Bearing steels

It is extraordinary that a steel bearing can survive stress pulses of 2 GPa some half a million times a minute, over the service life of an aero engine. Or that it can be expected to reliably support the stochastic loads created by the buffeting of sails on giant offshore windmills designed to rescue the world from carbon dioxide catastrophes and wars driven by the thirst for oil. Bearing steels are the unsung heros of most of the arduous technologies that improve the quality of ordinary life; for the person pulling the rickshaw in Kolkata to the farmers harvesting the vast bread baskets of the prairies.

And yet, the vast majority of bearing steels have their origins in the dim and distant history of tool steels. Tool steels must obviously be hard but do not necessarily have to be tough. A bearing consists essentially of parallel rings with some form of rolling element (balls, cylinders) accommodating the relative motion of the inner and outer rings. It therefore needs to sustain periodic contact stresses as the rolling element traverses the substrates. These loads are mostly a combination of torsion and compression, so it is not surprising that Stribeck in 1901 considered the 1C–1·5Cr tool steel for bearing applications, and that this steel was adopted by Fichtel and Sachs in 1905 for manufacture. Naturally, as technology became ever more demanding, so did the adaptation of the original tool steels, with dramatic improvements in cleanliness which led to corresponding enhancements in rolling contact fatigue life.

Developments in the aircraft industries led the demand for higher operating temperatures, and hence the adoption of secondary hardening tool steels for aero engine bearings, followed by the case hardening versions to enhance core toughness. We are fortunate to have been able to persuade Zaretsky, one of the pioneers of the subject, to contribute a historical perspective to this special issue.[1]

An area of considerable uncertainty in bearing metallurgy is the relationship between microstructural changes and failure during service. Some of these changes are obvious in etched metallographic samples, for example the white etching regions which are often associated with microscopic cracks or are found in association with failed bearings. There is a nice assessment of white matter in the paper by Evans[2] in the context of the bearings for windmills; the paper represents a critical assessment and I particularly empathise with the conclusion that it is not known whether white matter is a symptom or a cause of cracking.[3] It is suggested by Kang and co-workers[4] that ‘models are now able to link’ the structural damage phenomena; this may be premature, but limited progress using unlinked models has been reported in the literature, for example.[5,6] I have my doubts about multiscale modelling as a philosophy,[7] where redundant work must be done to link the scales, with benefits which are small in comparison – a better approach may simply be a pragmatic one where individual scale models are used as appropriate; in other words, a tool-box of models.

Inclusions, including sulphides, are well established to be the initiating sites for rolling contact fatigue damage. Hashimoto *et al.*[8] find that the fatigue life should be a function of the orientation of the elongated inclusions with respect to the rotation direction. It has of course been known for some time that strings of non-metallic particles aligned normal to the contact surface are much more harmful than those parallel to that surface.[9,10] Hashimoto *et al.* conducted their experiments using contact stress of 5·3 GPa, which is much larger than typical in service; it is not clear therefore whether the orientation dependence of the fatigue life can be assumed to be as pronounced at lower stresses.

The role of silicon (up to 1 wt-%) in modifying the classical 1C–1·5Cr bearing steel is discussed by Kim and Lee,[11] who point out that silicon enhances the tendency to decarburise during the manufacturing process. They also claim an improvement in rolling contact fatigue performance, but it should be emphasised that the contact stress used in their experiments are extremely large at 5·8 GPa, and the comparisons have not been made at constant hardness.

It is often said that laboratory casts of bearing steels are not as pure as the industrial alloys produced by specialised bearing steel manufacturers. For example, the routine technologies available for the production of experimental cannot achieve oxygen concentrations of 6 wt-ppm, values routinely possible in industry. The paper by Trojahn[12] is particularly interesting in that it demonstrates that a cheap steel with a low oxygen concentration will not perform as well in a bearing application as one made using best practice but with the same oxygen content. This is because effort must be expended to ensure that the large inclusions which determine bearing life are kept to a minimum.

Another paper (apart from Zaretsky) on aero engine bearing steel deals with a case hardened M50NiL alloy,[13] tested in rolling contact using a very large contact pressure of some 5·5 GPa. It is demonstrated that, in these circumstances, the entire surface region undergoes hardening. But, unexpectedly, the extent of hardening is a maximum at the surface (i.e. a shallow depth where measurements could be made) and decreases monotonically with depth. I say ‘unexpectedly’ because the Hertzian stresses are in fact a maximum below the surface, so it is not surprising that a 2D finite element model failed to reproduce the experimental observations. It may be that the contact stress is too large so that the surface itself is significantly plasticised. A second observation is that in the 52100 type steels, rolling contact actually produces softening below the surface because of mechanical tempering (reviewed in Ref. 3); it is pertinent to enquire why this does not occur in the carbon rich case of the M50NiL.

