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Friction of diamond, syndite and amborite sliding on various alloys

C. J. FREEMAN*, J. E. FIELD
Department of Physics, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

This study describes the movement of styli of diamond, Syndite and Amborite (products of De Beers Industrial Diamond Division, Charters, UK) back and forth across a range of substrate materials and the coefficients of friction recorded. Syndite and Amborite are products made by heating polycrystalline diamond or cubic boron nitride at high pressure in the presence of suitable metallic binders. Diamond, Syndite and Amborite all have applications in machining, wire drawing, turning etc., though the relative performance depends on the material being worked. Results for a range of metals and alloys are discussed. It is shown that the trends found in machining practice are also reflected in the frictional properties. Although the loads and speeds are much lower in the friction experiments, it appears that monitoring the friction for repeated traversals does give important information and allows a more controlled study of the processes occurring between the stylus and work-piece such as film transfer, the effect of lubricants etc.

1. Introduction

The frictional properties of diamond, Syndite and Amborite are important, due to the increased industrial use of these materials in processes such as machining, wire drawing, turning, boring, milling etc. Diamond has great attractions in most of these operations because of its combination of high hardness and high thermal conductivity, which both surpass those of other materials [1]. Syndite is produced from selected synthetic polycrystalline diamond by subjecting it to high temperatures and pressures in the presence of cobalt. The temperatures and pressures are sufficient for some diamond growth and plastic deformation to take place and the particles are usually bridged, forming a skeleton structure [2, 3]. The cobalt phase is ca. 12% by weight. Different grades of Syndite are available depending on the diamond particle size [4]. The hardness value of ca. 48 GPa at 1 kg load [3] and thermal conductivity [5] are ca. 50 and 80% of type II (low nitrogen content) diamond but the fracture toughness (K_{IC}) is a factor of ca. 2.4 times higher. The material can be formed into discs or blocks of several mm [4] and can be backed, if required, by other solids. The greater flexibility in shape and size and the increased toughness can in many situations offset the lower hardness and conductivity.

However, diamond and its products do not machine ferrous alloys well. This has been explained by the carbon being lost from the tool to form a carbide [6, 7, 8]. For this reason, composites have been developed with cubic boron nitride particles sintered in the presence of a metal binder phase. Amborite is such a product, with aluminium nitride and aluminium diboride as the binder phases. Its hardness is ca. 29 GPa at 1 kg load (i.e. ca. 30% of diamond) [3].

The objectives of this paper were to measure the frictional coefficients of diamond, Syndite and Amborite when sliding against various substrates and then to investigate any correlations with machining experience.

2. Experimental procedure

The apparatus used in this study is similar to that used by Enomoto and Tabor [8] and is shown in Fig. 1. The arm consists of a light duralumin beam which is pivoted, counter-balanced and carries a stylus at one end. This can be loaded on to a flat specimen which is tracked by an electric motor. The frictional force between the stylus and sample is measured with strain gauges.

Before each set of friction experiments, the strain gauges were calibrated and the arm balanced. The strain gauges were calibrated by applying a load to each side of the stylus support in turn. The output from the strain bridge was then noted for each different load (50 mN to 1 N) and a calibration graph plotted to give the calibration coefficient. The average friction coefficient for each cycle was calculated by taking the mean of the friction coefficients of the two traversals of each cycle.

The diamond, Syndite and Amborite styli were all in the form of Knoop indenters (i.e. pyramidal, with diagonals in the ratio 7 : 1 [10]). They were oriented so that the sample crossed parallel to their major axis. The styli were all ultrasonically cleaned in acetone before use.

The traversed samples were in various forms. The metallic and alloy samples were machined blocks about 20 mm thick with their top surfaces ground and polished with water-soluble diamond paste (down to

*Present address: Exploration Department, British Gas plc, 59 Bryanston Street, London W1A 2AZ, UK.

