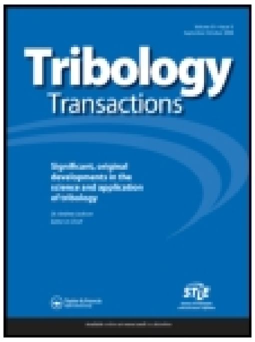

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Microstructural Alterations in Bearing Steels under Rolling Contact Fatigue Part 1—Historical Overview

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Microstructural alterations in bearing steels during rolling contact cycling have been reported in the literature for more than half a century. These structural changes are primarily caused by the decay of parent martensite and have been designated as white and dark etching regions due to their preferential etching characteristics. One of the most striking features of the white etching bands is their repeatable directionality, which has puzzled investigators for decades. Despite numerous attempts, a satisfactory explanation for the orientation of these bands is still not available. In this article (Part 1), an overview of the phenomenon is presented with detailed discussion of various experimental observations from the literature. The article also examines the previous approaches adopted to explain white etching bands and address their limitations. In Part II of the article, a J2-based elastic–plastic finite element model coupled with a carbon diffusion model is developed that directionally predicts the occurrence and orientation of the white etching bands.

KEY WORDS

Microstructural Alterations; White Etching Bands; Dark Etching Regions; Carbon Diffusion

INTRODUCTION

Bearings are perhaps one of the most important components in tribomachinery and are commonly used to support large loads and allow for rotary motion. They may be required to sustain severe static as well as cyclic loads while functioning reliably in extreme environments. Although the concept of employing rolling motion to support complex machinery and mechanisms has been known for thousands of years, the general usage of rolling bearings did not occur until the industrial revolution (Harris *(1)*). Since the 1940s, the continuous increase in the demand for bearings has warranted better knowledge and understanding of bearing operation (i.e., elastohydrodynamic lubrication, bearing dynamics, rolling contact fatigue [RCF], etc.). It is suggested that if a bearing is installed properly and operated under designed loading and lubrication and kept free of foreign contamination, the main mode of bearing damage is due to RCF (Sadeghi, et al. *(2)*). The stresses experienced by the bearing during dry contact can be estimated using the Hertzian theory, which recognizes some of the key parameters controlling RCF; that is, contact pressure, geometry, and the mechanical properties of the material (Kang, et al. *(3)*). Two categories in which RCF may be manifested are (1) surface-originated pitting and (2) subsurface-originated spalling. Surface-originated pitting occurs due to the presence of surface distresses such as dents, fretting scars, etc., on the surface of the contacting bodies. However, if the contacting bodies are relatively smooth, then the main mode of RCF is subsurface-originated spalling. Under subsurface-initiated spalling, a fatigue crack typically appears near the presence of an inclusion or material inhomogeneity inside the material domain and gradually propagates to the surface, forming a fatigue spall. Sadeghi, et al. *(2)* recently provided a comprehensive review of different experimental, analytical, and computational models available in the literature for subsurface-originated RCF.

Along with the above-mentioned fatigue damage, one of the most distinctive features of bearing material damage due to contact cycling is microstructural alterations. The microstructure of bearing steel—for example, AISI 52100—consists of homogenously distributed primary spherical (Fe, Cr)$_3$C carbides in a matrix of martensite. The steel microstructure also contains about 6–10% retained austenite. It has been well recognized that noticeable structural changes may take place in bearing steel as a result of cycling stressing during service operations. In 1947, Jones *(4)* was among the first to point out these changes with the observation of an altered microstructure beneath the ball track of bearing inner races operated for extended periods at high loads. Jones *(4)* called these regions *troostite*, which is an archaic term for tempered martensite, and pointed out that pitting damage occurred as a direct consequence of these structural alterations (Bush, et al. *(5)*). This region appears dark when observed under an optical microscope after etching and hence is more commonly known as the *dark etching region*. Other researchers have described this region as low-temperature bainite (Kuroda *(6)*) or ferrite (Martin, et al. *(7)*; Tricot, et al. *(8)*; Borgese *(9)*).

