even dilute emulsions (1% oil by volume) are effective boundary lubricants, and this effect is attributed to the particular way in which the counterface is modified by the formation of a boundary lubricating film.

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## 1 INTRODUCTION

Wear rates of plastics and composite materials during sliding against a metal counterface are determined essentially by two factors:

- (i) the 'inherent' wear resistance of the material, which is primarily a function of its mechanical properties, and
- (ii) the way in which the initial topography of the counterface and the sliding surface of the composite material are modified during sliding.

With repeated sliding over a counterface, modification of the original topography invariably occurs, and this factor generally dominates the sliding behaviour of the system. There are two ways in which the countersurface can be modified:

- (i) by adhesion of wear particles to the wear track (transfer), and
- (ii) by wear.

In general, both of these processes result in a reduced effective counterface roughness, and hence in a lower composite wear rate.

During sliding under dry conditions, a uniform coherent layer of wear debris may, in some cases, be built up as sliding proceeds, in others, wear debris accumulates at the edges of the wear track, and very little remains within the wear track itself. Modification of the sliding surface of the composite appears to be a result of readhesion of wear debris. With filled materials, the filler particles or fibres frequently become masked by a surface layer of back-transferred material.

Wear of the counterface during dry sliding often accompanies the formation of transfer films. Counterface wear is very small with unfilled polymers, but with filled materials the filler itself can be abrasive towards the counterface. Whereas mild abrasion is normally highly beneficial, leading to a significant reduction in composite wear rate, excessive abrasion can result in roughening of the counterface, and a corresponding increase in wear rate<sup>1,2</sup>.

When sliding takes place in the presence of a liquid, these processes of counterface modification are significantly altered, and a number of additional effects are produced. Fig 1 shows schematically the influence of a variety of fluids on the wear rates of three types of plastics materials<sup>3</sup> - a crystalline thermoplastic (curve A), two amorphous thermoplastics (curves B and C) and three composite materials (curves D-F). The identities of these materials and also

of the liquids are listed in Table 1. Each liquid is represented in Fig 1 by a letter, according to its solubility parameter,  $\delta$ .

Fig 1c demonstrates the first major effect of liquids on the sliding behaviour of plastics materials. Wear rates in all the liquids are higher than during dry sliding because transfer films are no longer produced. In addition, the formation of back-transferred films on the composite surface is prevented and this can lead to increased wear of both composite and counterface<sup>2</sup>, because there is direct contact between filler particles and the counterface.

The behaviour of the amorphous thermoplastics embraces two further effects (Fig 1b). In some liquids, wear rates are similar to, or lower than those measured in dry conditions. In other liquids, however, wear rates are high, and particularly in those whose solubility parameters are close to that of the polymer. Such liquids are generally strongly absorbed by the polymer. It was suggested that these high wear rates occur because the surface layers of the polymer are considerably weakened by plasticisation. Also, any wear that originates via a tensile component of the applied stress may be exacerbated by the ability of these liquids to promote environmental stress cracking and crazing<sup>3</sup>. With the liquids that are not strongly absorbed, wear rates are reduced, primarily because the liquid can act as a boundary lubricant. However, examination of the worn polymer surfaces suggests that some plasticisation of the surface layers may occur, even in those liquids which are not compatible with the polymer.

Lubricated wear rates of the crystalline polymer (Fig 1a) are all either the same or lower than the dry value. Liquids are not readily absorbed by such polymers, and so the wear rate is determined primarily by the ability of the liquid to act as a boundary lubricant. This could also be an important secondary effect with the PTFE composites (curves D and E, Fig 1c), which, likewise, do not absorb fluids. The shapes of the wear rate vs  $\delta$  curves for the PTFE composites are similar to curve A. POM was the only crystalline thermoplastic polymer examined during the previous study, and one objective of the present work was to investigate the wear properties of other crystalline polymers during lubricated sliding.

A significant observation from Fig 1 is that wear rates of all polymers are higher in water than in any other liquid, except in those cases where the liquid is strongly absorbed; coefficients of friction are invariably highest in water<sup>3</sup>. The poor boundary lubricating properties of water have also been demonstrated by friction measurements with a wide range of polymers<sup>4-9</sup>. These results are of considerable practical importance, firstly because water is both a widely used

process fluid and a common contaminant, and secondly because the low viscosity and low pressure coefficient of viscosity of water imply that lubrication by water is often likely to be within the boundary regime<sup>10</sup>.

The objectives of the present work were

- (1) to extend previous measurements of lubricated wear rates to other unreinforced thermoplastic polymers whose mechanical properties are not significantly affected by liquids,
- (2) to examine the effects of water on the wear behaviour of different types of polymers and composites during boundary lubricated sliding, and
- (3) to investigate the possibility of improving the boundary lubricating properties of water by the use of oil-in-water emulsions.

## 2 EXPERIMENTAL

Measurements of wear rates and coefficients of friction were made, in both dry and lubricated conditions, on a pin-on-disc apparatus of the type described previously<sup>11</sup>. The polymer pin was a 6.4 mm ( $\frac{1}{4}$  inch) diameter cylinder with a truncated conical end of 90° apex angle, and wear of the pin was determined by periodic measurement of the wear scar diameter. The initial diameter was approximately 1 mm. Tests were terminated as soon as a linear relationship had been established between wear volume and distance of sliding, in order to minimise the possibility of hydrodynamic lubrication becoming significant. The applied load was 10 newtons and the (constant) linear sliding speed was within the range 0.15-0.25 m s<sup>-1</sup>. It has been shown<sup>3,11</sup> that under these conditions lubrication is generally characteristic of the boundary regime.

The counterface in the majority of experiments was an austenitic fully-stainless steel (S130B; 17-19% Cr, 7-11% Ni), randomly abraded on 600 grade silicon carbide (SiC) paper to a roughness of 0.15  $\mu$ m Ra. In other experiments, a glass counterface was used, prepared to a surface roughness of 0.3  $\mu$ m Ra by random abrasion against 280 grade SiC paper. A fresh track was used for each run.

The polymers and composite materials used are listed in Table 2. With most materials, pins were machined directly from commercial samples. The preparation of the carbon fibre reinforced composites has been described elsewhere<sup>12</sup>; other pins were machined from samples compression moulded in the laboratory. Organic liquids were 'laboratory' grade and were used without further purification. Aqueous solutions of surface active agents were made-up by weight of solute in laboratory distilled water. Oil-in-water emulsions were made-up by volume using a commercial, low viscosity, spindle oil-based cutting/hydraulic oil, formulated

for use as an emulsion. The emulsifier was of the sodium naphthasulphonate type and the oil contained naphthemic acids and a number of undisclosed additives. Freshly-made emulsions were used for each test.

Surface tensions of aqueous solutions and emulsions, at 30°C, were measured from the differential capillary rise in two calibrated capillary tubes of different diameters, using a simple apparatus described elsewhere<sup>13</sup>. Viscosities of the oil/water emulsions were measured using a capillary viscometer. Densities were estimated from the weight of 5 cm<sup>3</sup> of solution, drawn by pipette from the liquid at 30°C.

### 3 RESULTS

#### 3.1 Wear of PPS and unfilled PTFE in organic liquids

Wear rates of PPS and unfilled PTFE measured during lubricated sliding on the pin-on-disc apparatus are shown in Fig 2; the letters referring to the liquids are listed in Table 1. It is apparent that overall, the wear rates of both polymers show a similar pattern to that exhibited by POM (Fig 1a). Wear rates of PTFE are lower in all liquids than during dry sliding; the wear rate is highest in water and there is a tendency towards lower wear rates in liquids with low solubility parameters. Wear rates of PPS show the same trend, although the wear rate in water is higher than for dry sliding.

Coefficients of friction were all lower during lubricated sliding (as for POM<sup>3</sup>), with the value in water higher than in other liquids. As before, however, the range of values of coefficient of friction is too narrow to discern a significant relationship with wear rates.

These results confirm the effects of liquids on the wear behaviour of polymers which do not absorb liquids, and show that significant reductions in wear rates are possible using liquids not normally considered to be efficient boundary lubricants.

#### 3.2 Wear of polymers and composites in water

##### 3.2.1 Thermoplastic polymers

Wear rates and coefficients of friction of some unfilled thermoplastics were measured, in separate experiments, during dry and water-lubricated sliding. The results are shown in Fig 3, with the polymers arranged in order of decreasing lubricated wear rate. It is clear that, while wear rates in water may be greater or less than the dry wear rate, in general the difference between the two is small. Coefficients of friction are always lower in water.

Water-lubricated wear rates are highest, and are higher than during dry sliding, for those polymers which are either amorphous or brittle - PPS, PMMA and PPO. With the more ductile polymers, *eg* PTFE, nylon 6.6, wear rates are lower in water. The thermoplastic polyurethane (PU) is an exception - the water-lubricated wear rate is significantly higher than the dry value; this polymer also has a relatively high coefficient of friction in water. The lowest wear rates in water are exhibited by the 'tougher' polymers - nylon 6.6 and UHMWPE. Indeed, the wear rate of UHMWPE in water-lubricated conditions is lower than for any other material examined in this work. This polymer is used almost exclusively in hip joint prostheses<sup>14</sup> and would probably find more general application in water-lubricated bearings, were it not for its low softening point and relatively poor load bearing capabilities.

