Initiation and propagation of cracks under rolling contact fatigue in bearing steels

M. NAGUMO*, K. SUGINO*, K. AOKI* and K. OKAMOTO †
* Yawata Iron & Steel Co. Ltd., Tokyo Research Institute, Ida, Kawasaki-City, Japan.
† Yawata Iron & Steel Co. Ltd., Hikari Works, Hikari-City, Yamaguchi-Pref., Japan.

Summary

The failure of bearing steels under rolling contact fatigue is investigated from both the macroscopic and microscopic aspects. The distribution of the fatigue lives is analyzed statistically. The fatigue data can be divided into two groups. The probability of failure in the next cycle of the shorter life group increases proportionally with the fourth power of the number of cycles and that of the longer life group decreases slightly with the number of cycles.

Microstructural changes observed were characterised by dark-etching zones and 'butterfly' structure. Cracks propagate below the surface through the dark-etching zones in which martensite undergoes structural changes, and the rate of crack propagation is likely to be very high.

Microcracks were found to be associated with the 'butterfly' structures which originate at non-metallic inclusions. The growth of 'butterflies' is gradual and is markedly reduced within the dark-etching zone. Failure of specimens which belong to the longer life group is considered to be governed by the initiation of microcracks and of those which belong to the shorter life group, by the growth of cracks to final failure.

Introduction

The fatigue failure, or flaking of bearing steels under rolling contact has certain characteristic features. These are, (1) very hard bearing steels undergo structural alterations during cyclic stressing; (2) the shear stresses due to the contact load are not uniformly distributed over the specimen but are concentrated under the surface below the contact area; (3) cracks often grow from subsurface origins. Thus although studies based on fracture mechanics have been made on the propagation of fatigue cracks [1-6], the results cannot be directly applied to the rolling contact situation.

The failure of rolling bearings has been treated statistically. The classical theory of Lundberg and Palmgren [7] is based essentially on the weakest link model of fracture and the failure of a specimen is identified with the random formation of microcracks in a volume element below the surface. In their theory a simplified assumption is made about the dependence of the probability of failure on the maximum shear stress, on the depth below the surface and on the number of cycles. The physical interpretation of the probability of failure is beyond the scope of the theory.

Actual distributions of fatigue lives are not always predicted by the theory.

Many researchers have observed the microstructural changes which develop with cyclic stressing under rolling contact [8-14]. Their results, however, sometimes differ, so that further investigation about the contributions of structural changes to the initiation and propagation of fatigue cracks is required.

In the present paper, the initiation and propagation of fatigue cracks under rolling contact are investigated. From a macroscopic point of view, the distribution of fatigue lives is analyzed statistically, while from a microscopic point of view, the micro-structural changes with increasing number of stress cycles are investigated.

Experimental results

Experiments were conducted with SUJ 2 (AISI 52100) through-hardened steels prepared by two different melting practices. One was a commercial electric-arc-melt (designated sample A) and the other (designated sample B) a vacuum-induction-melt made using electrolytic iron. The latter was remelted with a consumable electrode vacuum arc furnace in order to reduce non-metallic inclusions. Rolling contact fatigue tests were performed using a thrust type machine [15] at a maximum Hertzian stress of 500 kg/mm^2. The specimens were 60 mm$\times$60 mm$\times$5 mm thick. Surfaces of most specimens were polished with No. 320 emery paper and some were further polished with alumina.

As a standard method of analysis [16], the fatigue lives were plotted on Weibull [17] probability paper as shown in Fig. 1. The data cannot be represented by a straight line but fall into two segments. The plot of the data as a straight line, or the presentation of the data as a single Weibull distribution is not appropriate if the mechanism of failure is not identical among all specimens and/or if the probability of failure is not a power function of the number of cycles. Cases where a Weibull plot is composed of two segments often occur when two failure mechanisms are present. [18, 19]. The data shown in Fig. 1 are considered to represent such a situation, and different fracture mechanisms are assumed to dominate each segment of the plot. More fundamentally, applicability of the Weibull distribution itself should perhaps be examined.

