CHARACTERIZATION OF THE CAVITATION POTENTIAL
OF PYROLYTIC CARBON

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ABSTRACT
Cavitation erosion of pyrolytic carbon has been reported to occur in heart valves during accelerated testing. Recently observations of cavitation erosion damage in clinical explants have been made. Research studies were conducted using two methods to describe the cavitation erosion behavior of pyrolytic carbon. A cavitating water jet method was used to examine weight loss versus time as compared to other engineering materials. An ultrasonic horn method was used to describe cavitation erosion morphology of pyrolytic carbon surfaces. The cavitation behavior of pyrolytic carbon by both methods was highly variable. Cavitation resistance in the water jet model was initially high, but weight loss accelerated with increased exposure times. A microcracking phenomenon was observed to contribute to the accelerating weight loss. The ultrasonic horn model showed variable cavitation, with some samples substantially cavitated after 9 minutes of exposure and some essentially uncavitated after 12 minutes of exposure. Morphologically, cavitation damage occurred to a greater or lesser extent even over the surface of a single specimen. Mechanical and physical explanations of these results are discussed.
INTRODUCTION

Cavitation is the rapid and repeated growth and collapse of bubbles in a flowing liquid. This occurs when the local pressure in the flowing fluid falls below its vapor pressure, creating small cavities or bubbles in the fluid. When the bubbles then flow onward into a higher pressure region, they collapse violently. This violent collapse, if near the surface, may cause local material erosion in any solid within the region, or may, in a flowing blood stream, cause rupture of the cellular components of blood [1]. Cavitation can be caused by various flow conditions; in particular in mechanical heart valve applications by water hammer effects at valve closure and to a lesser degree by venturi effects around closed leaflets.

Cavitation erosion of pyrolytic carbon has been reported to occur under in vitro accelerated testing conditions [2,3] and has also been observed under more physiological conditions in artificial hearts [4,5]. Although cavitation was thought to be an artifact of in vitro test conditions, which do not fully represent physiological conditions, more recently cavitation erosion has been observed in pyrolytic carbon components from human explants [6,7], and was first noted by Zubarev [8] as early as 1976.

Although cavitation is for the most part a fluid dynamics problem, it has been noted that some material factors, such as surface finish, may have an effect on the formation of cavitation bubbles [9]. Certainly from a materials view, the effect of cavitation in terms of degree of erosion is highly material dependent. Because of the recent clinical observations of cavitation erosion in pyrolytic carbon, these studies were conducted to determine the relative cavitation
susceptibility and the morphological response of pyrolytic carbon to cavitation. This is an initial report on these studies.

METHODS AND MATERIALS

Two methods were used to create cavitation conditions in samples of pyrolytic carbon. An ASTM vibratory horn test [10] was used to examine cavitation erosion morphology and the effect of surface microporosity on cavitation behavior. A submerged cavitating water jet [11,12] was used to quantify weight loss versus exposure time. Cavitation erosion morphology was compared between these two methods to verify their equivalence qualitatively.

In the ASTM test configuration, the samples were placed under the tip of the ultrasonic horn at 1mm distance, or were glued to a stud which inserted directly into the horn. The ultrasonic horn was submerged in 37°C, de-aired distilled water, and operated for varying periods of time up to 15 minutes at 20 Khz and 150 watts input power.

In the cavitating water jet system, the sample is placed in a specially designed holding fixture and submerged in room temperature tap water. The water jet nozzle is clamped 1.5 inches above the test specimen. Water is pumped through the nozzle, acting as a venturi to create cavitation bubbles, and impinges on the material surface creating cavitation erosion. A jet pressure of 1300 psi delivering hydraulic power of about 11 hp was used.

Test specimen were of several types. Flat circular discs of pyrolytic carbon on a graphite substrate (manufactured by Carbomedics, Inc., Austin, Texas),
which were 0.060 inches thick and 1.0 inches in diameter, were used in both test systems. Eleven such samples, selected to be as identical as possible, were used in the cavitating jet experiments. Additionally, in the ultrasonic horn testing, representative samples of Edwards-Duromedics valve components both leaflets and housings were tested. All samples were examined for acceptable materials properties, such as hardness and silicone content, and their surface finishes were documented. Surface finish was typical of standard acceptable material as shown in Figure 1B. Acceptable surface finish was determined qualitatively by optical methods. All pyrolytic carbon surfaces have some porosity to some degree, as is evident in Figure 1A and B, demonstrating typical surface morphology of unpolished and polished pyrolytic carbon. It is important to note the fusion of carbon droplets seen in the unpolished state, and the small remaining pores on the polished surface.