### 3.2.2 Thermosetting resin composites

Wear rates and coefficients of friction for a selection of thermosetting resin composites are given in Fig 4. As with the thermoplastics, coefficients of friction are all lower in water, but there are two different types of wear behaviour. Four of the composites have dry wear rates which are an order of magnitude lower than in water. This is due to the formation of a coherent transfer film of wear debris during dry sliding; during water-lubricated sliding these films are completely absent.

The second type of behaviour is exhibited by those materials with wear rates which are lower in water than dry. Of these, the two asbestos reinforced phenolics do transfer some debris to the counterface during dry sliding, but coherent transfer films are not produced. Instead, most of the wear debris is pushed outside the wear track. Hence, dry wear rates are relatively high. In water, the counterface is polished by both of these composites, particularly by the asbestos *fibre* reinforced phenolic. It is this polishing action which results in low composite wear rates. The increased abrasiveness of the composites in water, which is in accordance with previous observations<sup>2</sup>, appears to be due to the inability of the wear debris to form a back-transferred layer on the composite surface, thus exposing the abrasive fibres to the counterface.

The epoxy/carbon fibre composite containing alumina is more abrasive and polishes the counterface in both dry and water-lubricated sliding. Wear rates are lower in water and again this is attributed to a greater degree of counterface polishing. The same results are obtained with POM containing alumina; wear rates are lower in both conditions of sliding than with the unfilled polymer (Fig 3).

The behaviour of the cotton fabric-reinforced phenolic is intermediate between the two types described above. During dry sliding, the composite does not form a coherent transfer film and so the wear rate is relatively high. Neither is the composite sufficiently abrasive to polish the counterface during water-lubricated sliding and so the wear rate remains high.

The filament-wound asbestos fibre has the lowest water-lubricated wear rate of all the commercial thermosets which were examined, and this is attributed to its particular ability to polish the counterface.

### 3.2.3 Counterface modifications

Visual observations of wear tracks produced by the thermosetting resin composites were described in the previous section. Fig 5a shows the transfer films produced by epoxy/bronze/PTFE/graphite (track 1) and epoxy/type 1 carbon fibre (track 3). In comparison, debris from the asbestos fibre-reinforced phenolic composite (track 2) is less well consolidated within the wear track. The wear tracks produced by the same composites in water (Fig 5b) show the greater degree of polishing achieved by the phenolic/asbestos fibre. The other two composites cause only slight wear of counterface.

Surface profiles of wear tracks produced by reinforced thermosets during water-lubricated sliding are shown in Fig 5c-e. Large differences in appearance of the wear tracks, for example between epoxy/bronze/PTFE/graphite and phenolic/asbestos fibre, are not reflected in the overall shapes of the surface profiles (Fig 5c and d). It is only in the fine structure that the wear track produced by asbestos fibre-reinforced phenolic seems to be smoother. The same is true for the two samples containing  $Al_2O_3$  (Fig 5e and f), despite their highly polished visual appearance.

The thermoplastic polymers produce very little modification to the counterface. During dry sliding, a dull band appears in the wear track, as though the small amount of debris which adheres to the wear track becomes degraded during repeated traversals. Transfer films of the type produced by composites filled with PTFE graphite etc, are not formed with any of these polymers. In water, no transfer is observed whatsoever and no wear of the counterface can be detected by profilometry.

### 3.3 Wear of polymers in oil-in-water emulsions

The use of additives to improve the boundary lubricating properties of oils is an established technology. Such additives, for example the fatty acids, amides etc, function by forming adsorbed films from solution on the sliding surfaces

which help to prevent direct contact between the sliding surfaces. Unfortunately, these substances are insoluble in water and cannot, therefore, be used in the same way as with oils. However, stable emulsions of oil and water can be prepared, and this is a possible method for improving the lubricating properties of water<sup>15</sup>.

Coefficients of friction and wear rates of PPO and POM in O/W emulsions of different oil contents are shown in Fig 6. These results demonstrate clearly how effective are small amounts of oil in improving the lubricating properties of water. Coefficients of friction are lower in the emulsions than in water alone, and are as low in the 1 vol % oil emulsions as in pure oil. The coefficient of friction of PPO is reduced by more than that of POM, relative to the values in water. Wear rates of these two polymers appear to have minimum values as the oil content is increased and further experiments in more dilute emulsions showed that the minimum for PPO occurred at about 1 vol % oil in fact between 0.2 and 5 vol %. Wear rates were reproducible to within a factor of 2-3 as shown by the repeat results for PPO in Fig 6a.

Very little modification of the counterface occurred in all these experiments apart from a slight change in reflectivity within the wear track. This effect was too small to be detected by profilometry. Perhaps the most significant observation was that, before clearing, the wear track produced by both polymers appeared to be covered by a thin, paste-like film of wear debris and fluid.

Wear rates of PPS and PTFE were also measured in O/W emulsions, and these results are given in Fig 7. The behaviour of PPS (Fig 7a) is very similar to PPO. With PTFE, however, (Fig 7b) a minimum wear rate is not apparent, although coefficients of friction follow the same trend as for the other three polymers. In addition, no wear debris from the PTFE pin was observed on the counterface in any of the emulsions.

There are a number of explanations which may account for the ability of small concentrations of oil to reduce the friction and wear rates of polymers in water. One possibility is that the presence of the oil droplets increases the effective viscosity of the lubricant within the area of contact between the sliding surfaces, thus increasing any contribution from hydrodynamic lubrication. However, there is certainly no significant increase in the bulk viscosity of the emulsion containing 1 vol % oil, as the results in Table 3 show; only when the oil content is increased above 5 vol % is there any appreciable rise in viscosity. In addition, Spikes *et al*<sup>16</sup> have shown that the elastohydrodynamic properties of dilute O/W emulsions are little different from those of water alone. Thus, only with PTFE, where the wear rates decrease monotonically with increasing oil content, could a rise in 'local' viscosity explain the results.

A second possibility is that one of the additives in the oil is mildly corrosive towards the counterface. Effects of corrosion on wear have been reported by Lancaster<sup>11</sup> for carbon fibre-reinforced composites sliding against a stainless steel counterface in sea water and other aqueous solutions. The results of an experiment to examine possible effects of counterface corrosion by a 1 vol % oil/water emulsion using PPO are given in Fig 8. On changing from water to the emulsion (point A) there is an immediate drop in friction and wear. On reversing this change, at point B, both friction and wear increase to almost the same values as during the initial water-lubricated period. Thus, any permanent effect due to corrosion of the counterface during sliding in the O/W emulsions is very small.

This conclusion is reinforced by the results shown in Fig 19 for sliding of PPO and POM in O/W emulsions against a glass counterface. With only minor differences, the effect of increasing oil content on the friction and wear of PPO and POM is the same as against stainless steel. In particular, there is a minimum wear rate, albeit more shallow, for both polymers in the 1 vol % emulsion. Hence the effects observed cannot be due to any specific interaction between the emulsion and the metal counterface.

### 3.4 Wear of polymers in aqueous solutions of surface active agents

An essential ingredient of an oil intended for use as an emulsion is the emulsifier. By their nature, emulsifiers are surface active agents because each molecule contains both polar (hydrophilic) and non-polar (lipophilic) functional groups. Hence, these substances are very similar in structure to conventional boundary lubricants. Spikes<sup>17</sup> has found that a mixture of two emulsifiers (sorbitan trioleate and polyoxyethylene sorbitan trioleate) in solution in liquid paraffin is an effective boundary lubricant for steel sliding on steel. Likewise, aqueous solutions of a singular non-ionic detergent have been shown to reduce the coefficient of friction of polymers sliding against themselves<sup>9</sup>.

Wear rates of PPO and POM were measured during sliding in aqueous solutions of a 1:1 mixture of sorbitan monopalmitate and polyoxyethylene sorbitan monopalmitate. This emulsifier combination is typical of those used for stabilising O/W emulsions<sup>16</sup>. The results are given in Fig 10. Wear rates were also measured in aqueous solutions of an ionic surface active agent, sodium 1-dodecyl sulphate, and these results are given in Fig 11. The effects of concentration on coefficients of friction and wear rates for both polymers resemble those found with the O/W emulsions (Fig 6), and the resemblance is particularly strong with PPO. Wear rates in both types of solution are greatly reduced at very low solute

concentrations in comparison to wear rates measured in water; also, increasing the concentration does not lead to significantly lower wear rates. The wear tracks appeared to be similar to those produced in the O/W emulsions, *ie* a semi-liquid transfer film and very mild counterface wear. Thus, the ability of O/W emulsions to reduce the coefficient of friction and wear of PPO can presumably be attributed largely to the boundary lubrication provided by the emulsifier.