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Bush, et al. *(5)* conducted detailed experimental analysis and pointed out that (1) the altered structure resembles tempered martensite; (2) the alterations develop only when the operating stress is above a certain threshold level; (3) the transformation is initiated in localized areas, in the region of maximum orthogonal shear stress; and (4) the rate of nucleation of altered regions tends to increase as the contact stress in increased. They also observed that the hardness decreases in the microstructure altered zone below the surface. In addition to the troostite-type region, Jones *(4)* was the first to report a fine structure of grey lines interlaced within the dark etching region. Similar observations were made by Gentile, et al. *(10)*, Bush, et al. *(5)*, Kuroda *(6)*, Martin, et al. *(7)*, Buchwald and Heckel *(11)*, and others, who called this constituent the *white phase*, *white etching areas*, *light etching areas*, or *grey lines*, depending on their appearance under an optical microscope after etching. Adjoining these white bands, high-magnification microscopy revealed the existence of another structure that does not etch significantly, is narrower than the white bands, and does not break during tempering (Borgese *(9)*). This structure is referred to as *lenticular carbide*.

Bush, et al. *(5)* reasoned that the lenticular carbides are a consequence of plastic deformation of the spherical carbides present in the pristine bearing steel microstructure. However, Borgese *(9)* suggested that the lenticular carbides are formed due to diffusion of carbon caused by the stresses experienced during rolling contacts and, after diffusion, the carbon precipitates in the form of lenticular carbides. This theory was further enhanced by Buchwald and Heckel *(11)*, who developed an analytical model for the growth of white bands in the material microstructure. They proposed that the formation of white areas is due to dissolution of the carbides caused by compressive strain and increased dislocation density in these areas. Martin, et al. *(7)* proved that the formation of lenticular carbides cannot be due to the deformation of preexisting carbides as proposed by Bush, et al. *(5)*. However, they could not provide any explanation for their existence. The experimental analysis performed by Buchwald and Heckel *(11)* showed that volume fractions of proeutectoid carbides are dissolved during the microstructural alteration in addition to the solution of tempered carbides as shown by previous studies (Martin, et al. *(7)*; O'Brien and King *(12)*).

Lund *(13)* was among the first to differentiate the white etching region into 30 and 80° bands. That study revealed that with increasing rolling contact stressing time, two or three phases can be identified in the material microstructure. First, a dark etching region resembling troostite becomes evident. Next, growth of the dark etching zone is observed and unetched bands are developed parallel to the race in transverse direction rising toward the track at an angle of 20–25°. And finally, further growth of the dark etching area accompanied by a second set of oriented unetched phase rising toward the surface at angle of 65–70° is detected. Similar observations were made by Beswick *(14)* regarding measurement of the percentage carbon content in white etching regions using microscopy. Lund *(13)* also conducted studies to evaluate the hardness of the altered regions. The analysis demonstrated that the degree of softening depends on the extent to which the dark etching region has formed in the material microstructure. This is in direct contrast to the observation made by Swahn, et al. *(15)*, who reported that the hardness first increases and then softening occurs.

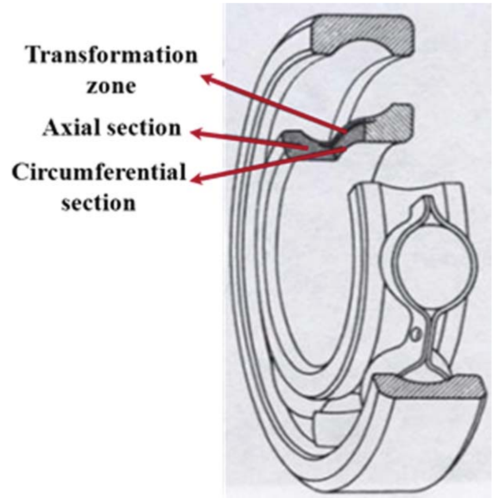

Fig. 1—Cross section of different sections of the bearing raceway (Osterlund and Vingsbo *(25)*) (color figure available online).

