

## DISCUSSION

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The authors of this paper are to be commended for their laborious efforts directed toward the investigation of the tribological behavior of ion implanted steel constituents. High temperature, high current ion implantation was demonstrated by these authors as an effective practice for the in-situ synthesis of wear-resistant nitride phases. Furthermore, these authors demonstrated the usefulness of the conversion electron Mossbauer spectroscopy (CEMS) for the analyses of tribological surfaces. This is in keeping with a recent article by McHargue [1] which discussed the use of CEMS for analyzing the ion-implanted ceramic surfaces. In addition to CEMS, did these authors consider using the transmission electron microscopy (TEM) technique or grazing-angle X-ray diffraction method to verify and to further analyze the nitride phases they reported? Because, according to the Fe-N phase diagram [2], a range of nitride phases may co-exist. This is particularly true for the ion-implanted surfaces where a concentration gradient is always present. Huang and Hochman [3], and Fayeulle et al. [4] used TEM in their study and presented a much clearer picture of not only the phases that formed but also the defect networks within the implanted regions.

These authors focused more on  $\alpha$ -Fe than on AISI 304 steel. They reported marked improvements in the wear resistance of all the implanted AISI 304 steel specimens, yet fell short in giving a mechanistic explanation. According to Kotari et al. hard CrN may form on nitrogen implanted AISI 304 steels during exposure to elevated temperatures [5]. Could the authors comment on the possibility that increased wear resistance reported for the AISI 304 steel disks implanted with nitrogen at elevated temperatures might have been due to the formation of hard CrN precipitates beneath the surface? Did they employ CEMS to analyze these implanted 304 steel disks?

The test conditions were selected according to the wear mechanism maps of Lim and Ashby [6]. It must be understood that these wear mechanism maps are for unlubricated sliding contacts.

It is well-known that sliding interfaces can react with the constituents of liquid lubricants. This often results in low wear and low friction. Did the authors consider such a possibility? Surface reactivity of implanted and unimplanted steels for lubricating media may differ considerably, hence modify the wear behavior.

The last point that I would like to raise relates to Fig. 7. It is shown that compared to the fixed-pin-on-disk configuration, the oscillating-pin-on-disk configuration produces much greater wear on the disks. They attributed higher mass losses in the oscillating-pin cases to a much uniform wear situation, whereas lower mass losses in the fixed-pin cases were blamed on a continuing support by the edges of the wear groove and on the entrapment of the nitrogen-bearing wear-debris particles within the wear tracks. Although both the edge effect and the nitrogen bearing particles were absent, Fig. 7 shows that the same trend persists for the unimplanted disks. Would they like to comment on this? Did they obtain a surface profile across the wear track that was formed during an oscillating-pin-on-disk test? Did they assess the sliding distance for each case? Finally, it would have been more meaningful for com-

parative purposes if they had expressed their wear data in terms of a wear rate unit (e.g.,  $\text{mm}^3/\text{N.m.}$ ) rather than the disc mass loss in (mg).

## Additional References

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- 2 Wriedt, H. A., Gokcen, N. A., and Nafziger, R. H., "The Fe-N (Iron-Nitrogen) System," *Bull. All. Pha. Diag.*, Vol. 8, 1987, pp. 355-375.
- 3 Huang, P., and Hochman, R. F., "Post-implantation Heat Treatment of Nitrogen-implanted 440C Stainless Steel," *Mat. Sci. Eng.*, Vol. A115, 1989, pp. 257-260.
- 4 Fayeulle, S., and Treheux, S., "TEM Study of the Structural Changes of Nitrogen Implanted Iron Alloys," *Nucl. Inst. Meth.*, Vol. B7/8, 1985, pp. 171-176.
- 5 Kotari, D. C., Nair, M. R., Rangwala, A. A., Lal, K. B., Prabhawalkar, P. D., and Raole, P. M., *Nucl. Inst. Meth.*, Vol. B7/8, 1985, pp. 235-241.
- 6 Lim, S. M., and Ashby, M. F., "Wear Mechanism Maps," *Acta. Metall.*, Vol. 35, 1987, pp. 1-24.

## Authors' Closure

The authors appreciate the thoughtful and thorough review conducted by Dr. Erdemir. He points out quite properly the desirability of verifying conversion electron Mössbauer spectroscopic (CEMS) results by using transmission electron microscopy (TEM) or grazing-angle x-ray diffraction. The nitride phases identified by CEMS were verified routinely in this study using conventional X-ray diffraction (XRD). This part of the work is described in more detail in the reference by Williamson et al. (1989). It is noteworthy that conventional X-ray diffraction yielded signals with sufficient strength to do this, probably because the higher temperatures and doses used in the work facilitated thicker layers and because discs with relatively large, uniformly treated and worn surfaces were used. Additional work utilizing TEM is planned, but has not been accomplished.

As the discussor points out, a range of nitride phases can co-exist in nitrogen-implanted layers. This was generally observed. In fact there were cases where two phases were present in almost equal concentrations (solid triangles in Fig. 3). In the paper, however, it is the dominant phase that is identified. It is also noted that the implantation was carried out at higher temperatures than those used by previous researchers. This facilitated nitrogen diffusion and seemed also to favor the formation of one of the nitrides over a particular range of implantation conditions.

This paper does indeed focus primarily on  $\alpha$ -Fe as the discussor indicates. The presentation of extensive wear, Auger electron spectroscopic, CEMS and XRD data collected on nitrogen-implanted AISI 304 and 310 stainless steels is planned for the 1990 STLE annual meeting in Denver. A startling conclusion of this work is that strengthening of surface layers leading to improved wear resistance in these materials is induced by solid solution hardening rather than the formation of CrN precipitates.

The authors acknowledge the fact that lubricant reactions could be occurring, but no evidence of such reactions was observed on either the disc surface or the wear debris by the surface analytical techniques being applied. The only evidence of chemical change induced during wear testing has been the observation of some oxygen (typically on the pin surface but occasionally on discs worn for times approaching 100 h). It is also noted, in support of the wear test conditions selected, that

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