Cavitation erosion morphology was examined using surface optical and scanning electron microscopy (SEM). Polished cross-sections of test specimens were also examined by optical microscopy for projecting microcracks.

Weight loss versus exposure time was examined only in the cavitating water jet system. Specimen were removed from the test at 6, 8, 10, 12 and 14 minute intervals, visually inspected for gross cracks, dried in a vacuum oven for a minimum of 12 hours to remove all water, and immediately weighed on an analytical balance. Upon completion of all measurements, the specimen were returned to the testing for further exposure.
RESULTS

Cavitation erosion in pyrolytic carbon appears morphologically similar to that in other materials. Figure 5 2A and B compare the surfaces of aluminum and pyrolytic carbon after the cavitating jet test. On closer microscopic examination erosion is typified by focused pitting with apparent separation of individual or groups of the small nucleated droplets that form the pyrolytic carbon structure (Figure 2C). At the base of these pits, the initiation of microcracking can be seen (Figure 2D). Microcracking is even more apparent in cross-section shown in Figure 2E.

The effects of cavitation on pyrolytic carbon are highly variable. Figure 3A and B shows two specimens that were acceptable carbon components. These two specimens were tested in the vibratory horn system: one shows essentially no cavitation damage after 12 minutes of exposure, while the other is extensively pitted after 9 minutes of exposure. A closer examination of the cavitated sample reveals that certain areas within this individual piece are more highly damaged than other areas. The circular pattern of cavitation damage is typical of the test system, but the variability around the circle is a characteristic of the material. The effect of surface finish variations is the subject of further studies in progress.

The cavitating jet was used to examine weight loss versus exposure time. Table 1 presents the data for all samples by time; means and standard deviations are given. Figure 4 presents the data graphically as compared to previously reported data on aluminum, leaded bronze, and stainless steel.
DISCUSSION

Weight loss versus time studies indicate that non-porous surface pyrolytic carbon has an initially high resistance to cavitation erosion. As exposure to cavitation increases, erosion begins gradually and then accelerates; however, as acceleration occurs the variability of the effect also widens. This indicates that the response of pyrolytic carbon to cavitation is somewhat unpredictable, probably due to the randomness of the size of the fragments removed by cavitation. The resistance to cavitation of pyrolytic carbon lies between aluminum and leaded bronze.

It is helpful to examine the morphological observations to understand the basis for the variability in the weight loss tests. Pitting from cavitation starts as slow erosion of carbon droplets from the surface. Cavitation proceeds to deepen and widen the initial surface pits. As cavitation progresses, the pitting expands and microcracks initiate and extend. As microcracks join, larger fragments of material break loose, and eventually the sample will fracture due to the attendant weakening of the part by material loss and to the force of cavitation. The connection of microcracks and separation of larger pieces, thus creates variability in weight loss data. The extension of microcracking from the base of a cavitation pit can lead to a flaw large enough to result eventually in fracture of the component and suggests the existence of a fatigue mechanism in pyrolytic carbon.

Another source of weight loss variability can be seen in the varying local response to cavitation among and within components. The reasons for this variability are not obvious, but may relate to local mechanical properties (i.e. hardness), chemical composition (i.e. silicone content), or surface finish.
CONCLUSIONS

Studies of the response of pyrolytic carbon to cavitation erosion have produced the following conclusions:

1. Pyrolytic carbon has a resistance to cavitation erosion lying between aluminum and leaded bronze.

2. Initially, the resistance to cavitation erosion is high, but with increased exposure the resistance drops, probably due to the microcracking phenomenon.

3. The cavitation erosion resistance of pyrolytic carbon is somewhat variable.

4. Cavitation occurring near pyrolytic carbon not only results in particle erosion, but also creates extending subsurface microcracking, which can eventually lead to fracture.

Studies of this cavitation phenomenon continue. Further quantification of the effects are needed. Then establishing a relationship between physiologically occurring phenomena in various mechanical valves and the cavitation resistance of pyrolytic carbon will be necessary.
# TABLE 1

CUMULATIVE WEIGHT LOSS VERSUS TIME DATA

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<th>EROSION TIME</th>
<th>Sample No</th>
<th>6 Min.</th>
<th>8 Min.</th>
<th>10 Min.</th>
<th>12 Min.</th>
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Mean 0.02 0.12 0.46 0.91 1.49
Std Dev. 0.04 0.08 0.18 0.26 0.42

Cumulative weight loss in milligrams
- Test stopped after 11 minutes due to crack development.
- Sample broken.
- Sample cracked.
- Test stopped after 13 minutes due to crack development.
REFERENCES


