# DISCUSSION

*A. F. Conn*[1]—The authors are to be congratulated for a most thorough study of the micromechanisms responsible for cavitation erosion of soft aluminum. Although describing the loss of small pieces of material near the edge of pits, they did not say just how these pieces were caused to break off. I wonder if the authors would care to conjecture on how these pieces are removed?

*B. Vyas (authors' closure)*—Observation of the eroded surface of aluminum by SEM indicates that material is removed by ductile rupture at the edges of the deformation craters. This view is endorsed by optical metallography of cross sections of the sample, which shows internal void formation and necking of the edges of the craters; see Fig. 15.

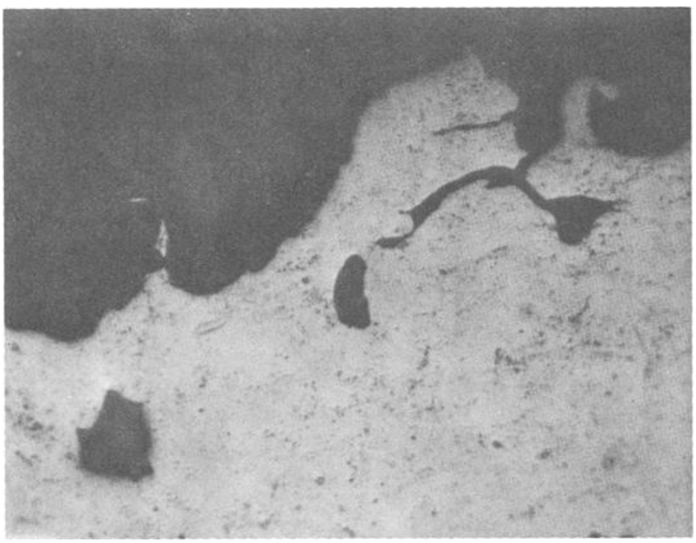

FIG. 15—*Cross section of eroded sample of aluminum showing necking at edges of the deformation craters after 120 s exposure to cavitation. Optical micrograph,* ×*260.*

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*W. T. Ebihara*[2]—The SEMs showing the apparent dislodgment of the aluminum grains are quite interesting. Would you please comment as to how this phenomenon could take place? Would the cavitation loading be of such magnitude to cause such displacement of grains or could this be caused by removal of the grain boundary atoms?

*B. Vyas (authors' closure)*—Removal of grain boundary atoms would be expected to produce a groove along the boundary, rather than the depression of whole grains as the micrographs suggest. Our calculations indicate that, for the latter to result from material removal over the whole surface of the grain, some weight loss should be detectable. Since we are not able to detect any loss in weight at this stage of the erosion process, we can only assume that the depression is a result of mechanical deformation. This is not unlikely if erosion is caused by a shock pulse as we propose. The magnitude of such a pulse would be easily sufficient to produce the observed effect.

*J. W. Tichler*[3]—By means of the SEM, the authors studied aluminum surfaces in the incubation stage and in the very beginning of what we call the stage of uniform material removal.[4] One of the significant observations is that the break-off of wear debris is ductile in nature, at least for aluminum. The material removal is apparently *not* due to a fatigue mechanism for this material.

Several authors proposed a statistical model for the breakout of wear particles from the eroding surface, based on the assumption that this breakout is due to a fatigue mechanism. This assumption is not necessary. The break-off of particles is a stochastic process, whether it is due to fatigue or not.

On the other hand, fatigue probably plays an important role in the mechanism of pit formation, as has been shown by Tichler and Scott.[5]

*B. Vyas (authors' closure)*—We thank Dr. Tichler for his comments. However, it cannot be concluded that pit formation due to cavitation is a fatigue process, simply because a certain group of steels is rated in the same order of performance for resistance to rolling contact fatigue and to cavitation erosion. As Dr. Tichler himself suggests,[5] an equally likely explanation is that cavitation occurs in the lubricant during rolling contact fatigue.

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[4] See page 56 of this volume (Tichler et al, "Applied Cavitation Erosion Testing").

[5] Tichler, J. W. and Scott, D., *Wear*, Vol. 16, 1970, pp. 229–233.

*W. F. Adler*[6]—I would like to congratulate Vyas and Preece for an excellent presentation of this most interesting and significant research. Since this research parallels a portion of the program in particulate and cavitation erosion at Bell Aerospace, I would like to take this opportunity to provide some perspective on the importance of studying erosion mechanisms during the very early stages of the erosion process.

