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Particle Removal in the Ablation of Artificial Graphite

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Introduction

IN considering the ablation behavior of polycrystalline, artificial graphite in dynamic, oxidizing environments, it is becoming increasingly evident that conventional thermochemical phenomena are frequently inadequate to explain the total observed erosion.[1–6] Various investigators have theorized that mechanical and aerodynamic removal of particulate matter occurs in addition to oxidation and may be caused by vibration,[2] aerodynamic shear,[3–5] and pressure gradients.[5]

Evidence offered in support of this mechanical and aerodynamic removal has been circumstantial in nature, i.e., after-test surfaces that are rough and irregular, greater observed erosion than can be accounted for by thermochemical calculations, and greater erosive effect of higher pressure environments. Recently, however, direct experimental evidence has been obtained at this laboratory. The purpose of this Note is to present this direct evidence of particle removal as well as evidence that such removal is linked to oxidation. Also presented is a theoretical mechanism relating particle removal to oxidation.

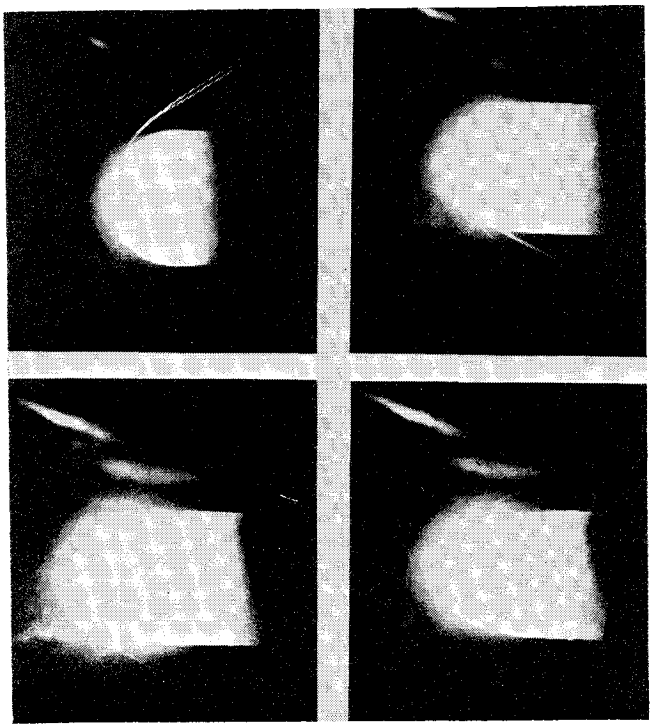

Fig. 1 Luminous traces from an eroding graphite specimen.

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Data and Observations

Figure 1 presents a chronological sequence of four frames from close-up, high-speed motion pictures (220 pictures/sec) of a graphite specimen eroding in a high-temperature Mach 2.5 airstream (stagnation-point cold wall heating rate 565 w/cm^2, stagnation pressure 5.6 atm). Figure 1 clearly shows luminous traces of particles leaving the surface. As time progresses, the surface acquires an irregular configuration. By means of much higher-speed motion pictures (average 5500 pictures/sec) as many as 250 separate traces have been observed leaving an eroding surface during 1 sec of ablation. This number is conservative because many escaping particles are too small to observe or are obscured by the specimen or its luminosity; however, the order of magnitude illustrates the extent to which particle removal can contribute to total erosion.

It is recognized, of course, that such luminous traces from an ablating surface have been observed previously in the case of charring ablators. This series of photographs is, however, the first known direct photographic evidence for graphite—a material which has considerably greater mechanical integrity than hydrocarbon chars and, in addition, lacks the internal generation of pyrolysis gases, which is sometimes held responsible for the removal of pieces of char. Estimates of particle sizes from these observations indicate the largest particles to be on the order of one-half the maximum size of a filler grain. It is suspected that the majority of particles lost consist of grains or partially oxidized grains with only rare instances of agglomerates of grains being lost.

Direct photographic observation of particle removal is more frequent at higher stagnation pressures than at lower pressures. However, even at lower pressures, in cases in which direct photographic observation of particles has not been achieved, circumstantial evidence for particle removal is often strong (i.e., after-test surfaces are rough and pitted). In these cases, it is believed that the particles removed consist largely of partially oxidized filler grains too small to be seen by the photographic techniques employed.

The mechanical and aerodynamic forces that cause particle removal are not, by themselves, solely responsible for such removal. They must be accompanied by oxidation. This is demonstrated by tests made in both oxidizing and inert heated test streams. Figure 2 presents a photograph of an untested graphite specimen in comparison with specimens tested in nitrogen and air. The greatly increased erosion of the specimen tested in air is evident. The rough, irregular surface of this specimen is characteristic of a significant degree of particle removal. The specimen tested in nitrogen has undergone negligible erosion, but the difference in its surface appearance from the untested specimen indicates that some material, perhaps already loose, has been removed from the surface. High-speed motion pictures taken during the tests of these specimens indicate appreciable particle removal only from the specimen in the oxidizing environment. Furthermore, photomicrographs of sections through the surfaces of these specimens (Fig. 3) show considerable roughness and protruding grains associated with the specimen tested in air, whereas the surface of the specimen tested in nitrogen is similar to that of the untested specimen. These results lead to the conclusion that it is necessary for oxidative weakening of

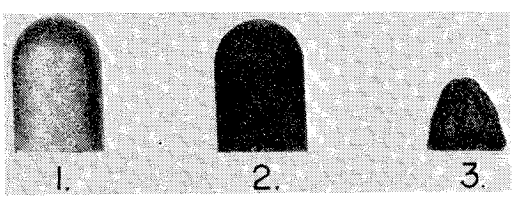

Fig. 2 Comparison of graphite specimens: 1) untested, 2) tested in nitrogen, 3) tested in air.

