DYNAMIC FRIABILITY OF OXIDISED NUCLEAR GRAPHITES

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Introduction

A friable material is one that is partially reduced to powder when a static or dynamic stress is applied. The friability of nuclear graphites is a potential problem in graphite moderated, gas cooled nuclear reactors such as the Advanced Gas Cooled Reactors, AGR, that are operated in the United Kingdom. Friability of moderator graphites may result from point stresses that may occur due to distortion of graphite bricks. Such distortions may result from dimensional changes due to irradiation. Also, friability may also develop during loading and unloading of fuel stringers and operation of control rods. The risk of both types of friability may increase with time as a result of radiolytic oxidation of the graphite by the coolant gases.

In previous papers [1-4] we have reported on the friability of nuclear graphites subject to static stresses produced by a blunt indentor. Here, we report the dynamic friability of an unirradiated AGR moderator graphite and the effects of thermal oxidation by carbon dioxide.

Experimental

The graphite used in this work is BAEL IM1-24 grade that is used as a moderator in some AGRs. The graphite was thermally oxidised in a horizontal tube furnace at 900 ^{o}C in flowing, preheated, pure CO_2 (10 ml/min). A higher flow rate (50 ml/min) was used during the heating to 900 ^{o}C to purge the furnace tube. The graphite was oxidised to various extents up to a weight loss (burn-off) of 30%.

The apparatus used to measure dynamic friability, shown schematically in Figure 1, is effectively an instrumented lathe adapted to measure wear parameters. A 3 mm wide tungsten carbide grooving tool was mounted on a sliding bed (not shown) and a constant load applied using a weights and pulley system (also not shown) to bring the tool in contact with the graphite rod, nominal diameter 10 mm. Accurate rates of rotation of the graphite rod in the range 0-50 rpm were attained using a computer controlled stepper motor and gear box that were mounted on bearings so that they could rotate freely until the strain gauged beam was in contact with a support pillar.

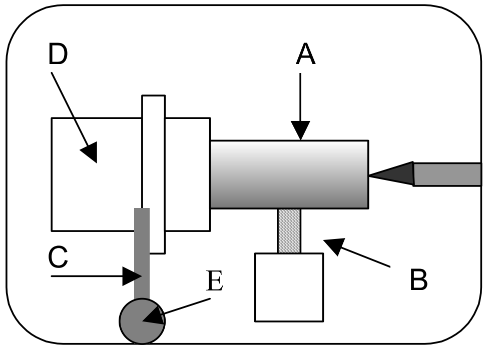


Figure 1. Apparatus for measuring dynamic friability of graphite (schematic).
A, graphite rod; B, tungsten carbide grooving tool; C, strain gauged beam; D, stepper motor, gear box and chuck; E, support pillar.

The strain gauge beam used to measure torque was calibrated against a torque driver connected to the chuck that held the graphite rod in place. In a typical experiment the graphite rod was rotated at constant speed against the grooving tool that was applied at constant load, while measuring torque as a function of time and volume of graphite removed.

Results and Discussion

Figure 2 shows the effect of increasing tool load on the measured torque for the unoxidised graphite. At low loads the measured torque is less than ~0.3 Nm, because there is insufficient force applied by the cutting tool to penetrate the surface of the graphite rod. Thus, the cutting tool is sliding over the surface at low loads. For loads above a threshold value, ~500 g, the torque increases progressively as the tool cuts deeper into the graphite.

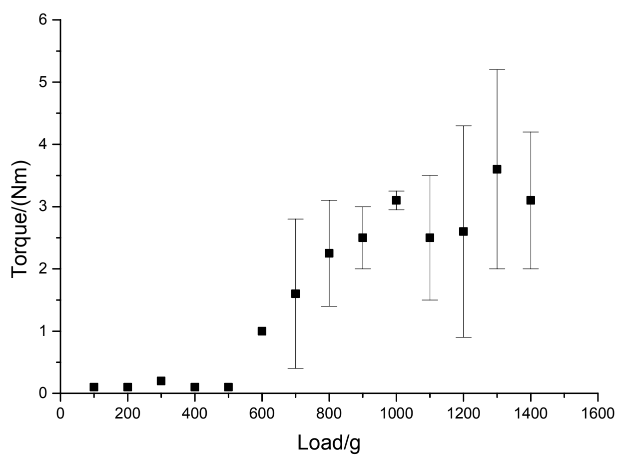
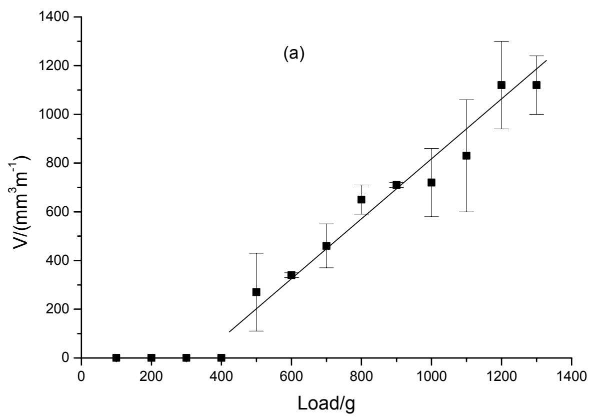


Figure 2. Effect of tool load on torque for unoxidised IM1-24 graphite. Rotational speed 50 rpm; error bars show ±2 standard deviations.