A statistical theory of fracture was formulated by Hirata [20, 21] and by Yokobori [22] in a general form. According to their treatments, the probability μ of the occurrence of failure in the next cycle after N cycles is given as

$$\mu = -\frac{d \ln P(N)}{dN} \qquad (1)$$

where $P(N)$ is the survival function, i.e. the probability that the failure occurs after more than N cycles. The form of dependence of μ on repeated cycles implies the mechanism of failure. The fatigue lives are plotted against the logarithm of $P(N)$ in Fig. 2, where it is found difficult to fit a simple function for $\mu(N)$ over the whole range of lives.

When different mechanisms of failure are presumed to dominate each segment of the Weibull plot shown in Fig. 1, each group can be considered as a sample from different populations. From the slope of the Weibull plot, it is apparent that the distribution of the shorter life group approximates to a normal distribution and that of the longer life group to an exponential distribution. The determination of the exact distribution, is the problem to be solved. These two distributions may, in general, overlap at the intersection of the two segments. However, the probability density function of the shorter life group is almost symmetrical with the peak at the center of the cycle range of the shorter life group. This implies that the overlap of the two distributions is, if any, very small and there is little error if the separation into two groups is done at the intersection shown in Fig. 1.

The survival function of each group is given in Fig. 3a, 3b respectively. Regression analyses were performed to determine the distributions and the following functions

$$\log P_1(N) = a + bN + cN^5 \qquad (2a)$$

$$\log P_2(N) = \frac{1}{\alpha}(N-\gamma)^\beta \qquad (2b)$$

were found to fit the data for the shorter life group and for the longer life group respectively. The solid lines in Fig. 3 were calculated from these functions by using the constants shown in Table 1. The probabilities of failure $\mu(N)$ were written using equation 1 as

$$\mu_1(N) = \zeta + \eta N^4 \qquad (3a)$$

$$\mu_2(N) = \kappa(N-\gamma)^\lambda \qquad (3b)$$

for the respective groups. The constants are also shown in Table 1. The probability of failure of the shorter life group in the next cycle increases with the number of cycles, while that of the longer life group decreases slightly as the number of cycles increases.

Microscopic observations were made on commercial steel specimens subjected to rolling contact fatigue by using a ring-type testing machine [23]. The applied Hertzian stress was 500 kg/mm^2, the same as in the thrust type test. One structural change is the dark-etching zone formed below the surface, and this is probably the structure observed by Jones [24] and Bush *et al.*, [8]. The depth at which the dark-etching zone is formed almost coincides with that where the shear stress is a maximum, i.e. 0·33 mm for the static loading and 0·25 mm for dynamic loading. The dark etching zone is a structural modification of martensite. The final structure appears similar to tempered martensite in which dislocations forms cells, but in the intermediate stage the changes proceed with the development of band-like structures as shown in Fig. 4. Therefore the alteration is not a simple tempering of martensite by heat developed during a test. The width of the zone and the density of the altered martensite patches increase with the number of cycles as shown in Fig. 5, and the hardness within the zone decreases in this zone. The origin of failure is found to lie in this zone and secondary cracks which start from the failure point are also found there. These facts indicate that a dark etching zone is the most favourable path for the final propagation of cracks.

Another structural change is characterised by white etching areas or 'butterfly' structures which originate at non-metallic inclusions. A typical example is shown in Fig. 6. This structure probably corresponds to that first reported by Styri [25]. In a butterfly, spheroidized cementites are subjected to large plastic deformations and microcracks are often present on the periphery. Microcracks other than those associated with butterflies are never observed within failed specimens. The 'butterflies' slope upwards towards the surface in the direction of ball travel, but the mechanism of their formation is not clear. The change in number, location and size of butterflies with number of cycles is shown in Fig. 7. It should be noticed in this figure that the growth rate of 'butterflies' is low and is much reduced in the dark-etching zone. New formations of butterflies are also reduced in the dark-etching zones.