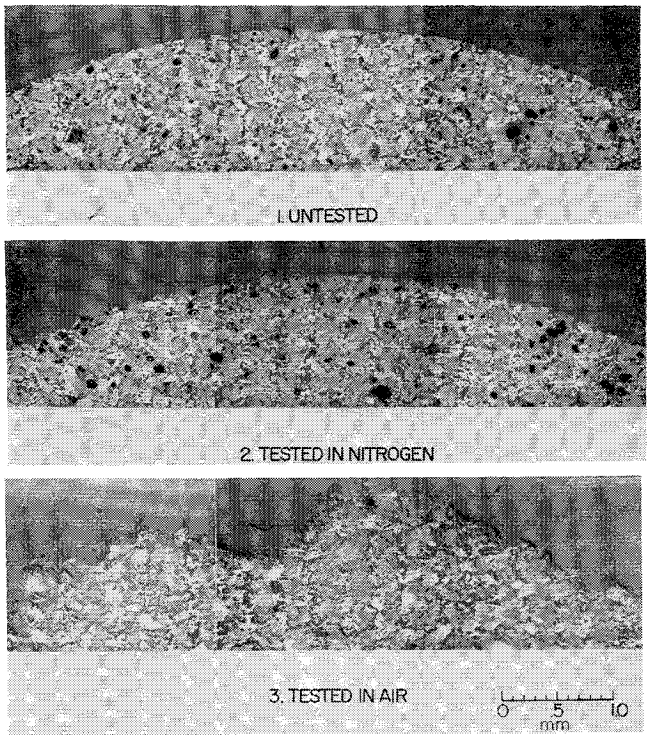

Fig. 3 Comparison of photomicrographic sections of graphite specimens.

the binder matrix to occur before filler grains can be readily removed by external forces.

Mechanisms of Binder Weakening

A number of mechanisms can be proposed to account for the weakening of the binder matrix. Which mechanisms are operative or predominate in any situation will depend considerably on the temperature, pressure, and flow velocity of the environment. Among the possible mechanisms are reaction of the gaseous reactant with the binder in the pores due to penetration of the reactant into the pore structure,[1] higher recession rate of the binder because of its lower density than the filler,[5] thermal stress cracking of the binder due to severe temperature gradients, sublimation of the binder bridges within the pore structure,[5] and preferential sublimation of the binder compared with the filler.

One potentially important mechanism, which may not be as apparent as those already mentioned, perhaps warrants some discussion. This mechanism is based on the assumption that the binder phase in graphite is inherently more reactive than the filler phase. That is, at a given temperature and concentration of oxygen, the binder will oxidize faster than the filler. Preferential oxidation of the binder has been suggested before[4,6] and the assumption seems to be well founded. Based on this assumption it is obvious that at temperatures at which the reaction rate is controlled by chemical kinetics, the binder will recede faster than the filler. It is not as obvious, however, that preferential recession of the binder can occur even at higher temperatures at which the reaction rate is diffusion controlled.

For diffusion controlled reactions, the observed reaction rate is limited by the rate of diffusion of oxygen to the reacting surface and, thus, chemical kinetics can often conveniently be disregarded. However, at the reacting surface the reaction proceeds according to conventional kinetic laws provided, of course, that the oxygen concentration considered is the concentration immediately adjacent to the surface (as opposed to the freestream concentration). It is obvious that this oxygen concentration, although small, must be nonzero, otherwise no chemical reaction could proceed. (In practice, this concentration generally cannot be measured, which is, of course, one reason why the concept of diffusion control is utilized.) However, whatever the oxygen concentration, and in whatever manner it may vary over the surface, it cannot vary discontinuously. Accordingly, at an interface between two adjacent solid phases, both phases will see the same concentration. But, as stated previously, whenever two phases with different reactivity see the same concentration the more reactive phase will oxidize faster. Thus, in the case of graphite, at each interface between binder and filler, the binder will recede faster and thereby expose the filler grains making them more vulnerable to mechanical and aerodynamic forces.

Conclusions

Direct experimental evidence obtained with high-speed motion pictures demonstrates that mechanical or aerodynamic removal of incompletely oxidized particulate matter contributes to the total ablative mass loss of polycrystalline, artificial graphite in dynamic, oxidizing environments. This removal is facilitated by the weakening of the binder matrix by oxidation. A mechanism for this weakening, based on the greater oxidative reactivity of binder than filler, is proposed. This mechanism should be effective in diffusion controlled environments as well as in kinetically controlled environments.

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Lift Effectiveness of Slender Wings with Streamwise Root Gaps and Fences

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Introduction

THE presence of a streamwise root gap has a large effect on the lift effectiveness of slender wings which has been explained[1,2] on the basis of slender wing theory. One application is to the case of missile configurations equipped with all-moving low aspect ratio control surfaces. However, a similar effect is present[3] in wind-tunnel measurements made on slender half-models using the tunnel wall as a plane of symmetry. This is particularly relevant to dynamic testing where a streamwise root gap is required for mechanical

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