influence of manufacturing or testing variables. The purpose of the phase I tests reported here was to establish manufacturing and testing conditions for evaluating the fatigue strength of the electron beam melted bearing steel.

In test A surface texture and lubricant film thickness combined to cause point surface origin spalling damage that would not be expected to provide a true evaluation of the contact fatigue strength of the material. Test B could have provided truer evaluation; however, the time to failure appeared to be prohibitively long and testing was, therefore, discontinued.

Ideally, in order to evaluate the true strength of a material the natural stress concentrations within the material should initiate the fatigue damage as in the conventional steel bearings. The various types of non-metallic inclusions are the primary stress concentrations intrinsic to a material; however, in bearing steel processed by EB or CV melting the inclusions are small and widely distributed. The result is that surface texture and film thickness can play an equally vital role in the fatigue damage of high quality steels. This makes it difficult and expensive to test bearings under conditions that will give inclusion initiated fatigue damage in high quality steels.

Considering the above discussion, test C has shown for practical purposes that EB melted carburizing bearing steel and CV melted carburizing bearing steel give comparable fatigue strength. However, if test conditions and bearing surfaces were made ideal so that the inclusions in the material were the sole stress concentrations one of the steels might be superior in fatigue strength over the other. From the scanner-computer results the CV cups would be expected to have the shortest relative life if only nonmetallic inclusions were responsible for the initiation in the EB and CV steels.

The EB steel showed comparable fatigue strength to the CV even though it had alloy adjustment to correct hardenability. The virtual absence of manganese, thus, presents no problem affecting the fatigue strength of EB steels. It should be noted, in addition, that the CV steel received 260 percent more hot working because of ingot size than the EB steel, a factor which would normally improve the inclusion limited fatigue life of bearings.

The future of EB melted bearing steels depends upon the success of making larger ingots of superior quality to CV steels or equivalent quality to CV at a lower cost. This is analogous to the early work with evaluation of CV and induction vacuum melted steels where problems were encountered in determining the true fatigue strength of those materials.

The comparison of the premium steels (CV and EB) to conventional bearing steel showed a significant difference in both the scanner-computer ratings of inclusions and in the bearing life tests. This improved performance of the premium steels is attributed to the absence of the occasional size 8 inclusions often found in conventional steel. The magnitude of the improvement factor for the CV steel over the conventional steel averaged 7 in these tests and the EB versus the conventional behaved similarly. The magnitude of improved life appeared to be dependent upon lubricant viscosity with the greater improvement being related to the lower viscosity lubricant. This would be in agreement with [12] where propagation of inclusion origin fatigue spalls was shown to be dependent upon lubricant viscosity and/or film thickness.

Conclusions

1 Cold hearth electron beam remelted 4620 modified bearing steel had fatigue strength comparable to consumable electrode vacuum arc remelted 4620 modified, bearing steel.

2 The premium steels (CV and EB) showed superior contact fatigue strength over the conventional steel under each test condition. The magnitude of improved life was greater in the lower viscosity lubricant used for the tests.

3 Adjustment upward of silicon, nickel, and molybdenum content to compensate for manganese loss in the EB steel had no adverse affect on bearing fatigue strength compared to standard 4620 CV melted steel.

4 Combined effects of surface texture and lubricant film thickness are significant competitors with inclusions in initiating contact fatigue spalling in high quality vacuum refined steels. The full value of such steels can only be realized with improved knowledge and control of these effects.

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DISCUSSION

J. L. Chevalier[3]

The author has presented some interesting data on a new production technique which has the possibility of improving the fatigue life of rolling-element materials. However, there are several points the discusser would like clarified and several which he would like to comment on.

It has been shown that a significant increase in rolling-element fatigue life can be obtained by proper control of the hardness of the bearing race and rolling elements [13, 14].[4]

A question therefore arises regarding the hardness value of the cones and rollers used in this investigation and whether these hardnesses were controlled.