The results for POM are less convincing. Wear rates in the emulsifier solutions (Fig 10b) are not reduced to the same extent as in dilute O/W emulsions, and in SDS solutions the wear rate falls monotonically with increasing concentration. Thus, it appears that the boundary lubricating effects of dissolved additives are selective, and depend on the nature of the polymer.

#### 4 DISCUSSION

The friction of polymers during lubrication by pure liquids, and by liquid mixtures and aqueous solutions has been interpreted in terms of the ability of the liquid to wet the polymer once the surface tension falls below a critical value<sup>7-9</sup>. Measurement of the surface tensions of the O/W emulsions (Table 3) shows that in the present case, wetting is not an important factor in reducing the wear rates of the polymers. For example, the surface tension of the 1 vol % oil emulsion is higher than the critical surface tension for wetting of both PPO and POM (41 and 29-38 mN/m respectively<sup>18</sup>), but this emulsion is an effective lubricant for both polymers. The most probable explanation is that an adsorbed layer forms on the counterface because both metal and glass surfaces are wet by all organic liquids examined in this Report. The ability of this adsorbed film to reduce the wear rate of the polymers is then likely to depend on its resistance to disruption. This, in turn, depends on both the adhesion and also the cohesion within the adsorbed layer. Thus, a possible explanation of the result that PPS and PTFE have lower wear rates when lubricated by n-hexadecane than by n-hexane (Fig 2) is the increased cohesion within an adsorbed layer of n-hexadecane, as a result of its longer chain. This hypothesis might be examined further by measuring wear rates of polymers in homologous series of liquids, analogous to the friction measurements of Fort<sup>6</sup> with poly (ethylene terephthalate) sliding in various n-alkanes, fatty acids and alcohols.

Wear tracks produced during sliding in O/W emulsions resemble those described by Lancaster<sup>19</sup> for carbon fibre reinforced epoxy composites sliding in lubricants such as di-2 ethyl hexyl sebacate. Analysis of the latter showed that the transfer film contained both matrix resin and lubricant and the results obtained with thermoplastic polymers sliding in O/W emulsions are consistent with

a similar explanation. The particular effectiveness of the O/W emulsions with PPO may thus be attributed to the ease with which PPO can be plasticised and therefore become intimately mixed with the other constituents in the transfer film. Both POM and PTFE are less affected by fluids and so wear debris is not easily incorporated into the boundary lubricating layer.

The minimum wear rates observed with PPO, POM and PPS in the 1 vol % oil emulsion are not easily explained. A minimum in surface tension with increasing concentration of an aqueous solution of ionic surface active agent has been reported<sup>20</sup>, which implies increased surface activity and hence, possibly, lower wear rates. Such minima in surface tension occur when there is more than one surface active species present<sup>21</sup>, as is the case with the O/W emulsions. However, there are other, equally speculative explanations. For example, as the oil concentration is increased, the emulsifier molecules may form aggregates, analogous to micelle formation in simple solutions of amphipathic substances. The mobility of molecules in such aggregates is reduced<sup>22</sup> and this may affect the rate at which boundary lubricating films can reform after being disrupted during the sliding process. However, despite uncertainties about the precise mechanisms involved, the important practical conclusion is that wear rates of thermoplastic polymers may be significantly reduced in dilute O/W emulsions, primarily as a result of the way in which the counterface is modified during sliding.

Wear rates of thermosetting resin composites in water also depend on counterface modification, but with these materials polishing of the counterface is more important. For three composites for which data are available, wear rates in water (Fig 4) are in reverse order of abrasiveness of the filler; asbestos fibres are more abrasive than type 2 carbon fibres which, in turn, are more abrasive than type 1 carbon fibres<sup>23</sup>. These results are in full accordance with the observations of counterface polishing described in section 3.2.3. In contrast, counterface modifications play no part in the wear of thermoplastic polymers in water alone. Wear rates of these materials are thus determined mainly by the mechanical properties of the polymers themselves and the results of Lancaster<sup>24</sup> suggest that the toughness, as expressed by the product of strength and elongation to break, could be relevant in this respect. Although wear rates of filled thermoplastic polymers have not been examined in this work, it is reasonable to expect that counterface modifications by fillers would be broadly similar to those with reinforced thermosetting resins, and thus produce corresponding effects on wear rates

It is interesting to compare the wear rates of the thermosetting resin composites with those measured using a journal bearing test rig<sup>25</sup>. Comparative data

are available for two of the materials. Wear on the journal bearing rig was measured in water-lubricated conditions at 22kg load and 500 rev/min. For epoxy/bronze/PTFE/graphite wear rates measured with the pin-on-disc apparatus and on the journal bearing rig are  $4 \times 10^{-5}$  and  $5 \times 10^{-9} \text{ mm}^3/\text{Nm}$  respectively; the corresponding values for the asbestos fibre/phenolic composite are  $4 \times 10^{-6}$  and  $4 \times 10^{-8} \text{ mm}^3/\text{Nm}$ . From the very large discrepancies between these two sets of results, it seems likely that hydrodynamic effects are influencing the journal bearing wear rates. These effects could arise in two ways; firstly, it is known that polymers undergo transitions from boundary lubrication to hydrodynamic lubrication more readily than metals<sup>26</sup> and secondly, for materials with low elastic moduli there is a greater possibility of hydrodynamic lubrication occurring on an asperity scale. The latter phenomenon has been invoked by Lewis<sup>27</sup> to explain results obtained with water lubricated PTFE/carbon-composite thrust washers. It is apparent that the precise role of hydrodynamic lubrication with different sliding configurations needs to be more closely defined.

## 5 CONCLUSIONS

- (1) Wear rates of thermoplastic polymers, sliding in oil in water emulsions containing as little as 1% by volume of oil, can be reduced by up to fifty times, under conditions of boundary lubrication.
- (2) The effectiveness of these emulsions is attributed largely to the preferential adsorption of emulsifier on the sliding surfaces. The boundary lubricating layer may also contain polymer wear debris, and hence the effects depend also on the nature of the polymer.
- (3) Wear rates of thermosetting resin composites in water depend primarily on the ability of the filler to polish the counterface.
- (4) Wear rates of thermoplastic polymers in water depend on their mechanical properties. In general, polymers with high values of the product of strength and elongation to break have low wear rates.
- (5) Further work is required to determine how the extent of fluid-film lubrication during sliding in pin/disc configurations depends on the mechanical properties of the composite materials.

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Table 1POLYMERS AND LIQUIDS IN FIG 1(a) Polymers

- A \*Polyoxymethylene (POM)
- B \*Poly(dimethyl phenylene oxide) (PPO)
- C \*Poly(methyl methacrylate) (PMMA)
- D Polytetrafluoroethylene (PTFE): 25 wt % type 1 carbon fibre
- E \*PTFE - polyimide
- F Epoxy - 60 vol % type 1 carbon fibre

\* Commercially moulded sample

(b) Liquids

- a Poly(dimethyl siloxane)
- b n-Hexane
- c n-Hexadecane
- d Cyclohexane
- e Tricresylphosphate
- f Toluene
- g Carbon tetrachloride
- h Diethyl hexyl sebacate
- i Benzene
- j Acetone
- k n-Octanol
- l n-Propanol
- m Dimethyl formamide
- n Methanol
- p Ethylene glycol
- r Formamide
- s Water

Table 2POLYMERS AND COMPOSITES USED IN WATER-LUBRICATED EXPERIMENTS(a) Thermoplastics

Poly(phenylene sulphide) (PPS)

\*Poly(methyl methacrylate) (PMMA)

\*Poly(dimethyl phenylene oxide) (PPO)

\*Polytetrafluoroethylene (PTFE)

\*Polyethylene } - low density, LDPE  
                  } - ultra high molecular weight (UHMWPE)

\*Polyurethane (PU)

\*Polyoxymethylene (POM)

\*Nylon 6.6

(b) Thermosetting

\*Epoxy/bronze/PTFE/graphite

\*Phenolic/cotton fabric/PTFE

Epoxy/60 vol % type 1 carbon fibre

Epoxy/60 vol % type 2 carbon fibre

\*Phenolic/asbestos mat

\*Phenolic/cotton fabric

\*Phenolic/asbestos fibre

Epoxy/60 vol % type 2 carbon fibre + 0.1 wt % 3  $\mu$ m  $Al_2O_3$ 

\* Commercially moulded sample

Table 3  
RELATIVE VISCOSITIES AND SURFACE TENSIONS OF OIL IN WATER EMULSIONS MEASURED AT 30°C

Vol % oil	Relative viscosity	Surface tension $\text{mN m}^{-1}$
0	1.00	71.5
1	1.02	53.2
5	1.11	45.2
25	2.06	33.2
100	35.0	28.5