As might be expected, a similar relationship is found for the volume of graphite removed as a function of tool load, Figure 3(a). Here, the amount of graphite removed, V, is expressed as volume per unit sliding distance (mm^3m^{-1}).



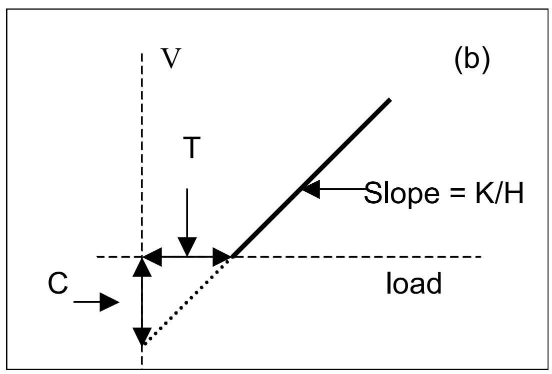


Figure 3. (a) Effect of tool load on the volume of graphite removed per unit sliding distance, V. Rotational speed, 50 rpm; error bars are 2 standard deviations.
(b) Fit of Fig 3(a) to the modified Archard Equation, see text.

At low loads below a threshold value, ~400 g in this case, there is no graphite removed because the tool is sliding over the graphite surface. Above the threshold load the amount of graphite removed per unit sliding distance increases progressively with tool load in an approximately linear manner.

The relationship between the volume of graphite removed per unit sliding distance, V, and the tool load, L, Figure 3 (a), can be fitted to a simple adaptation of the Archard wear equation that was originally derived for sliding wear of metals and alloys, although an equation of similar form is also found for abrasive wear [5]. The modified Archard equation is

$$V = KL/H + C$$

where K is the Archard wear coefficient, H is the hardness of the graphite and C is a constant. This is shown schematically in Figure 3(b) where it is clear that the Archard slope, K/H is related to the cutting threshold load T by K/H = C/T. Thus, T = CH/K, in other words, the threshold cutting load, T, is directly related to the hardness of the graphite, as might be expected.

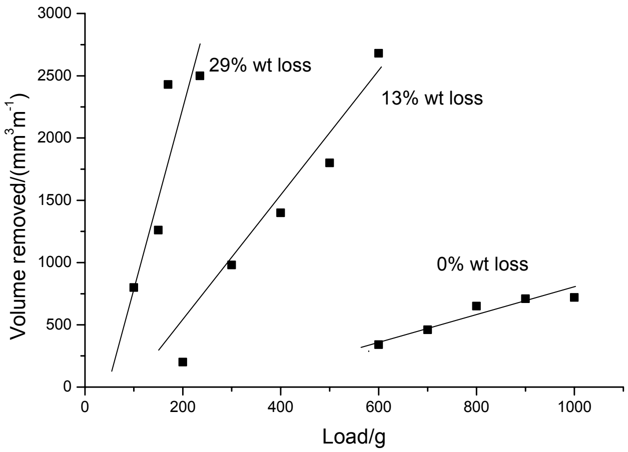


Figure 4. Effect of oxidation upon the wear of IM1-24 graphite.
Rate of rotation = 50 rpm

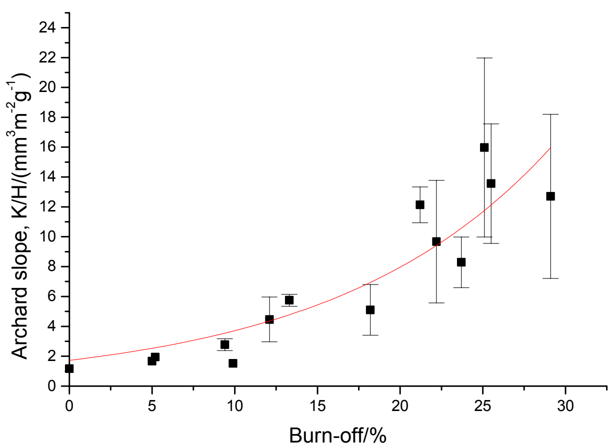


Figure 5. Variation of the Archard slope K/H with extent of oxidation of IM1-24 graphite. Error bars are ±2 standard deviations