Gigacycle fatigue testing using piezoelectric devices is now well established as a subject, and has challenged the concept of a fatigue limit, i.e. a stress below which a material will not fail by fatigue. Bathias,[14] in this

Published by Maney on behalf of the Institute
DOI 10.1179/026708311X13206608250748

sense, does not reach new conclusions regarding bearing steels but the paper does highlight, once again, the importance of factors which initiate cracks as opposed to those which promote crack growth. One aspect not covered is the utility of push–pull tests of the kind assessed, in the context of bearings where the damage is usually associated with rolling contact. The stress system associated with rolling contact is quite different from tension–compression, so that the damage mechanisms are also likely to be different.

The paper by Tonicello *et al.*[15] is rather refreshing in that it asks the difficult questions about the role of ceramic rolling elements in contaminated environments. It is argued that because of its strength and high modulus, ceramic debris tends to create deeper dents in the steel race. They also introduce the technique of thermoelectric power to characterise the evolution of phase transformations in bearing steels.

To finish off provocatively, I wonder whether it is time to think whether experiments done with unrealistically large contact stresses are terribly relevant, whether push–pull tests have outlived their usefulness, whether white matter matters as much as toughness, and whether it is time now to deliver on multiscale modelling rather than sing its praises. The editor would wholeheartedly welcome communications to this journal on any of these aspects. I would like to express my gratitude to the authors who delivered manuscripts following my invitation; the list of invitations was more comprehensive and based on an objective search of the databases. But I realise that it is hard to commit time, more than anything else, to a venture such as this. After all, bearing specialists are busy making the world go round.

H. K. D. H. Bhadeshia

Metallurgy and Materials, University of Cambridge, UK
hkdb@cam.ac.uk
Guest Editor

References

1. E. V. Zaretsky: 'Rolling bearing steels – a technical and historical perspective', *Mater. Sci. Technol.*, 2012, **28**, (1), 58–69.
2. M.-H. Evans: 'Butterflies and white etching cracks causing white structure flaking in wind turbine gearbox bearings', *Mater. Sci. Technol.*, 2012, **28**, (1), 3–22.
3. H. K. D. H. Bhadeshia: 'Steels for bearings', *Progr. Mater. Sci.*, 2012, **57**, 268–435.
4. J. H. Kang, B. Hosseinkhani, and P. Rivera: 'Rolling contact fatigue, bearing steels, multiscale mod- elling, kinetics, microstructure control, fatigue', *Mater. Sci. Technol.*, 2012, **28**, (1), 44–49.
5. I. Vannier, H. Combeau, and G. Lesoult: 'Numerical model for prediction of the final segregation pattern of bearing steel ingots', *Mater. Sci. Eng. A*, 1993, **173**, 317–321.
6. E. S. Alley and R. W. Neu: 'Microstructure–sensitive modeling of rolling contact fatigue', *Int. J. Fatigue*, 2010, **32**, 841–850.
7. H. K. D. H. Bhadeshia: 'Mathematical models in materials science', *Mater. Sci. Technol.*, 2008, **24**, 128–135.
8. K. Hashimoto, K. Hiraoka, K. Kida, and E. Costa Santos: 'Effect of sulphide inclusions on rolling contact fatigue life of bearing steels', *Mater. Sci. Technol.*, 2012, **28**, (1), 39–43.
9. E. N. Bamberger: 'Effect of materials – metallurgy viewpoint', in 'Interdisciplinary approach to the lubrication of concentrated contacts', (ed. P. M. Ku), NASA SP–237, 409–437; 1970, Washington, DC, NASA.
10. J. Courbon, G. Lormand, G. Dudragne, P. Daguler, and A. Vincent: 'Influence of inclusion pairs, clusters and stringers on the lower bound of the endurance limit of bearing steels', *Tribol. Int.*, 2003, **36**, 921–928.
11. K. H. Kim and J. S. Lee: 'On the microstructure and properties of Si-modified 100Cr6 bearing steels', *Mater. Sci. Technol.*, 2012, **28**, (1), 50–54.
12. W. Trojahn: 'Bearing steel quality and bearing performance', *Mater. Sci. Technol.*, 2012, **28**, (1), 55–57.
13. N. K. Arakere and G. Subhash: 'Work hardening response of M50-NiL case hardened bearing steel during shakedown in rolling contact fatigue', *Mater. Sci. Technol.*, 2012, **28**, (1), 34–38.
14. C. Bathias: 'Gigacycle fatigue of bearing steels', *Mater. Sci. Technol.*, 2012, **28**, (1), 27–33.
15. E. Tonicello, D. Girodin, S. Sidoroff, A. Fasekas, and M. Perez: 'Rolling bearing applications: some trends in materials and heat treatments', *Mater. Sci. Technol.*, 2012, 28, (1), 23–26.