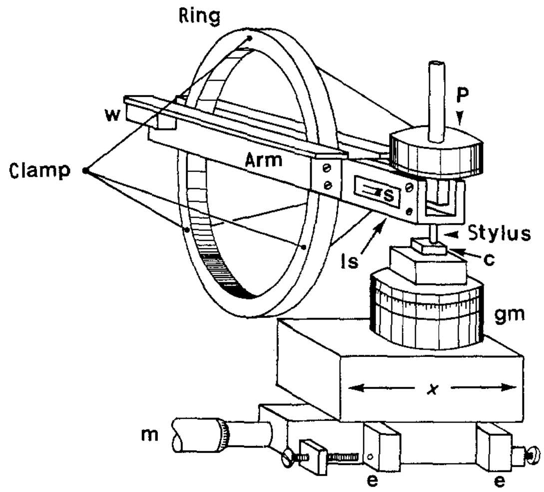

Figure 1 Schematic diagram of the friction apparatus. The micrometer, m, drives the specimen, c, and goniometer, gm, in the x-direction between the microswitches, e. The stylus is attached to the arm by the leaf springs, ls, and to the arm. s is a strain gauge and w a balancing weight.

1 μm) and then cleaned in running water and acetone to obtain a grease-free surface. A few experiments were made with alloy styli on diamond, Syndite and Amborite tool blocks but the results were similar to the same material combinations, but with the diamond, Syndite and Amborite as styli. In a typical experiment, an applied load of 1.0 N was used and 20 cycles over the same track were performed at a speed of 0.2 mm sec^{-1}. The specimen surface and the tip of the stylus were examined after each experiment using both optical and scanning electron microscopy.

3. Results

3.1. Styli on D3 steel

Figure 2 shows the results of experiments on the annealed D3 steel (D3A). The coefficient of friction after 20 cycles for diamond is low (ca. 0.1), for Syndite is ca. 0.19 and for Amborite has a high value of ca. 0.39. Examination of the styli showed negligible transfer onto the diamond but significant transfer onto the Syndite and Amborite. The transferred film could be removed by fine polishing; the styli showed no visible damage.

The experiments were repeated with hardened D3 steel (D3H) of hardness about three times that of D3A (see Table I); the results are given in Fig. 3. The diamond curve is lower, the Syndite unchanged, the Amborite curve shows small changes over the first few cycles but plateaus at the same N = 20 value.

In general, the friction force, F, is equal to an adhesive term (the force F_A to shear asperity junctions) and a ploughing term (the force F_P to displace material producing a groove). The total force F is $F_A + F_P$ [12, 13]. In the case of diamond, the lower friction coefficient with the D3H is most probably due to a decreased ploughing term and this is consistent with the smaller track width found on the harder alloy. The small decrease in μ as N increases from 1 to 5 cycles suggests that a small amount of work hardening is taking place in the alloy. For the Syndite and Amborite, the styli showed no wear, but there was metallic transfer and a groove formed in the alloy. The grooves were of similar width independent of whether the sliding was on D3A or D3H suggesting that, though there was a ploughing term, the strong adhesion between binder and alloy largely determined the observed friction values.

The friction values for the first few passes of the Amborite stylus on the D3H are a little lower than on the D3A and this is consistent with a smaller ploughing term. However, above N = 10 the curves are identical, suggesting that a stable film of the alloy has now transferred. However, the fact that the value at N = 20 is higher than for Syndite suggests that the transferred films are never complete or thick enough to give D3 sliding on D3.

3.2. Amborite on other alloys

The friction between Amborite and a range of other alloys was studied. Amborite does not machine ferrous alloys (mild steel) and high nickel super alloys (Wynite, Nimonic 80A, Inconel 600) particularly well