Discussion

The distribution of fatigue lives shown in Figs. 1-3 indicates that the mechanism of failure is not the same in all specimens, the probabilities of failure being different depending on whether this is due mainly to the initiation or the growth of a crack. The stage leading to the initiation of a microcrack is as important as the growth stage particularly in the fatigue of a high-hardness steel in which crack propagation is considered to be very rapid once a crack is initiated [26].

The case where the probability of failure represents the mean rate of crack initiation has been examined by Yokobori [27] in the fatigue of annealed steels. In the present experiments, the probability of failure of the longer life group decreases slightly with or is almost independent of the number of cycles. This means that failure is a random phenomenon in this group. Specimens with fewer non-metallic inclusions or a better surface finish tend to have longer lives, because there are fewer defects to give rise to stress concentrations which can become the initiation sites

of microcracks. These observations are readily understood if the initiation of microcracks is the rate determining stage of failure which governs the distribution of fatigue lives. The probability of failure of the longer life group thus becomes the mean initiation rate of microcracks. That the probability of failure tends to decrease with repeated cycles may be partly ascribed to the formation of the dark-etching zone before the initiation of a microcrack, because the stress concentration at a defect is relaxed by the plastic deformation associated with the dark etching zone. Microcracks associated with 'butterfly' structures are the only microcracks observed within the fatigued specimens.

The growth of butterflies is gradual as shown in Fig. 7 and their size is at most 20-30 microns. Accordingly the final failure is not considered to be reached by the continuation of this growth. Thus, the growth of cracks to final failure should be distinguished from the initiation stage which includes the growth of microcracks at 'butterflies'. When there are sufficient sites present for the initiation of microcracks, their growth to final failure will govern the distribution of fatigue lives and the probability of failure will reflect such a situation.

Many theories have been presented concerning the growth rate of fatigue cracks, for example, the attainment of a critical value of strain hardening [28, 29], accumulated strain [1, 3] or accumulated hysteresis energy [2, 30] at the crack tip. Recently, Yokobori has proposed a theory of fatigue crack propagation in terms of the successive nucleations of microcracks at the crack tip [31] which predicts that the probability of cracking at the crack tip is a power function of crack length [32]. The plastic zone size ahead of the crack tip can be taken as proportional to the crack length [33]. Then if it is assumed that the plastic zone size increases proportionally with the number of cycles, the probability of failure becomes proportional to a power of the number of cycles in agreement with equation 3 (a) obtained experimentally for the shorter life group.

Crack growth will be assumed to occur when the amount of damage accumulated in the plastic zone ahead of the crack tip attains a critical value. When the growth stage governs failure, the probability of failure will thus be proportional to the amount of accumulated damage which increases with the number of cycles. In the rolling contact fatigue tests, the plastic zone is not always localized at the crack tip because the maximum shear stress often exceeds the yield strength of the material. The highly stressed plastic area moves as the ball travels, forming the dark-etching zone. Plastic deformation will proceed at the crack tip, but damage at neighboring parts can be large enough to cause propagation of the crack. In this case, the dark etching zone as a whole becomes the plastic zone through which the crack grows so that the damage accumulated in this whole region should be taken as the criterion for crack growth. As shown in Fig. 5, the density of the modified martensite patches increases with the number of cycles. Furthermore the decrease in the hardness of the dark-etching zone may cause an increase in the damage accumulated per cycle as the test proceeds. Thus the probability of failure, which is proportional to the accumulated damage, is expected to increase as a high power function of the number of cycles. This explains the form of equation 3 (a) which gives the probability of failure of the shorter life group.

The microscopic observation showed that the rate of growth and the new formation of 'butterflies' are both reduced in the dark-etching zone. Current theories of fatigue crack growth predict that decrease in the strength of a material will cause an increase in the plastic zone size and in the growth rate of cracks, which is contrary to the observations. Butterflies are possible sources of final cracks and even if microcracks other than those associated with butterflies contribute to the final failure, similar situations may occur during their growth. However, the plastic deformation at the crack tip has the effect of making the strain distribution more uniform and reducing the stress concentration by blunting the crack tip [34, 35]. The growth of an actual fatigue crack is not continuous as assumed in the theories, but periods of rapid growth alternate with dormant periods [36, 37]. Thus a temporary stop to the growth of microcracks in the dark-etching zone is probable. Now strain will concentrate in the softened area as cyclic stressing proceeds, thus growth of a crack will occur catastrophically within the dark-etching zone once sufficient damage is accumulated, leading to final failure.