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Fig 1

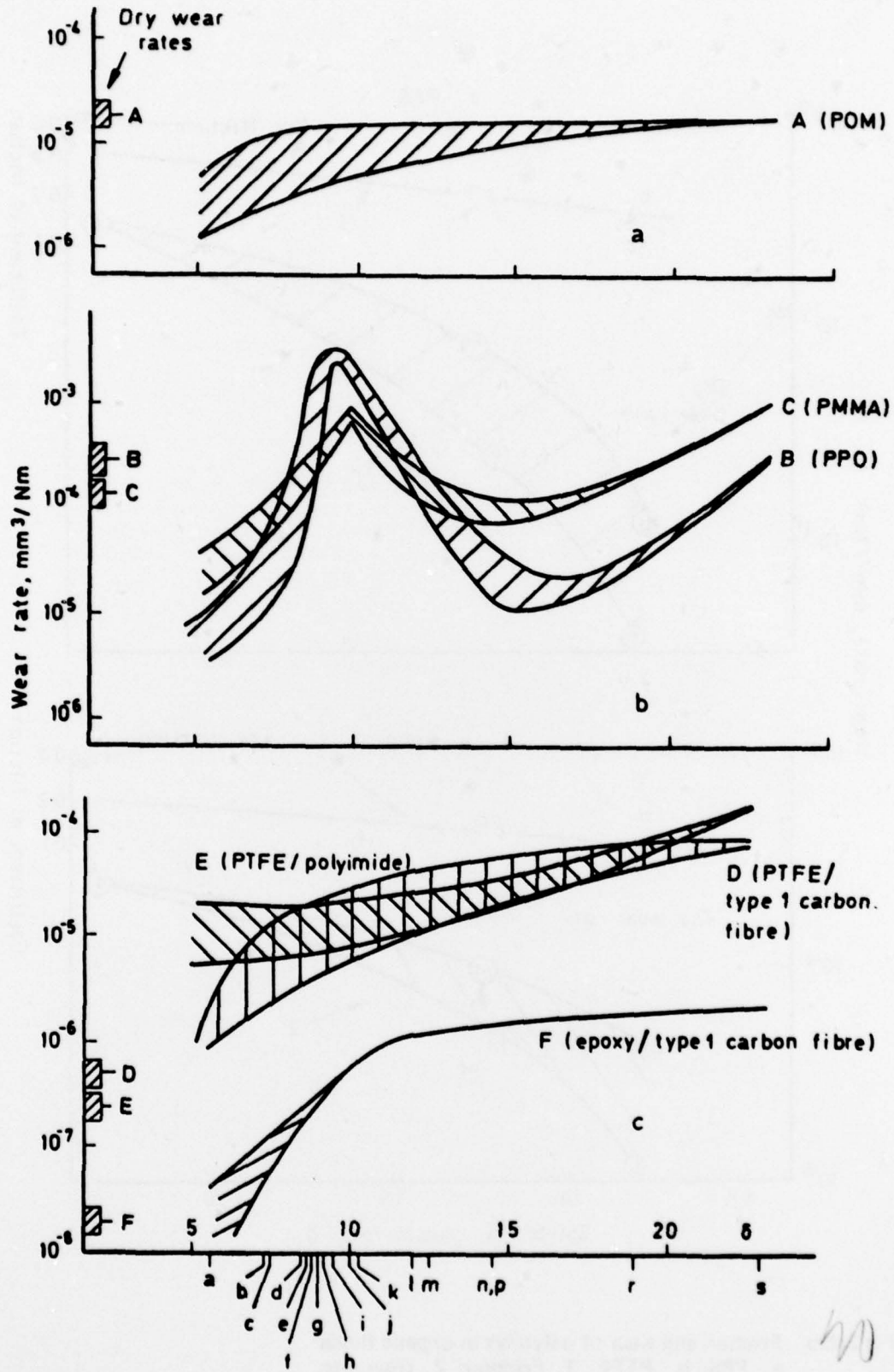


Fig 1 Effects of fluids on the wear rates of polymers

Fig 2a&b

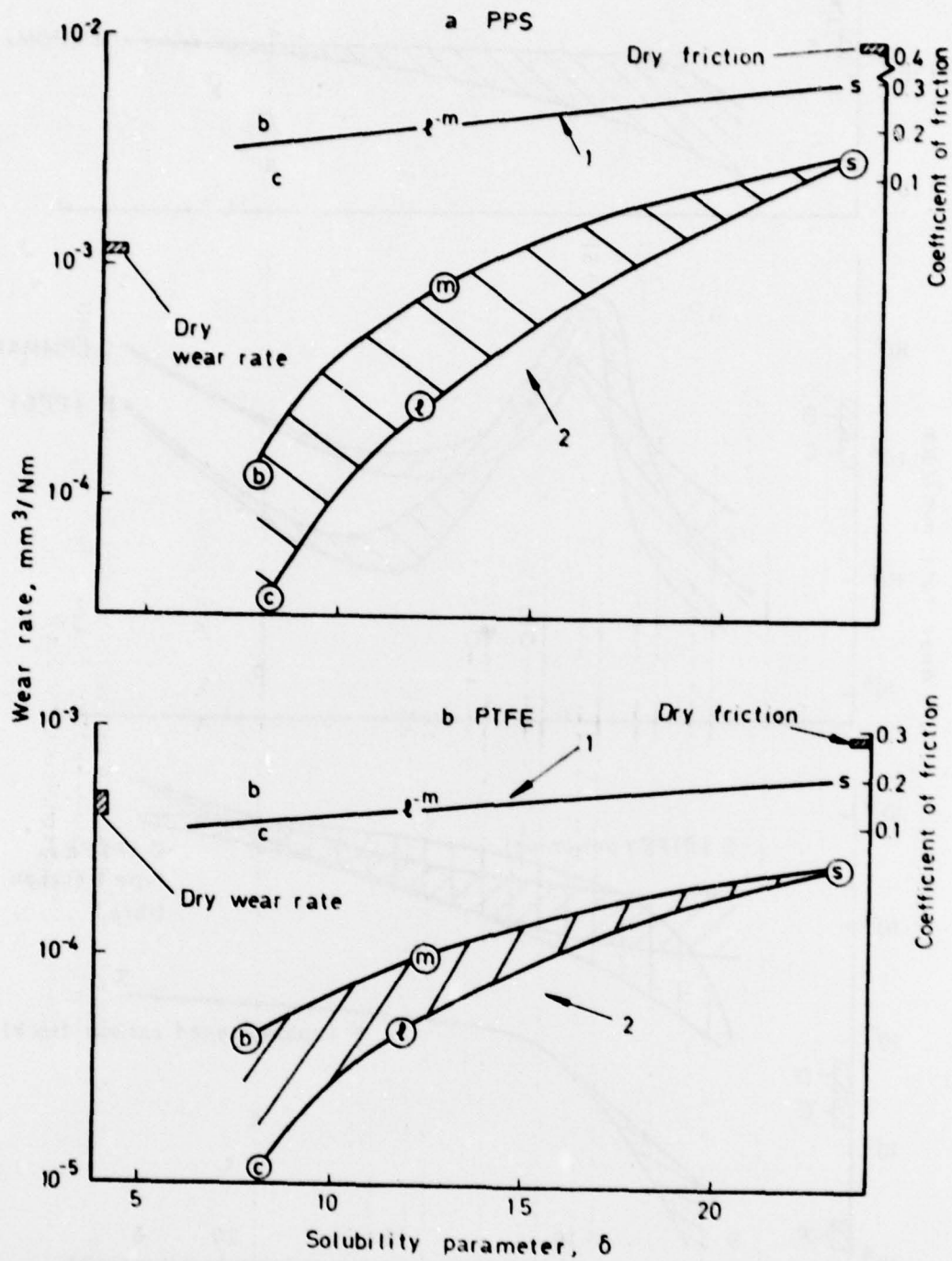


Fig 2a&b Friction and wear of polymers in organic fluids  
 a PPS; b PTFE. 1 Friction; 2 Wear rate.  
 Sliding speed  $0.15-0.25 \text{ ms}^{-1}$ ; load = 10 N; counterface - S130B stainless steel