Before proceeding further, it is important to define the different sections of the bearing raceways because they are mentioned consistently throughout the article. Figure 1 illustrates the different sections of the bearing raceway; that is, the (1) axial section and (2) circumferential section. In addition, the figure depicts the region where microstructural alterations occur. As discussed earlier, there is a distinct directionality associated with the white etching bands when observed under an optical microscope. Martin, et al. *(7)* conducted an in-depth analysis on the orientation of the white etching bands. They found that the angle of the bands was about 22 to 24° for deep-groove ball bearings, whereas for cylindrical roller bearings the angle was about 30°. Martin, et al. *(7)* also pointed out that the density of the white areas varies in a manner that is closely similar to the variation of shear stress with depth and that they have been observed to form at a particularly rapid rate around nonmetallic inclusions; that is, weak regions in the material. Analysis of the white areas in the axial section revealed that the starting line of white etching bands lies somewhere around the $0.524b$ depth below the contact surface and a maximum white area density occurs in the region between $0.592b$ and $1.053b$ (where b is the half-contact width). Thus, it is apparent that the maximum white area density corresponds closely to the depth of maximum unidirectional shear stress. The analysis performed by Martin, et al. *(7)* also hinted that there exists a minimum threshold load level below which no microstructural changes are observed. Until 1976, different researchers used dissimilar terminologies for the microstructural changes observed under RCF. Swahn, et al. *(15)* were among the first to present a unified terminology for the microstructural changes (i.e., the white and dark etching regions) in bearing steel. The sequence of events for the structural changes follows a pattern. First a ferritic phase is observed in the bearing microstructure, which consists of inhomogenously distributed excess carbon content, corresponding to that of the parent martensite. A mixture of this phase with residual martensite constitutes the *dark etching region*. Secondly, disc-shaped regions of ferrite, about 2 μm thick, inclined by about 30° to the raceway are sandwiched between carbide-rich discs appearing beneath the surface. The disc-shaped regions of ferrite appear white upon etching and hence are known as the *30° white etching bands* or *lower angle bands*, whereas carbides discs are commonly referred to as *lenticular carbides*. Finally, a second set of larger disc-shaped regions about 10 μm thick forming an angle of 80° to the raceway was observed in the material microstructure. These bands are called the *80° white etching bands* or *higher angle bands*.

Another important phenomenon associated with rolling contact cycling is the development of residual stresses below the surface and variation of material hardness. The residual stresses developed are three-dimensional in nature and their magnitude depends on the contact pressure and running time of the bearing. Voskamp and Mittemeijer *(16)* suggested that the normal component of the residual stresses plays a significant role in the propagation of subsurface fatigue cracks. Zwirlein and Schlicht *(17)* proposed that the superposition of residual stresses on the stresses developed under Hertzian contact can explain the formation of white etching bands in the bearing microstructure. The change in the hardness during RCF into the depth of the domain has been an issue of much debate over the years. Some researchers have reported that the hardness of the structure decreases and some have reported the opposite. A good resolution with regard to this issue was provided by Voskamp *(18)*, who explained that the hardness decreases with RCF due to the decay of the martensitic structure. The local increase in the hardness is caused due to transformation of the retained austenite into martensite.

Later studies in this area focused on developing analytical/numerical models that can predict the onset of microstructural alterations. Bhargava, et al. *(19)* developed an elastic–plastic finite element model in order to explain the formation of the white etching bands along with their peculiar orientation. Voskamp *(20)* used the X-ray diffraction technique and maximum diffraction intensity variation with depth to postulate that a preferred crystallographic texture is developed in the altered region below the bearing raceway. Initially, he reported a {100}<110> texture, but later, Beswick *(21)* found that the texture suggested by Voskamp *(20)* only formed for heavily loaded bearings. They suggested that for moderately loaded bearings, a {111}<112> texture develops, which leads to the formation of WEBs (white etching bands). Until the 1990s, the theories proposed for the development of white etching bands under contact cycling were mostly speculative. Because the bands are commonly observed around the regions of maximum shear stress, most theories centered around using the angles associated with maximum shear stress, maximum principal stress, or maximum plastic principal strain (as in the case of Bhargava, et al. *(19)*) to explain the formation of white etching bands. Polonsky and Keer *(22)* conducted an in-depth analysis of different theories proposed for the development of a white structure in rolling bearings. Their analysis identified several shortcomings in the different theories based on purely stress–strain analysis. They proved that the plastic deformation of the contacting bodies is the primary cause of structural alterations and that the different phases develop in the microstructure due to the diffusion of carbon from the martensite matrix. However, because their model was not developed enough to handle elastic–plastic Hertzian contact, they could not directly correlate dissipated plastic energy to subsurface carbon diffusion. They postulated how plastic deformation will aid in carbon migration in the bearing steel microstructure during contact cycling.