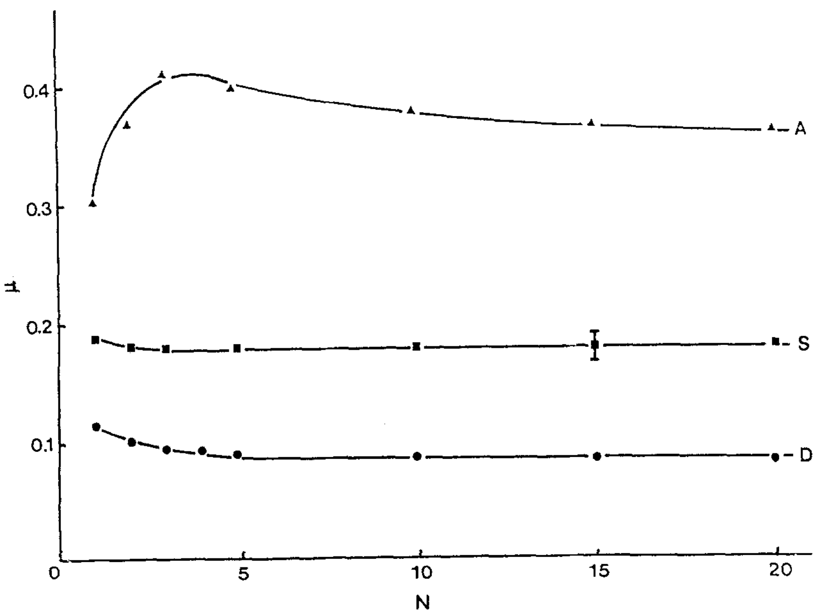

Figure 2 Friction of diamond D, (●), Syndite S, (■) and Amborite A, (▲) styli sliding on the annealed steel D3A, plotted against number of cycles.

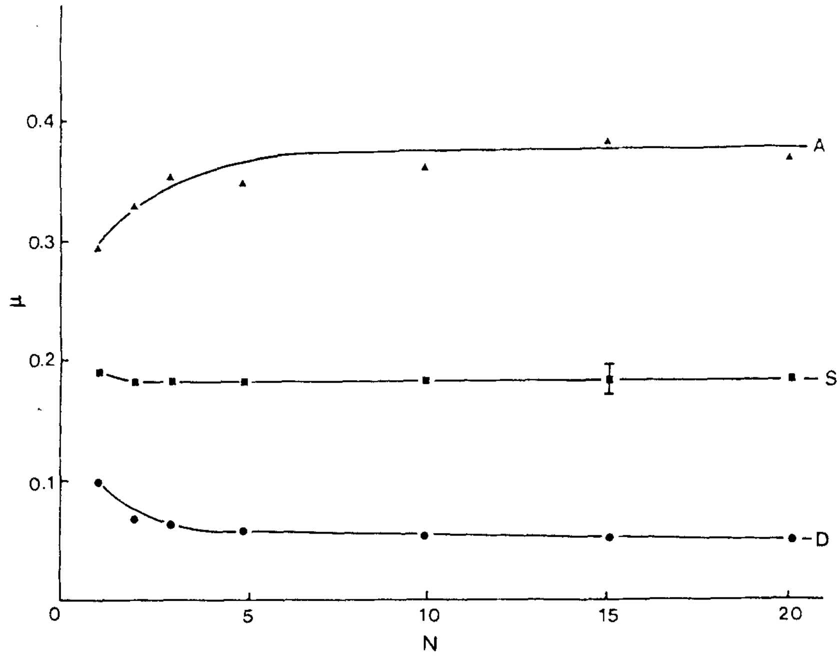

Figure 3 Friction of diamond D, (●), Syndite S, (■), and Amborite A, (▲), styli sliding on the hardened steel D3H, plotted against number of cycles.

[14], and it was of interest to see if this was reflected in the friction results. Nihard 2C was also included as an alloy which Amborite does machine well.

The results are summarized in Table I, and they show a good correlation between machining experience and the friction data. Alloys which Amborite machines well have $\mu <$ ca. 0.4 and track widths, for 0.1 kg loads, of ca. 30 μm. Alloys which machine badly have a higher μ in the range 0.4 to 0.54 and higher track widths of 45 to 60 μm. There is no correlation between hardness and friction for the alloys tested.

3.3. Effect of lubrication

The effect of lubrication on the friction of Syndite and Amborite on D3 steel was also examined. The metal was first cleaned with acetone and water, dried and attached to the specimen stage. Several parallel friction runs were then performed. A small amount of light oil was then added to the surface and the friction experiment repeated. The results for Amborite are shown in Fig. 4. It is seen that the friction is much lower when the metal is lubricated and almost falls to the diamond value (Fig. 3). There was similar behaviour with the Syndite.