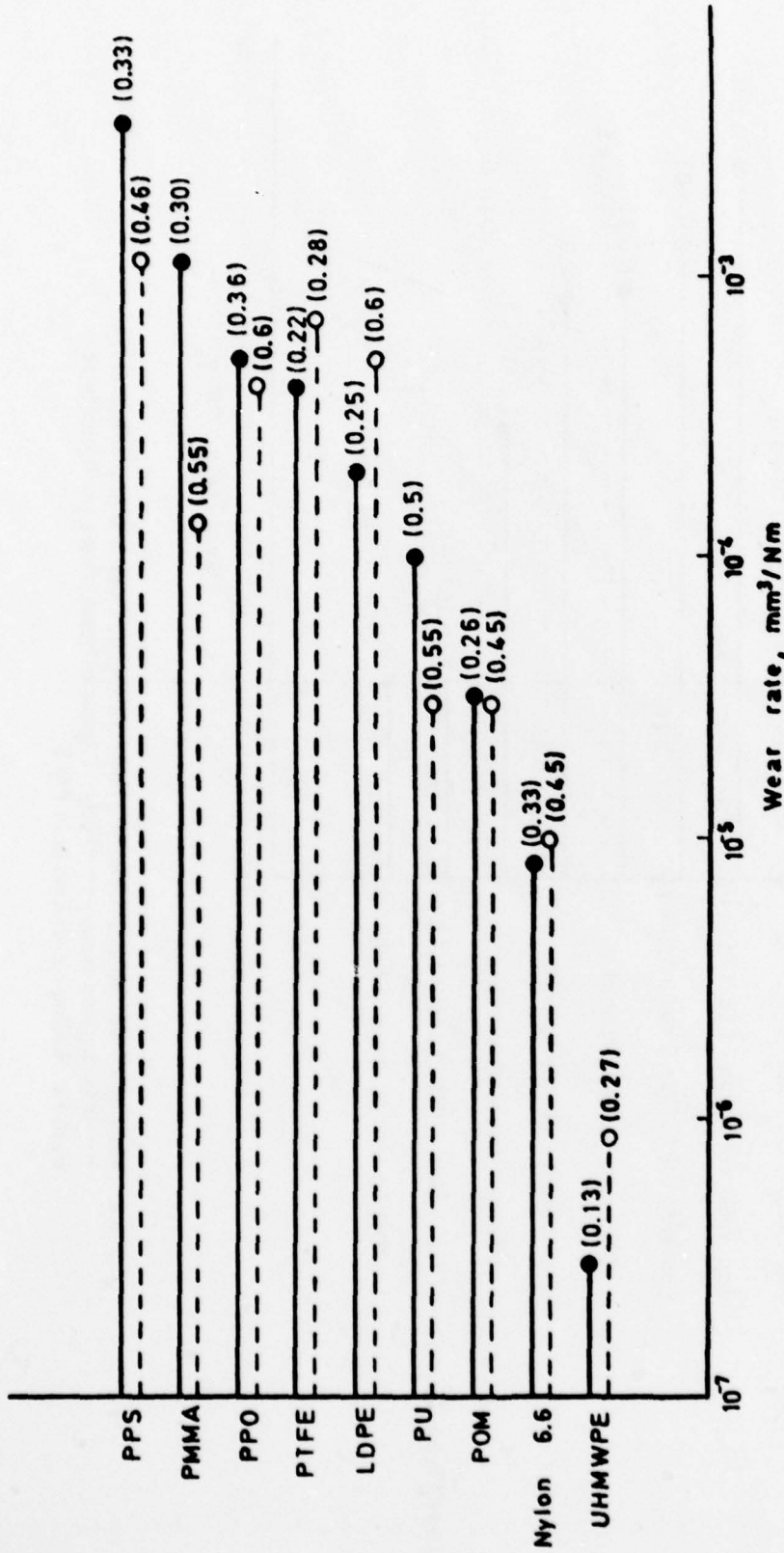


Fig 3 Wear rates of thermoplastic polymers dry and in distilled water  
 —●— In distilled water; ---○ Dry. Figures in brackets are coefficients  
 of friction. Sliding conditions as in Fig 2

Fig 4

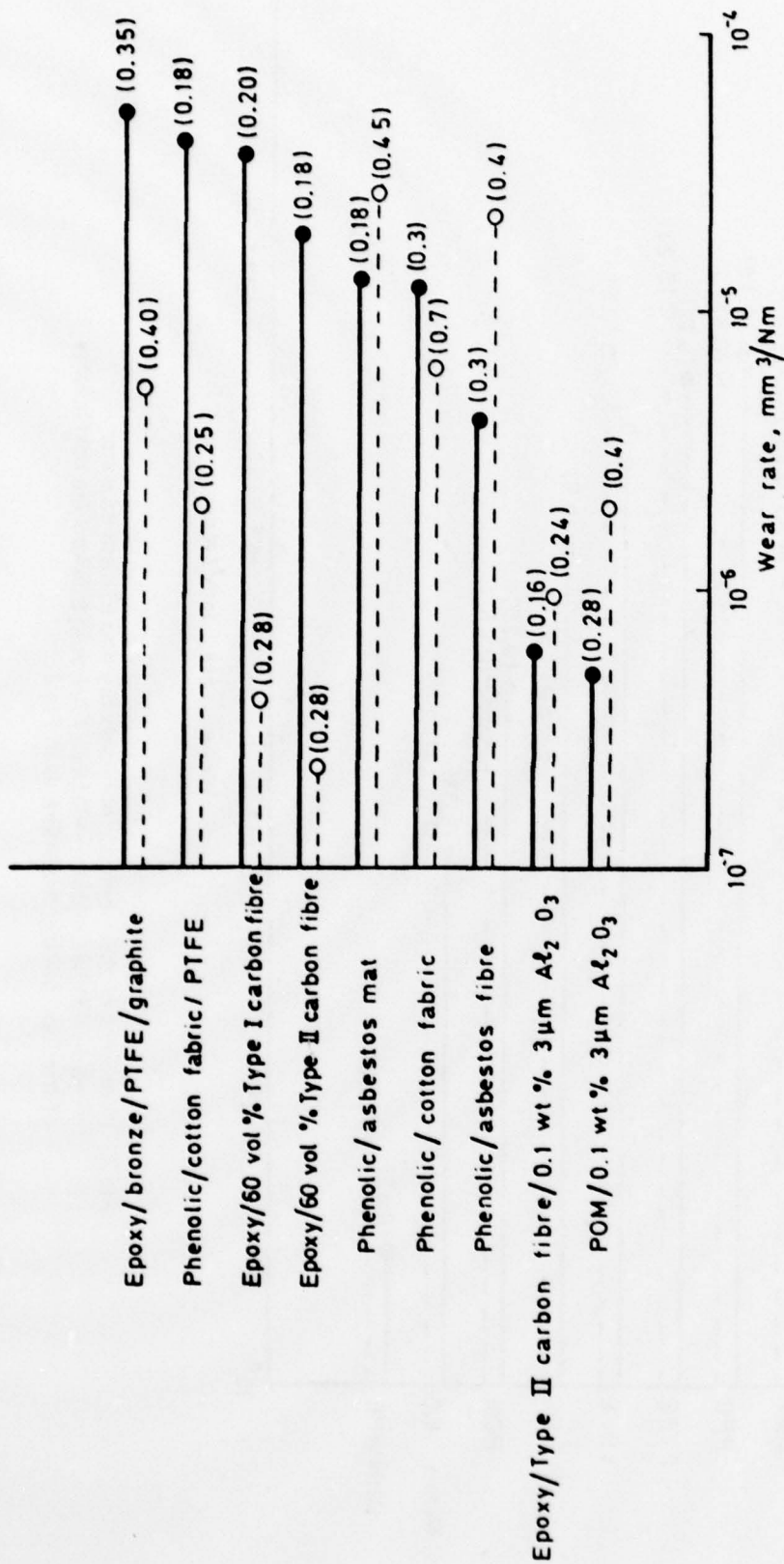
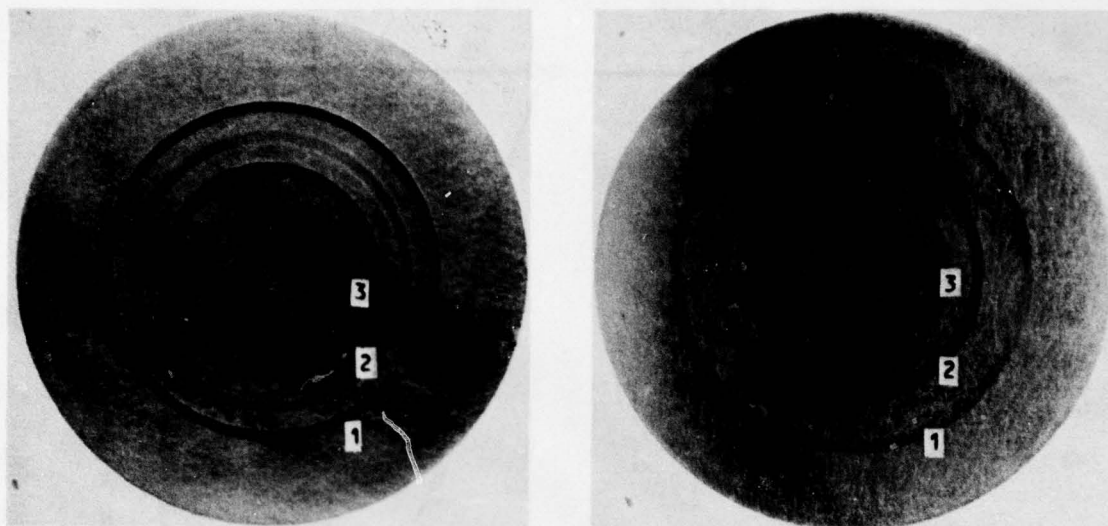