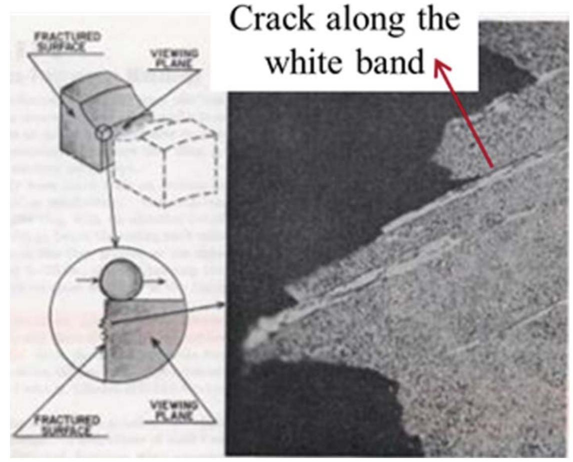

Fig. 2—Crack along the white etching band (Martin, et al. *(7)*) (color figure available online).

Recently, Forster, et al. *(23)* conducted metallurgical analysis on fatigue-damaged bearings manufactured from three different bearing steels: (1) AISI 52100, (2) AISI M50, and (3) M50 NiL. A similar analysis was conducted by Braza, et al. *(24)* in 1993. Their analysis confirmed that the additional alloying elements present in AISI M50 and M50 NiL provide secondary hardening during rolling contact cycling, which helps stabilize the microstructure compared to AISI 52100. Forster, et al. *(23)* found microstructural alterations in bearings made out of AISI 52100 and AISI M50 bearings. However, M50 NiL bearings did not show any microstructural alterations. With the advent of new and powerful computers and the need for developing computational models for bearing analysis, it is essential to capture the different aspects of bearing damage. Figures 2 and 3 illustrate how the phases that develop as a result of microstructural alterations act as stress risers, leading to the formation of cracks and premature spalling of the bearing raceway. As discussed by Sadeghi, et al. *(2)*, recent computational models are sophisticated enough to take into account the topology of the material microstructure in order to simulate fatigue damage of bearing components with similar scatter in fatigue lives that is commonly observed in bearing life analysis. However, the models are not yet advanced enough to capture the structural degradation from the standpoint of microstructural alterations. This article provides a brief historical background of important work conducted in the area of microstructure alteration under contact cycling. Furthermore, this article serves as a stepping stone for Part II, wherein the issue of modeling the white etching bands due to carbon diffusion is addressed.

MICROSCOPY OF ALTERED MICROSTRUCTURE

Over the last 65 years, researchers have employed different techniques such as optical microscopy, scanning electron