Conclusions

1. The distribution of rolling contact fatigue lives was analyzed statistically. The fatigue data were shown to be divided into two groups, and each group was considered to be a sample from a different population. The probability of failure in the next cycle of the shorter life group increased as the fourth power of the number of cycles while that of the longer life group decreased slightly with the number of cycles.

2. Microscopic examination of fatigued specimens showed two types of structural modifications: (a) dark-etching zone formed below the surface, and, within the zone, patches of martensite which undergo progressive modification as cyclic loading proceeds. The width of the zone and the number of modified martensite patches increase with the number of cycles. The dark-etching zone is the most favourable path for crack propagation, (b) a 'butterfly' structure which starts at non-metallic inclusions. Microcracks were often found on their periphery. The number and the size of 'butterflies' both increased with the number of cycles, but the rates of the growth and the number of new formations were reduced within the dark-etching zone. Microcracks other than those associated

with butterflies were not observed and the size of 'butterflies' is at most 20-30 microns.

3. Failure is considered to be governed by the initiation of microcracks for specimens which belonged to the longer life group and by the growth of cracks to final failure for those which belonged to the shorter life group.

Acknowledgements

The authors would like to thank Prof. T. Yokobori for his helpful advice and discussions. Their thanks are also due to Prof. S. Mizushima for the encouragement they have received during the course of the work.

References

1. McCLINTOCK, F. A., 'On the plasticity of the growth of fatigue cracks,' in 'Fracture of Solids', *Interscience Pub.*, p. 65, 1963.
2. LIU, H. W., 'Fatigue crack propagation and applied stress range. *Trans. ASME*, vol. 85-D, p. 116, 1963.
3. WEERTMAN, J., 'Rate of growth of fatigue cracks calculated from the theory of infinitesimal dislocations distributed on a plane,' *Proc. International Conference Fracture, Sendai, Japan*, p. 153, 1965.
4. RICE, J. R., 'Plastic yielding at a crack tip,' *Proc. International Conference Fracture*, Sendai, Japan, p. 283, 1965.
5. McEVILY, Jr. & JOHNSTON, T. L., 'The roll of cross-slip in brittle fracture and fatigue,' *Proc. International Conference Fracture*, Sendai, Japan, p. 515, 1965.
6. KRAFFT, J. M., 'On prediction of fatigue crack propagation rate from fracture toughness and plastic flow properties,' *Trans. ASM.*, vol. 58, p. 691, 1965.
7. LUNDBERG, G. & PALMGREN, A., 'Dynamic capacity of rolling bearings,' *Ingeniörsvetenskapsakademiens handlinger NR 196*, 1947.
8. BUSH, J. J., GRUBE, W. L. & ROBINSON, G. H., 'Microstructural and residual stress changes in hardened steel due to rolling contact.' *Trans. ASM.*, vol. 54, p. 360, 1961.
9. GENTILE, A. J., JORDAN, E. F. & MARTIN, A. D., 'Phase transformations in high-carbon, high-hardness steels under contact loads,' *Trans. AIME.*, vol. 233, p. 1085, 1965.
10. MARTIN, J. A., BORGESE, S. F. & EBERHARDT, A. D., 'Microstructural alterations of rolling-bearing steel undergoing cyclic stressing,' *Trans. ASME*, vol. 88-D, p. 555, 1966.
11. O'BRIEN, J. L. & KING, A. H., 'Electron microscopy of stress-induced structural alterations near inclusions in bearing steels,' *Trans. ASME.*, vol. 88-D, p. 568, 1966.
12. O'BRIEN, J. L. & KING, A. H., 'Cyclic-stress-induced microstructural changes in hardened bearings,' *J. Iron Steel Inst.*, vol. 204, p. 55, 1966.
13. SCOTT, D. & SCOTT, H. M., 'The application of electron microscopy to the study of pitting failure of rolling bearings,' *Proc. Eur. Reg. Conf. on Electron Microscopy, Delft*, 1960, vol. 1, p. 539.
14. SCOTT, D., LOY, B. & MILLS, G., 'Metallurgical aspects of rolling contact fatigue,' *NEL Report, No. 321*, 1967.
15. UENO, M., NAKAJIMA, H. & IKEDA, S., 'Ball-bearing steels made from the sponge iron as raw material,' *Tetsu to Hagane*, vol. 47, p. 124, 1961.