Fig 4 Wear of reinforced thermosetting resin composites, dry and in distilled water. —●— In distilled water; ---○--- Dry. Figures in brackets are coefficients of friction. Sliding conditions as in Fig 2



a

b

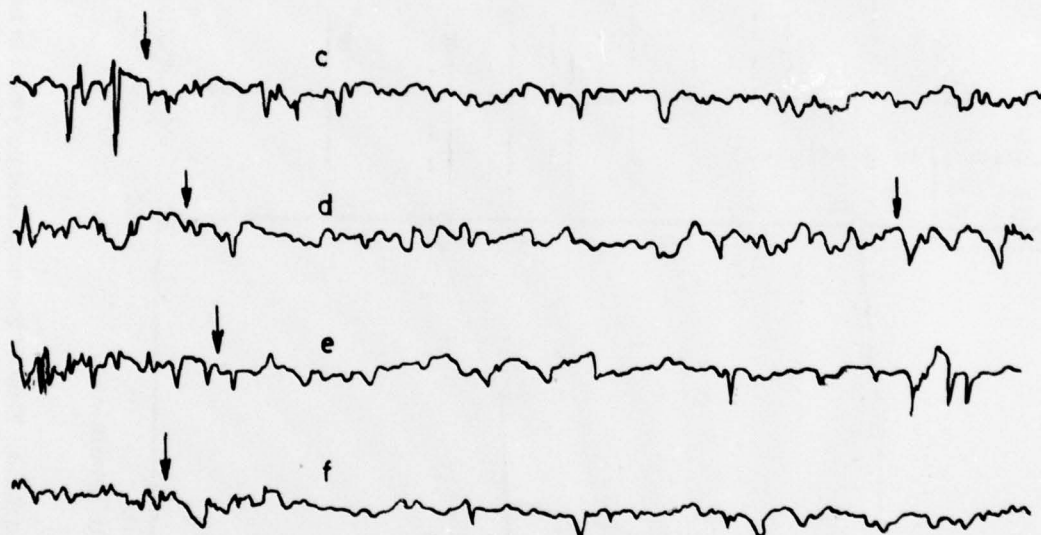


Fig 5a-f Photographs and profiles of wear tracks on stainless steel counterface

a Dry, b In distilled water

1 Epoxy/60 vol % type 1 carbon fibre

2 Phenolic/asbestos fibre

3 Epoxy/bronze/PTFE/graphite

c-f In distilled water. Vertical magnification x100; horizontal magnification x10000

c Epoxy/bronze/PTFE/graphite

d Phenolic/asbestos fibre

e Epoxy/60 vol % type 1 carbon fibre/0.1 wt %  $3 \mu\text{m Al}_2\text{O}_3$

f POM/0.1 wt %  $3 \mu\text{m Al}_2\text{O}_3$

Fig 6a&b

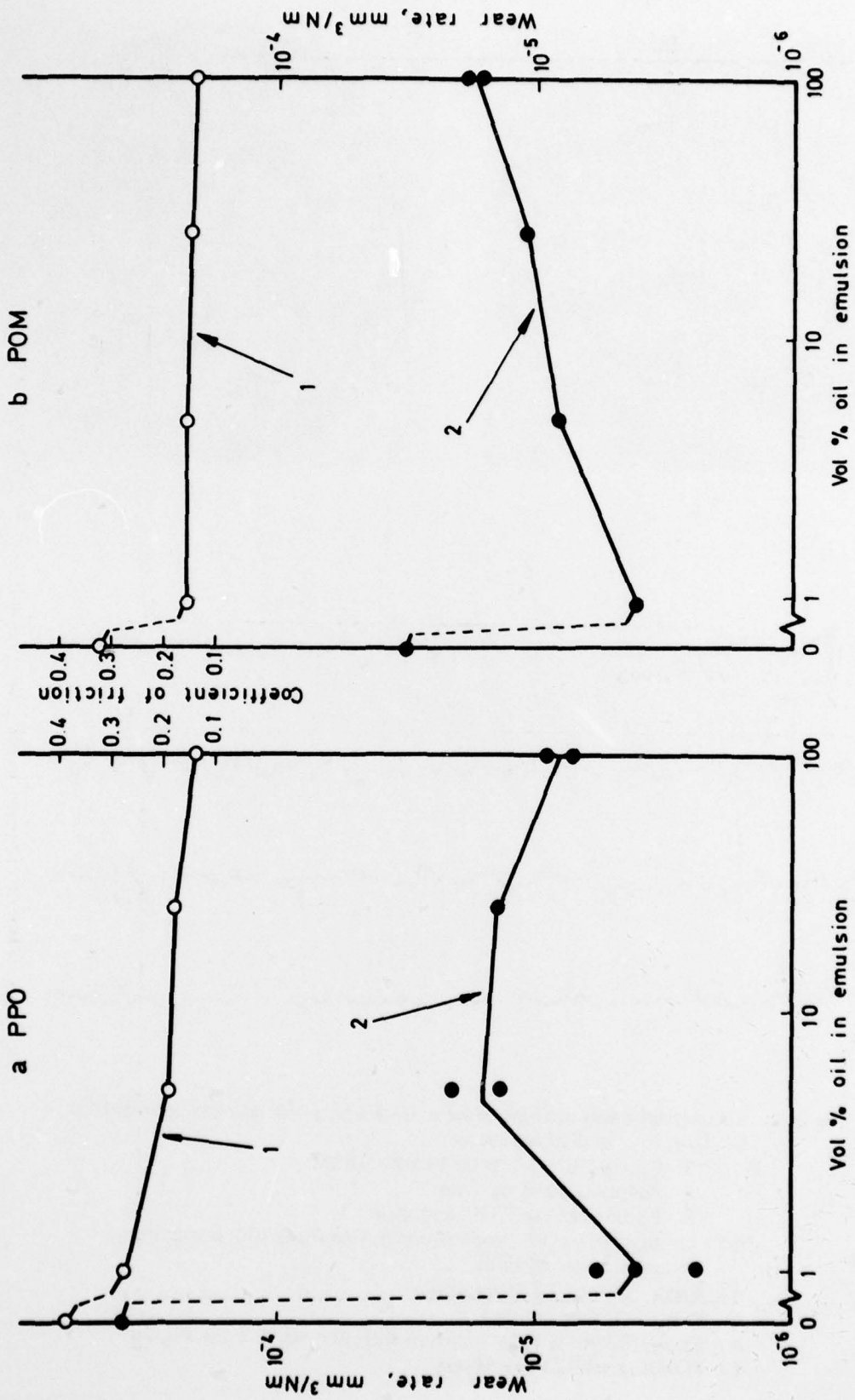


Fig 6a&b Wear of thermoplastic polymers in oil-in-water emulsions  
a PPO; b POM. 1 Friction; 2 Wear.  
Conditions as in Fig 2