Figure 4 shows qualitatively that the cutting threshold decreases and the Archard slope increases with increasing extent of thermal oxidation. Both of these trends can be explained by a decrease in the hardness of the graphite with increasing oxidation. Figure 5 shows that the Archard slope increases exponentially with the extent of burn–off, but also with increasing scatter in the results. The data can be fitted to K/H = 1.2exp 8.7x, where x is the fractional weight loss. An exponential increase in K/H has also been found for wear tests on a series of zirconias with increasing porosity contents [6]. This suggests that in both cases the dominant factor affecting the Archard slope is porosity.

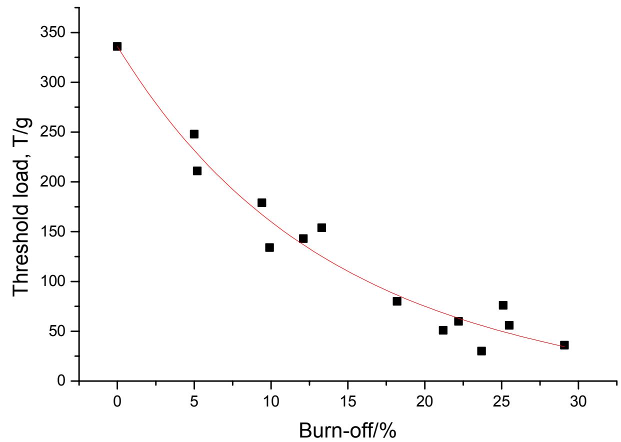


Figure 6. Variation of cutting threshold, T, with extent of oxidation of IM1-24 graphite.

The variation in threshold cutting load T decreases in an exponential manner with increasing oxidation, Figure 6. The data can be fitted to T = 336 exp(-8.8x). Pickup et al [7] found that the reduction 3-point bend strength and fracture toughnes, K_{Ic}, with increasing porosity following thermal oxidation of IM1-24 graphite followed similar exponential decays. As noted above, the threshold load is directly related to the hardness of the graphite. For metals and alloys, harness is directly related to yield stress. Polygranular graphites, such as IM1-24, do not exhibit yield behaviour as in metals and alloys. However, in the present case, it may be expected that the hardness of the graphite is related to its fracture behaviour under the complex stresses at the grooving tool tip. Thus, while direct relationships are not anticipated between hardness and 3-point bend strength or fracture toughness, indirect relationships between may be expected.

The threshold load is directly related to hardness, whereas the Archard slope is inversely related to hardness. Figure 7 shows plots of the threshold load and the inverse Archard slope, both normalised to the values for the unoxidised graphite. The normalised data follow very similar decay curves, but with some scatter. This emphasises again the importance of hardness in controlling the friability of the graphite. The figure also illustrates the role of increasing porosity following oxidation in controlling hardness.

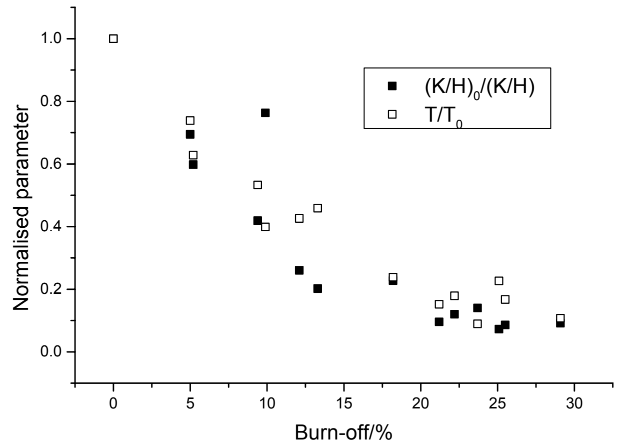


Figure 7. Effect of oxidation upon the normalised inverse Archard slope $(K/H)_0/(K/H)$ and normalised threshold load, T/T_0.

Conclusions

The effect of thermal oxidation on the friability of a nuclear graphite against a silicon carbide grooving tool was studied using a specially designed apparatus. The behaviour of the graphite was characterised by a region of low torque at low tool loads until a threshold load was reached above which the tool penetrated the graphite surface and the torque increased. Above the threshold load the volume of graphite removed increased in an approximately linear manner with tool load. This behaviour was fitted to a modified form of the Archard wear equation. With increasing extents of oxidation the Archard slope increased exponentially, whereas the threshold load decreased exponentially. Both trends emphasise the importance of hardness and increasing porosity following oxidation in controlling the friability of the graphite.

Acknowledgements

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