16. 'The Weibull distribution function for fatigue life,' *Material Research & Standard*, vol. 2, p. 405, 1962.
17. WEIBULL, W., 'A statistical distribution function of wide applicability,' *J. Appl. Mech.*, vol. 18, p. 293, 1951.
18. BERRETTONI, J. N., 'Practical application of the Weibull distribution,' *Industry Quality Control*, p. 71, Aug., 1964.
19. KAO, J. H. K., 'A graphical estimation of mixed Weibull parameters in life-testing of electron tubes,' *Technometrics*, vol. 1, p. 389, 1959.
20. HIRATA, M., 'Delayed fracture of glass,' *Kikai no Kenkyu*, vol. 1, p. 182, 1949.
21. HIRATA, M., 'Characteristics of the distribution of V-notch Charpy values,' *Rep. AT Committee, Japan*, 1961.
22. YOKOBORI, T., 'The theory of fatigue fracture of metals,' *J. Phys. Soc. Japan*, vol. 10, p. 368, 1955.
23. KURODA, M., 'On the mechanism of flaking due to rolling fatigue of ball and roller bearing steels,' *Trans. Japan Soc. Mech. Eng.*, vol. 26, p. 1258, 1960.
24. JONES, A. B., 'Effect of structural changes in steel on fatigue life of bearings,' *Steel*, vol. 119, p. 68, Sept. 30, 1946.
25. STYRI, H., 'Fatigue strength of ball bearing races and heat-treated 52100 steel specimens,' *Proc. ASTM*, vol. 51, p. 682, 1951.
26. THOMSON, R. F., 'Fatigue behaviour of high-carbon, high-hardness steel,' *Trans. ASM.*, vol. 56, p. 803, 1963.
27. YOKOBORI, T., 'The statistical aspect of fatigue fracture of metals,' *Rep. Inst. Sci. & Tech. Univ. Tokyo*, vol. 8, No. 1, 1954.
28. OROWAN, E., 'Theory of the fatigue of metals,' *Proc. Roy. Soc.*, *vol. A* 171, p. 79, 1939.
29. HEAD, A. K., 'The growth of fatigue cracks,' *Phil. Mag.*, vol. 44, p. 925, 1953.
30. FELTHER, C. E. & MORROW, J., 'Microplastic strain hysteresis energy as a criterion for fatigue fracture,' *Trans. ASME*, vol. 83-D, p. 15, 1961.
31. YOKOBORI, T., 'Nucleation theory of fatigue crack propagation,' in *Physics of Strength and Plasticity (The Orowan 65th Anniversary Volume)*, Argon, A. S. Ed., MIT Press, 1969.
32. PARIS, P. & ERDOGAN, F., 'A critical analysis of crack propagation law,' *Trans. ASME*, vol. 85-D, p. 528, 1963.
33. FROST, N. F. & DUGDALE, D. S., 'The propagation of fatigue cracks in sheet specimens,' *J. Mech. Phy. Solids*, vol. 6, p. 92, 1958.
34. FRIEDEL, J., 'Propagation of cracks and work hardening' in 'Fracture', Wiley, N.Y., p. 498, 1959.
35. TETELMAN, A. S., 'The effect of plastic strain and temperature on micro-crack propagation in iron-3% silicon', *Acta Met.*, vol. 12, p. 993, 1964.
36. LIPSITT, H. A., FORBES, F. W. & BAIRD, R. B., 'Crack propagation in cold-rolled aluminum sheet', *Proc. ASTM*, vol. 59, p. 734, 1959.
37. CHRISTENSEN, R. H., 'Cracking and fracture in metals and structure,' *Symposium Crack Propagation*, Cranfield, England, 1961.