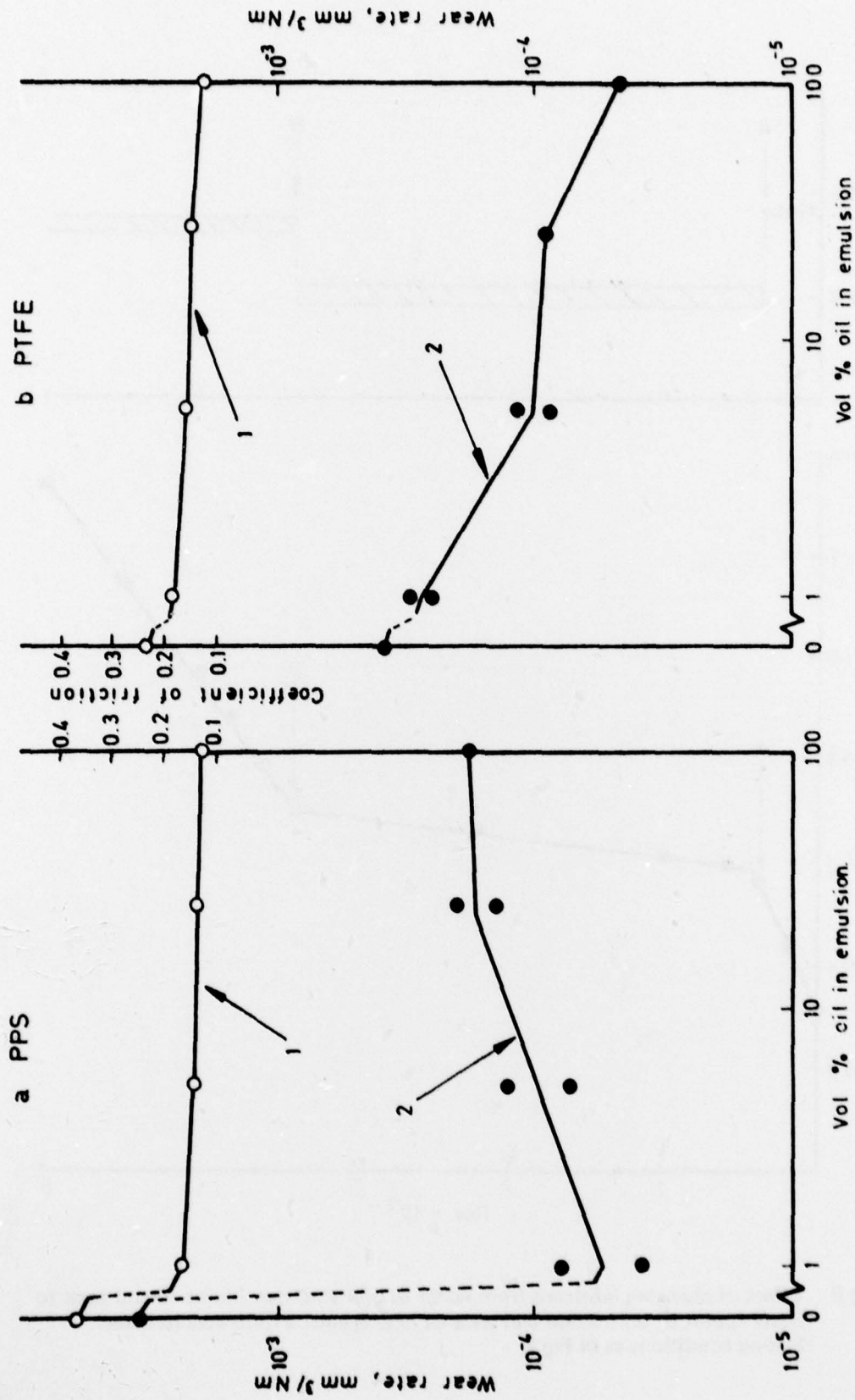


Fig 7a&b

Wear of polymers in oil-in-water emulsions. a PPS; b PTFE.  
 1 Friction; 2 Wear. Sliding conditions as in Fig 2

26

Fig 8

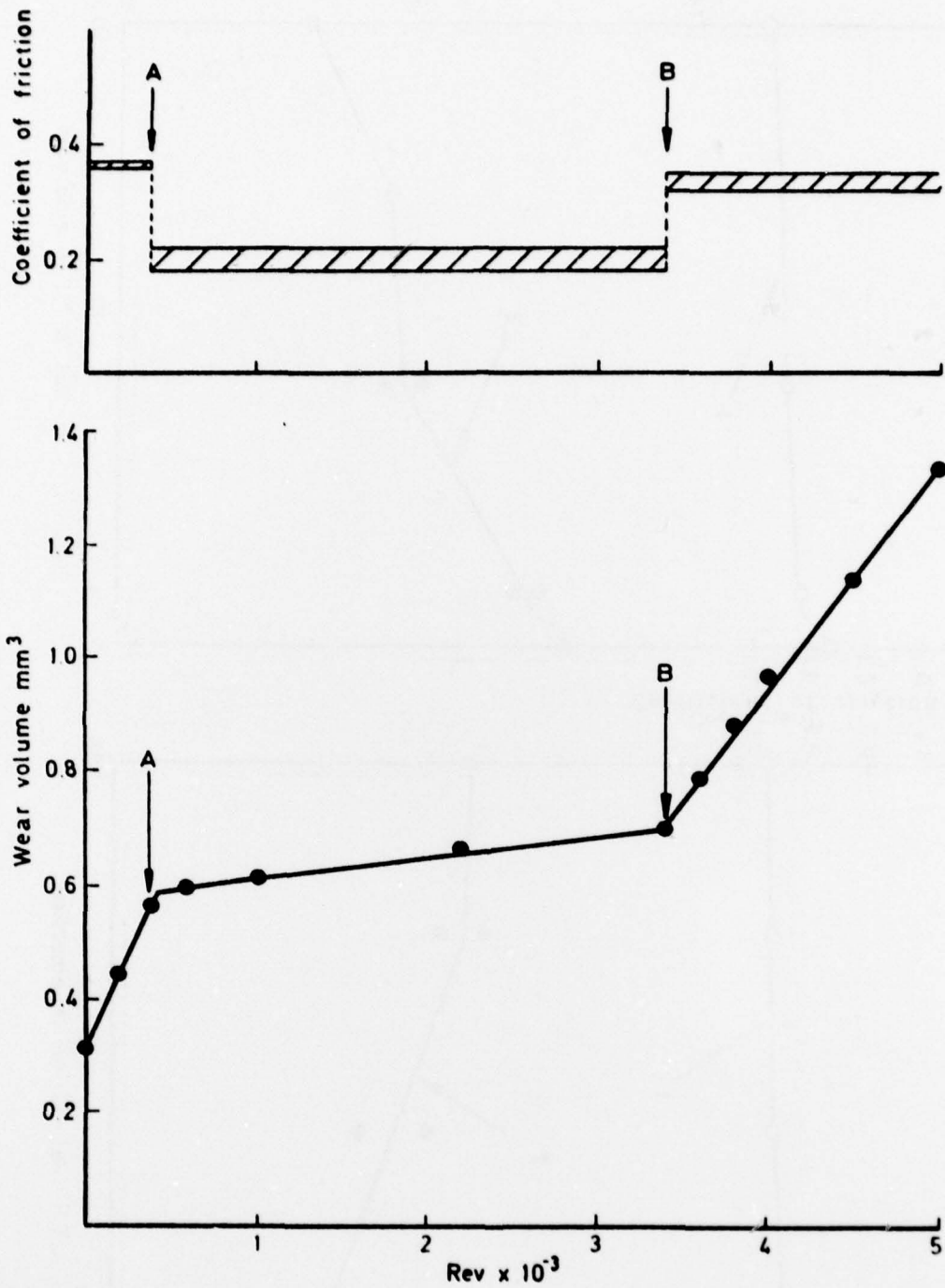


Fig 8 Effect of changing lubricant from water to o/w emulsion (point A) and back to water (point B) on friction and wear of PPO against S130B stainless steel. Sliding conditions as in Fig 2

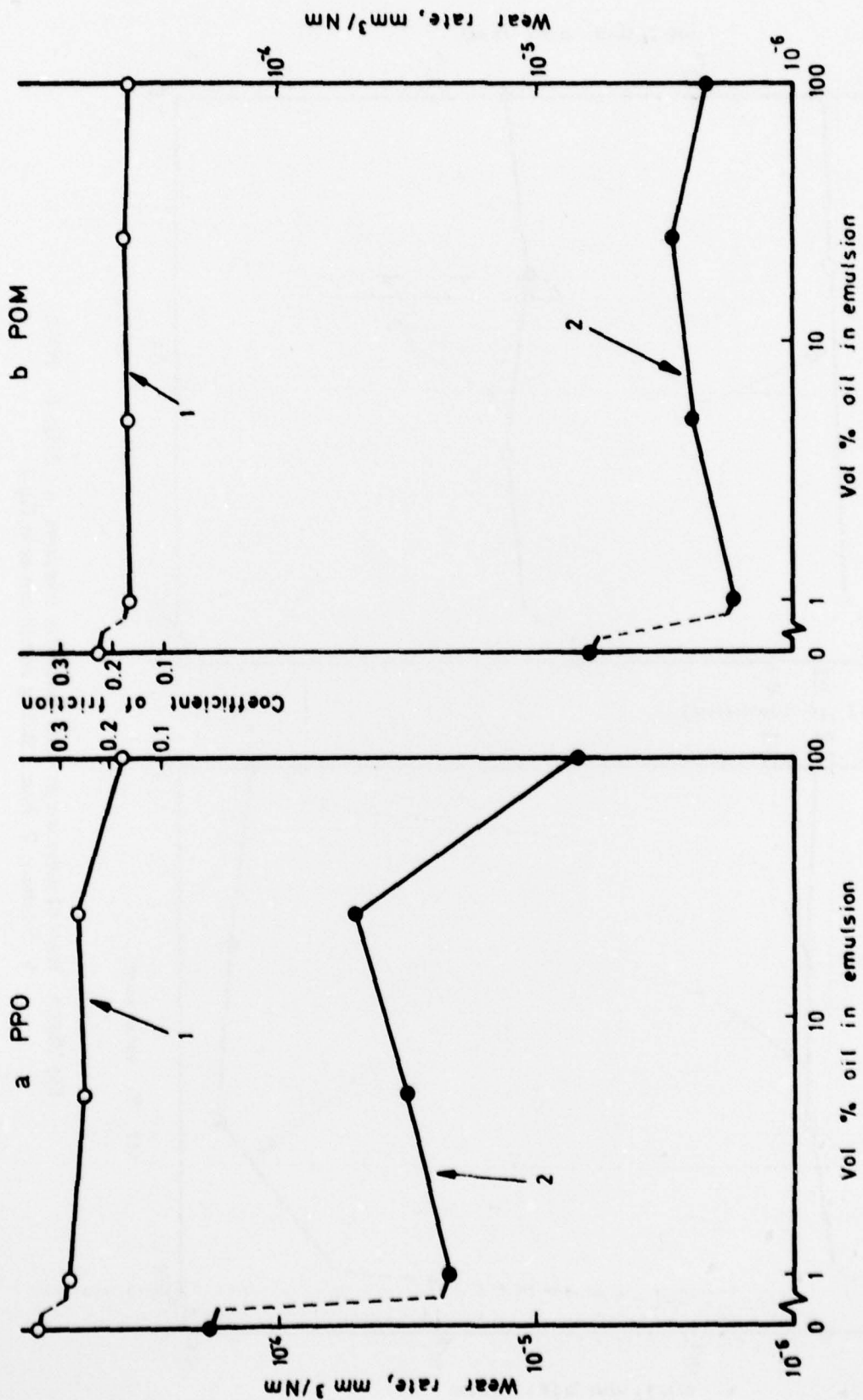


Fig 9a&b

Fig 9a&b Wear of polymers in oil-in-water emulsions. a PPO; b POM.  
 1 Friction; 2 Wear. Glass counterface; other sliding conditions as in Fig 2