Degradation of oil with time and accumulation of foreign particles in the oil can significantly reduce the life of rolling elements. If a 40 micron filter is used, 60 to 80 micron (2–3 mils) particles

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[4] Numbers in brackets designate Additional References at end of discussion.

can pass through the filter and circulate in the systems. If the elastohydrodynamic (EHD) film thickness in the experiment is on the order of a few microin., particles of this size will disrupt the EHD film and correspondingly reduce the life of the rolling elements. The mode of failure from particle contamination will generally be surface induced.

In each series of tests, was the oil changed after each test? What type of oil filter was used?

It is unfortunate that the author did not perform a Jernkontoret (JK) analysis of the materials studied so that a comparison of the two methods for determining material cleanliness can be made.

In assuming that the increase in life of the EB and CV material over the conventionally air melted material was due to the elimination of the size 8 inclusions, the author seems to have overlooked the fact that the number of inclusions in all size categories have been reduced and thus the total number of inclusions also. If the number of inclusions in each class are reduced, the probability of inclusions being in a critically stressed area of sufficient size to be detrimental is reduced.

Therefore, the reduction in the number of inclusions in the size categories 4 to 7 seems to be as significant as the elimination of the few size 8 inclusions.

It is rather unfortunate that the author chose to use condition "C," where he reduced the EHD film thickness by reducing bearing speed, rather than condition "B" to determine the fatigue life of the three materials. This was apparently done because of the length of time to perform each test. Because the failures for condition "C" are not all inclusion initiated, some uncertainty is introduced into the validity of the results. It would have been quite interesting to see which material (EB or CV) had the longer life under conditions where failures were subsurface originated. Another possible solution to reducing the time of testing of the bearings without changing the mode of failure would have been to increase the maximum Hertz stress.

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T. E. Tallian[5] and G. H. Baile[5]

The author has correctly analyzed the difficulties of material evaluation in roller bearings. Control of failures from surface defects, geometry, and finish is the primary problem.

It appears from the data that efforts to control these to the point where failures are truly inclusion-dependent were abandoned before they achieved full success. Hence, the data in the most important test group "C" are of doubtful value for comparison between EB and CV materials. This is recognized by the author.

Group B is closest to being a true representation of steel performance, and it does show that both CV and EB steels are indeed excellent. More perseverance with test Group B may have yielded the distinction between these steels the author seeks.

It is possible, on the other hand, that for these very clean EB and CV steels, failure from inclusions is postponed until it is no longer practically significant. If so, further cleanliness improvements would be of little value, and *consistency* of cleanliness must be the goal.

Turning now to some minor points:

1 The λ value for all 3 test groups is too low to insure absence of surface distress. It may well be that λ increased during run-in, to a sufficient value, say $\lambda = 3$, at least in test B, but that is not documented.

2 It is stated that the test C was conducted on bearings ground and honed to somewhat different specifications from those in tests A and B. The nature and direction of this difference is not clear.

3 It is interesting to note that while the predominant failure mode in test A was surface related, Fig. 8 shows a subsurface initiated spall from test A. This is presumably from the bearings made from conventionally melted steel.

W. J. Derner[6] and E. E. Pfaffenberger[6]

We feel the author is to be commended for contributing to the literature a demonstration of the potential for this infant steel melting process in producing premium quality carburizing bearing steels. A review of the paper, however, has raised several questions. First, in test group C, the premium quality steel not only exhibited a longer life than the conventional steel, it gave a different failure mode. It seems failures other than inclusion origin should have been treated as suspensions with respect to the objective of this test. Could this be done? That is, were there enough inclusion origin failures to allow this type of analysis? If so, what would be the quantitative effect on results?

Secondly, there seems to be rather wide variation in cleanliness rating between the consumable electrode vacuum remelt cups and cones on the one hand and rollers on the other. Can the author comment on any inference that can be drawn from this with respect to the variation in cleanliness from point to point within a single ingot?