4. Discussion

The frictional sliding of three important machining materials has been studied in experiments in which styli were passed across various test pieces. In general, the friction coefficient increased in the order diamond, Syndite, Amborite. The metallic binder phase in Syndite is cobalt. A stylus of pure cobalt rubbing on D3A gave a friction value which increased to a plateau value of ca. 0.3 after 20 passes. Thus, though there is only ca. 12% by weight of cobalt in Syndite, it significantly increases the friction value above that for a diamond stylus on D3A (Fig. 2). Experiments with a boron nitride crystal and styli of aluminium nitride

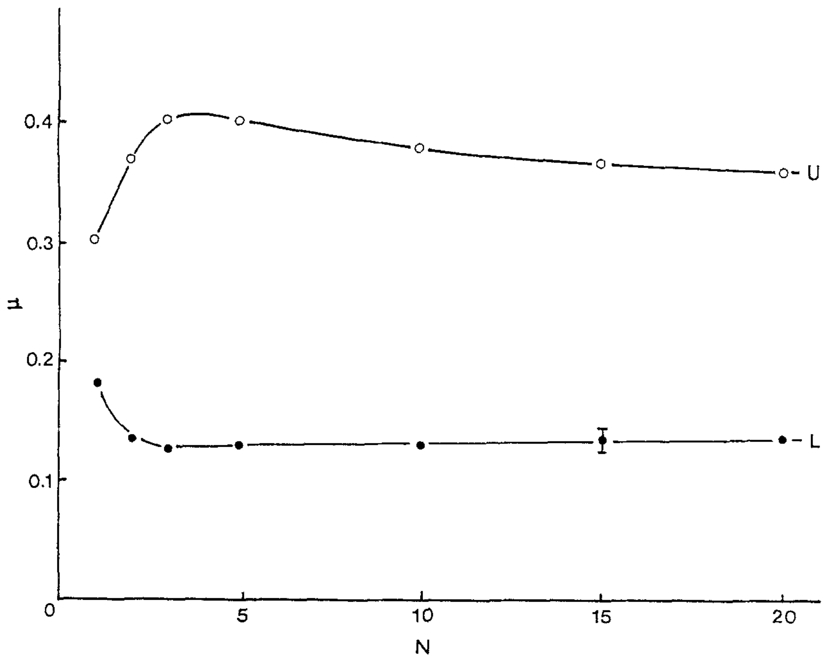

Figure 4 Friction of Amborite on the steel D3A; lubricated L, (●), and unlubricated U, (○), plotted against number of cycles.

TABLE I Vickers hardness, H, and coefficient of friction, μ, after 20 cycles, and 0.1 kg load, for an Amborite stylus on a range of metallic alloys

Metal	H/kg mm^{-2}	μ ($\pm$0.01)	Friction track widths/μm ($\pm$1 μm)	Machining experience G = good P = poor
D3A	230 $\pm$ 5	0.39	32	G
D3H	700 $\pm$ 10	0.39	33	G
Mild steel	200 $\pm$ 5	0.45	53	P
Wynite	230 $\pm$ 10	0.40	50	P
Nimonic 80	335 $\pm$ 10	0.50	45	P
Inconel 60	170 $\pm$ 5	0.54	60	P
Nihard 2C	620 $\pm$ 20	0.35	28	G

and aluminium diboride (the binder phases in Amborite) sliding on D3A gave high friction values (in the range μ = 0.3 to 0.4) after 20 passes. The high friction of Amborite is therefore not surprising.

There was little film transfer with diamond. The lower friction value of diamond sliding on D3H compared with D3A is consistent with a reduced ploughing term. The results for Syndite and Amborite on D3 suggest that film transfer is the key to their behaviour. However, since the Syndite and Amborite results do not plateau at the same value, it suggests that the situation with a complete film of D3 sliding on D3 is not achieved.

Oil lubricants had little effect on the diamond/alloy friction but reduced the friction of Syndite and Amborite to a value of similar magnitude to that of diamond on diamond, further evidence that there is little metallic transfer in the former case.

The results of Table I show that there is a good correlation between friction results and machining experience. Alloys which are not machined well have high friction values and large track widths for a particular load. The friction test, therefore, appears to have potential for sorting out which tool/work-piece combinations are likely to work well in practice, and whether particular lubricants are beneficial or not. Processes of film transfer etc. can also be studied more conveniently with the friction-type experiments. The process of film transfer is a quantity which can usefully be optimized. With brittle materials, a low friction is beneficial, since it affects the tensile stresses generated by sliding [15] and hence the wear. This suggests that no film transfer would be best. However, a transfer film can act as a protective layer. The compromise is between the larger stresses caused by the higher friction as the sliding interface and the reduced stresses at the tool caused by the film.

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