Fig 10a&b

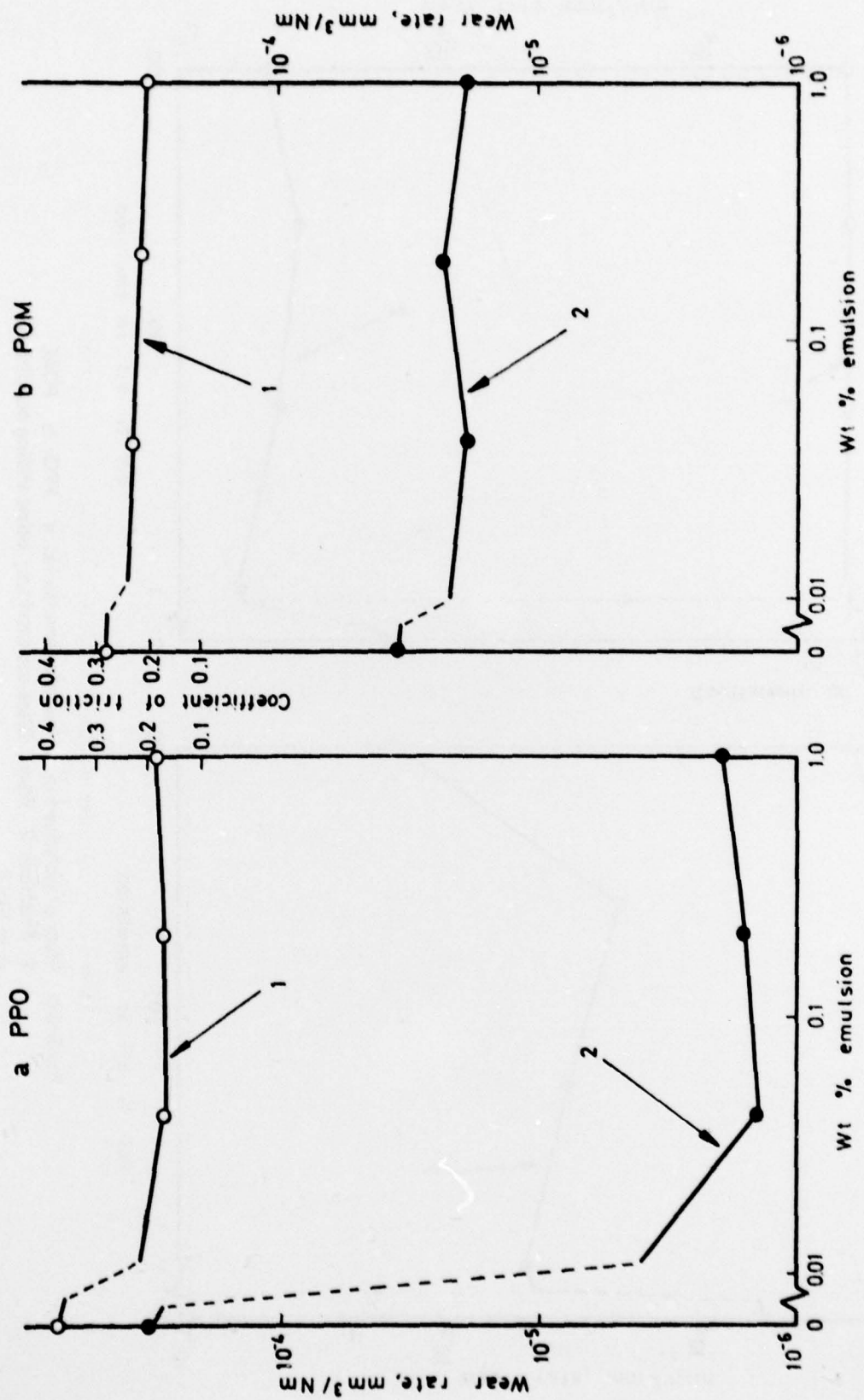


Fig 10a&b Wear of polymers in water-emulsifier mixtures. a PPO; b POM.  
1 Friction; 2 Wear. Sliding conditions as in Fig 2

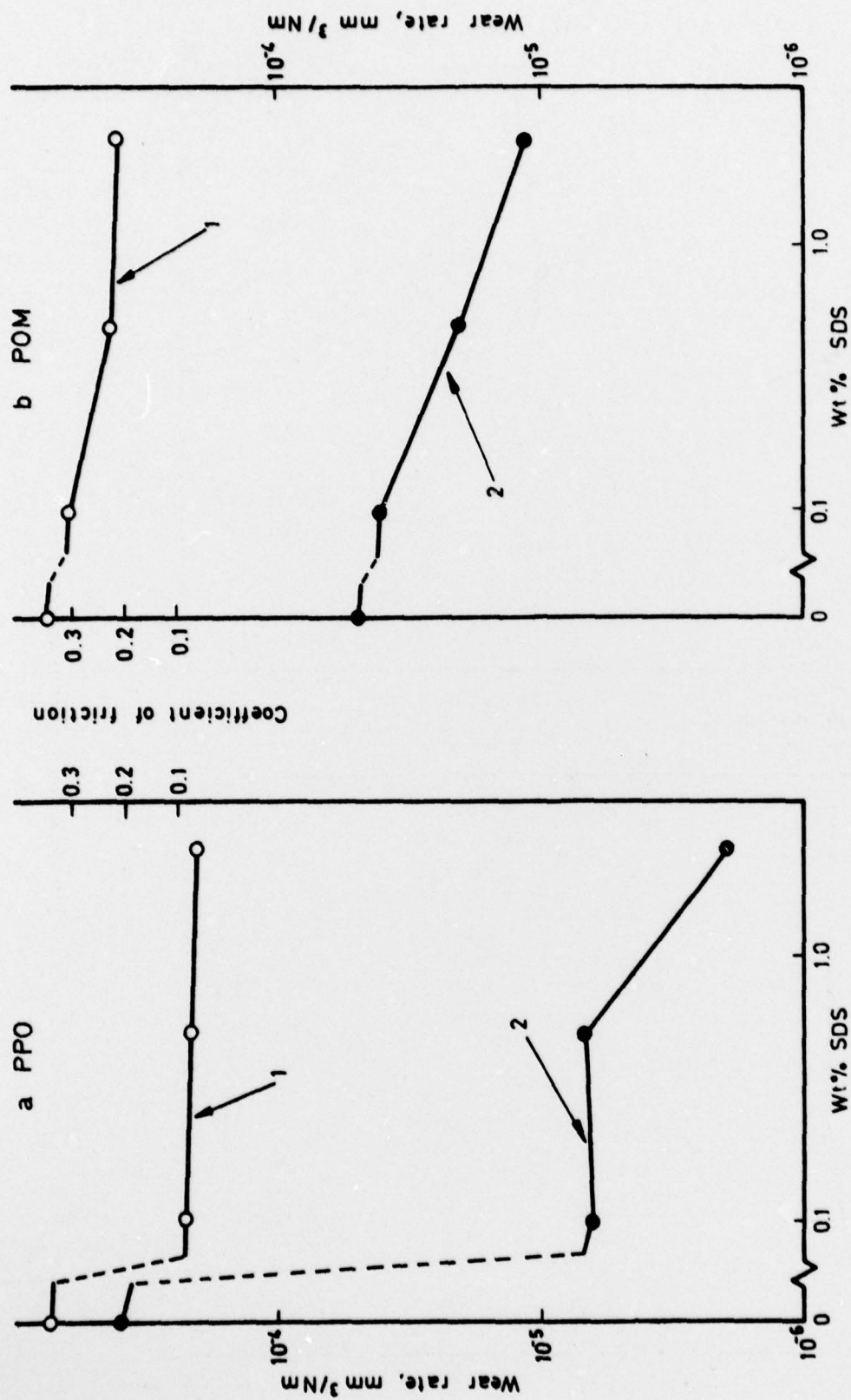


Fig 11a&b Wear polymers in aqueous sodium dodecyl sulphate solutions.  
a PPO; b POM. 1 Friction; 2 Wear. Sliding conditions as in Fig 2

Fig 11a&b

30