Finally, the author states that the improved performance of the premium steels is due to the absence of occasional size 8 inclusions. Did a post-mortem examination show that failures of the conventional steel bearings originated from inclusions of this size, or is it an intuitive statement? We feel that the general overall improvement in cleanliness, that is the reduction in the gross number of potential fatigue nucleation sites is equally important. By way of explanation, we feel that a number of smaller (say, size 6 or 7) inclusions in a highly stressed area can be much more damaging than a very few size 8 inclusions located in lower stress areas.

It was pointed out that the electronic scanner-computer cannot distinguish between types of inclusions. This may be a weakness in this cleanliness rating method, as some types of inclusions (sulfides for example) are usually not considered harmful. One final comment: The predominance of geometric stress concentration failures in test C suggests that if the user expects to obtain the full potential benefit of premium quality bearing steels, he should give consideration to the optimization of roller crowns to preclude this type of failure resulting from misalignment in nonaligning bearing types.

Author's Closure

All of the discussers commented on the important test "C" which fell short of its intended goal of establishing the ultimate contact fatigue strength of the CV and EB steels. Since the tests were already being run under accelerated loading conditions and past experience dictated that shortening testing time by additional loading would be unwise, the test condition "C" was chosen over "B." Improvements were made in internal geometry and surface texture for the bearings used in test "C"; however, post test examination showed that further improvements in surface texture at the ends of the contacting surfaces were needed. There

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were only 3 of the 25 failures that were possible inclusion origins in the CV and EB steels in test "C;" therefore, to consider the other types of failures as suspensions would result in very approximate life estimates.

Elimination of the intermediate size inclusions is as important as removing the size 7 or 8 (scanner-computer chart) in vacuum processing. It is clear from Figs. 2 and 3 that all sizes are reduced by EB and CV melting. Post test metallographic work on the spalled conventional steel bearings showed the predominant inclusion size responsible for the spall to be of the 7–8 size categories. However, in some other group of test bearings the predominant size inclusion may be 4–5. Heat to heat variations, variations within a heat, and the amount of forging reduction all play a role in the size inclusion that will be found in a particular bearing component.

A JK rating (ASTM specification A295 using E45 method A for high carbon grades of steel) was not used for rating the conventional steel because ASTM specification A534 using E45 method C rating is the industry-wide specification for conventionally melted carburizing grades of bearing steels. A third specification (A535) and method (D) is used for special vacuum melted steels such as CV and EB. Instead of trying to compare the three steels used in this work by any one or combinations of the foregoing methods the scanner-computer method was selected as the best overall method of comparison.

The variations in cleanliness rating between the rollers and the cups and cones noted by Messrs. Derner and Pfaffenberger are a result of the 50–60 times more reduction-in-area that the rollers received compared to the cups and cones. The ratings were made on the finished bearing components.

In answer to Mr. Chevalier's comments about degradation and accumulation of foreign particles two 40 micron filters were used in each test. One was a cartridge type and the other a mechanical type. The properties of the oils used were monitored by periodic sampling and the oils were discarded when any changes in acid number were noted (0.3 for the low viscosity mineral oil). The CV, EB, and conventional steel bearings were placed in each test (A, B, or C) systematically, i.e., CV, EB, Conv., CV, EB, Conv., etc., so any accumulated effects of debris or oil degradation were shared by all three steel variations. Test A was the only one where there may have been a chance that debris played a role in the CV and EB failure modes.

Messrs. Tallian and Baile commented on the low λ values in all three tests and they were correct in stating that the values were all too low to prevent surface distress. However, λ remained the same or even decreased slightly in test A instead of increasing to the value of 3.

Mr. Chevalier also questioned the control of hardness in these bearings. The hardness of all the components was 60–63 Rockwell "C," but the hardness did not vary with melting method and no attempt was made to control a hardness difference between the rollers and raceways.

The typical inclusion origin fatigue damage examples shown in Fig. 8 were on conventionally melted steel cones.