Table 1
Numerical values of the constants in equation 2 and equation 3.
The unit of cycles in 10^6.

	a	b	c	α	β	γ	ζ	η	κ	λ
SAMPLE A	1·86	$3{\cdot}4 \times 10^{-2}$	$-2{\cdot}2 \times 10^{-4}$	$-6{\cdot}4 \times 10^{4}$	0·68	6·6	$-7{\cdot}8 \times 10^{-2}$	$2{\cdot}5 \times 10^{-3}$	$2{\cdot}4 \times 10^{-5}$	−0·32
SAMPLE B	1·98	$-2{\cdot}3 \times 10^{-2}$	$-1{\cdot}2 \times 10^{-6}$	$-8{\cdot}4 \times 10^{5}$	0·72	16·5	$5{\cdot}3 \times 10^{-2}$	$1{\cdot}4 \times 10^{-5}$	$2{\cdot}0 \times 10^{-6}$	−0·28

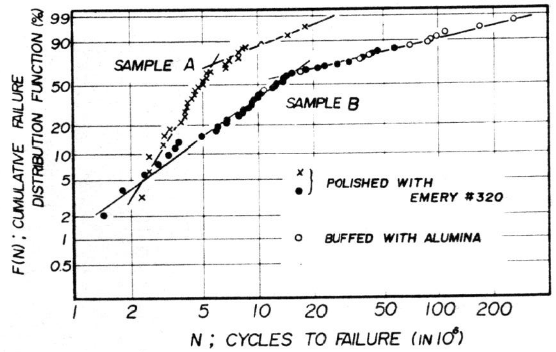

Fig. 1. The fatigue data plotted on the Weibull probability paper. Sample A is the commercial steel and sample B is the vacuum-melt.

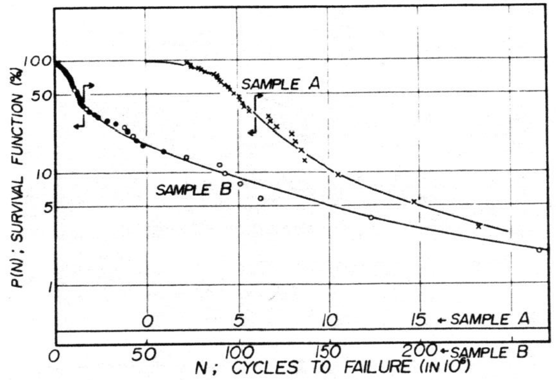

Fig. 2. Survival functions of the whole specimens. The arrows indicate the separation to the two segments shown in Fig. 1. Symbols are common to Fig. 1.

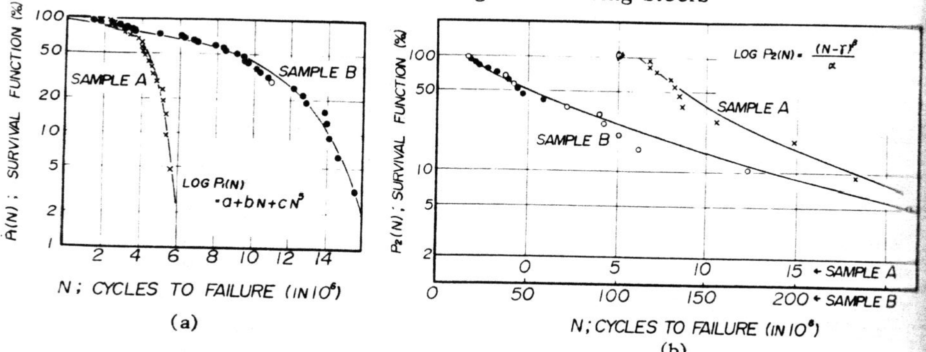

Fig. 3. Survival function of the shorter (3a) and the longer (3b) life group respectively. The solid lines are calculated ones using equation 2 and the numerical values listed in Table 1. Symbols are common to Fig. 1.