First, one has to decide whether the application for the experimentally evaluated erosion behavior is the development of more erosion-resistant materials of the same general character as some reference material or the estimation of the lifetime of a given material exposed to a specified erosive environment. Professor Thiruvengadam's models,[7] for example, are directed toward this latter objective. He is attempting to obtain a universal curve which describes the steady-state erosion rates for a variety of materials in terms of a limited number of engineering parameters. On the other hand, microscopic examination of the very early stages of the erosion process affords one the opportunity to discover what microstructural features of a given material contribute to its erosion behavior. The localized features of the material on a scale which interacts with the erosive medium control its erosive response. By understanding the material characteristics on a microscopic level which govern the erosion behavior, it may be possible to modify the microstructural characteristics to greatly improve a material's erosion resistance without changing its overall strength levels. This means that the incubation period can be extended as indicated in Fig. 16. It is conjectured that the same material properties which influence the onset of erosion damage will also have some influence on the erosion behavior during the steady-state erosion range in the manner suggested in Fig. 16. The long-term weight loss can be changed significantly by a possibly simple microstructural modification or by the selection of a metallic alloy from a homologous series once the controlling microscopic erosion mechanisms are understood.

Detailed microscopic investigations and metallographic analyses as represented in the work of Vyas and Preece provide the basis for isolating the material characteristics which most significantly affect the erosion behavior of that material. These characteristics can be quite distinct from the usual engineering properties: yield strength, ultimate strength, hardness, and so on. It is fairly well established that the initial erosive response of a metallic specimen is not governed by its mechanical characteristics

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[7] Thiruvengadam, A., *Proceedings*, Third International Conference on Rain Erosion and Associated Phenomena, 1970, p. 565.

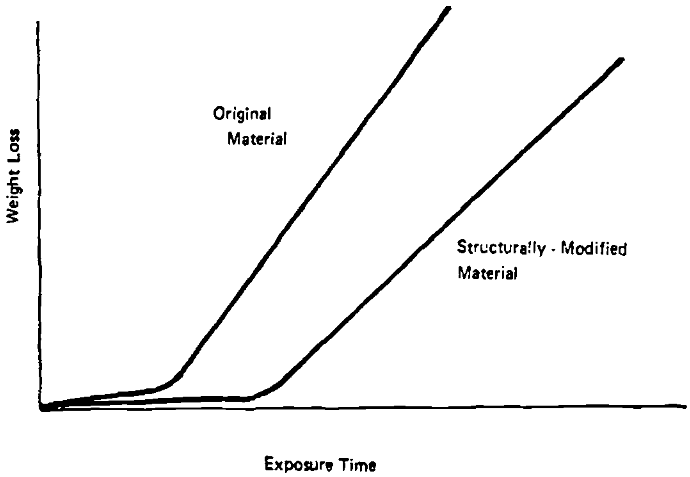


FIG. 16—*Modification in weight-loss data due to extended incubation period.*

evaluated on a gross scale[8,9] but by the microstructural features which interact with the erosive environment.[10,11] This observation can be further supported by the fact that erosion damage due to liquid droplet impacts occurs at impact pressures well below the ultimate and often even the yield strength of the specimen. Our microscopic investigations of rain erosion damage in annealed Ti-6Al-4V specimens reveal that damage occurs on a microscopic scale during the first few droplet impacts on the same area even when the magnitude of the maximum applied pressure pulse (computed according to the water hammer equation) is approximately one half the gross yield strength for this material.[11] On the basis of these microscopic investigations more representative analyses can be made of a material's response to an erosive environment. It is in this context that research along the lines presented by Vyas and Preece will greatly advance fundamental understanding of how to select and develop more erosion-resistant materials.

[8] Garcia, R., Hammitt, F. G., and Nystrom, R. E., in *Erosion by Cavitation or Impingement, ASTM STP 408*, American Society for Testing and Materials, 1967, p. 239.

[9] Morris, J. W. and Bates, C. H., *Proceedings*, Third International Conference on Rain Erosion and Associated Phenomena, 1970, p. 261.

[10] Hackworth, J. V. and Adler, W. F., "Microscopic Investigation of Cavitation Erosion Damage in Metals," presented at the Conference on the Role of Cavitation in Mechanical Failures, Boulder, Colo., Oct. 1973.

[11] Adler, W. F. and Vyhnal, R. F., "Rain Erosion of Ti-6Al-4V," presented at the Fourth International Conference on Rain Erosion and Related Phenomena, Meersburg, Germany, May 1974.