Fig. 4. The structural alterations of martensite within the dark-etching zone, showing the development of the band-like structure. The specimen is tested 1.50×10^6 cycles at the maximum contact stress of 500 kg/mm². (Transmission electron micrograph)

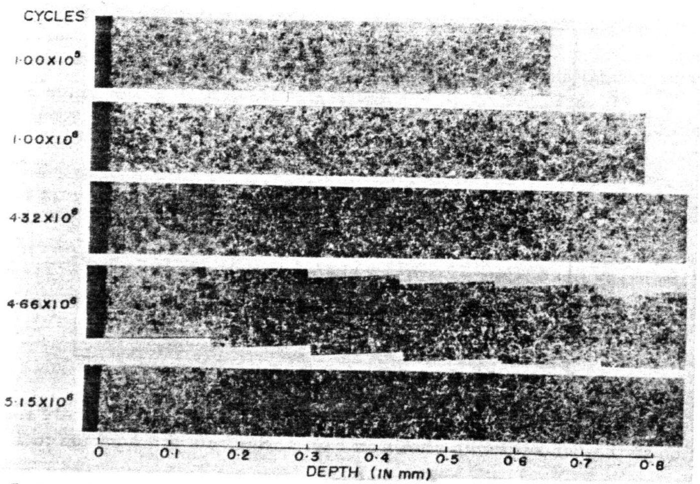

Fig. 5. Developments of the dark-etching zone below the contact surface at various stages. The maximum contact stress is 500 kg/mm².

Rolling contact fatigue in bearing steels

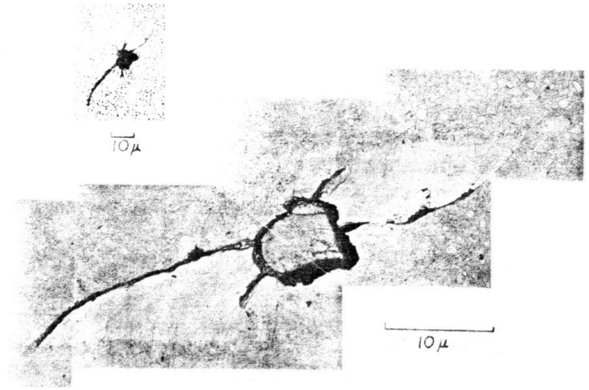

Fig. 6. A typical butterfly structure observed in a circumferential cross section of the tested specimen. (Optical and replica electron micrographs.)

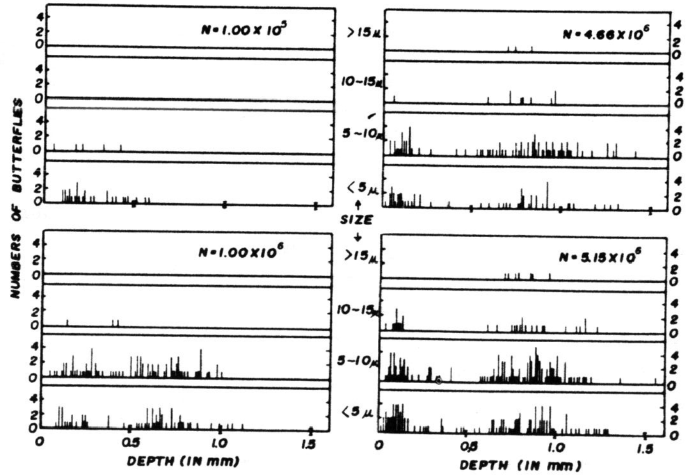

Fig. 7. Numbers, sizes and locations of butterflies in the specimens tested various cycles. The maximum contact stress is 500 kg/mm².