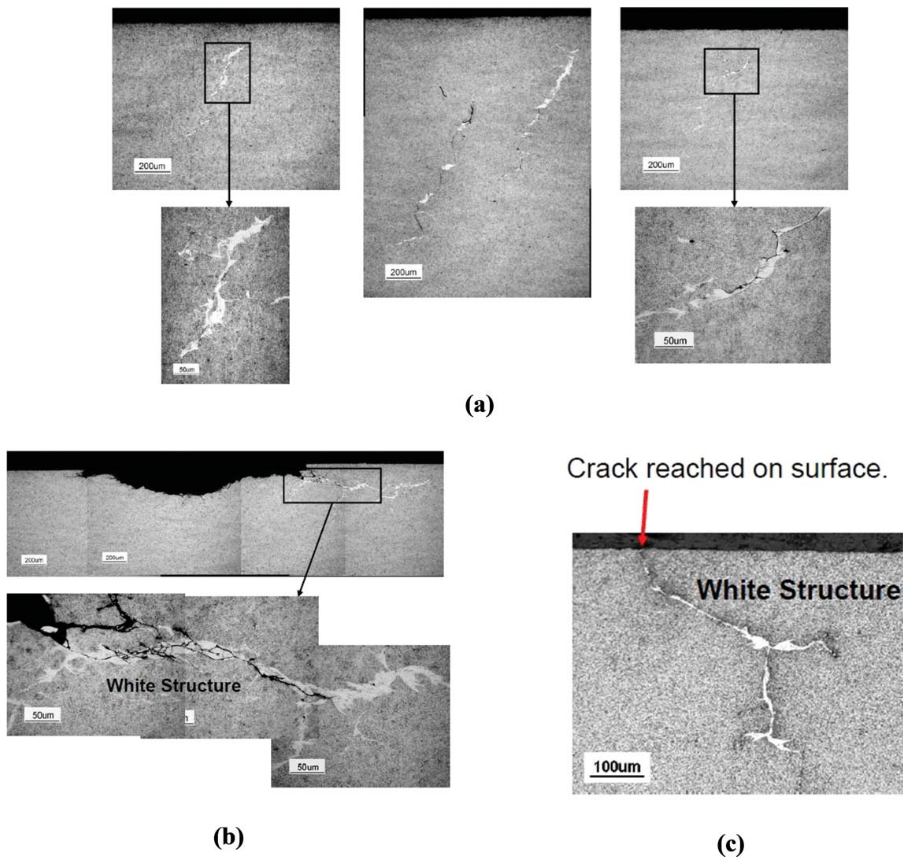

Fig. 3—Examples of structural alterations leading to cracking and subsequent spalling: (a) fracture origin in the white region, (b) flaking in the bearing for a high-speed shaft for wind turbine, and (c) crack reaching the surface *(46)* (color figure available online).

microscopy (SEM), transmission electron microscopy (TEM), etc., to study the structural decay observed in bearing raceways. Figure 4 illustrates the optical microscopy of the zone of structural changes in the longitudinal section with increasing number of cycles obtained by Swahn, et al. *(15)*. The etchant used in this analysis was nital. Figure 4a shows the dark etching region in the initial stages of bearing operation. With increasing number of fatigue cycles, the dark etching region grows in size and 30° bands become visible. Finally, after some more contact cycling, 80° bands are prominently observed in the altered region. Figure 5 illustrates the optical microscopy images of the axial section of the bearing raceway as captured by Martin, et al. *(7)*. The figure clearly shows the white etching bands along with the adjoining lenticular carbides. It is important to note that the thickness of the lenticular carbides is much smaller than that of the white etching bands. Osterlund and Vingsbo *(25)* indicated that the metallic crystal characteristics such as surface energy or grain boundary misfit energy determine the topography after etching and hence some phases appear dark and others appear white when observed under an optical microscope. They studied the effect of different etchants on the fatigued microstructures. The etchants used were nital, picral, and carbide. The studies indicated that only nital etching is effective for obtaining a good contrast for the dark etching region using optical microscopy. Gentile, et al. *(10)* reported that picral solution is best for observing the white etching bands. This is because nital etches ferrite grain boundaries and ferrite–cementite grain boundaries, whereas picral attacks the phase boundary between ferrite and cementite or other carbides but not the boundaries between ferrite grains (Vander Voort *(26)*). Osterlund, et al. *(27)* conducted high-resolution autoradiography for the determination of the carbon diffusion during rolling contact fatigue in ball bearings. Their analysis proved that carbon diffusion is the primary source for the observed structural changes during RCF. However, because they did not observe any marked carbon concentration gradients, they were unable to explain the driving force behind carbon diffusion. Lindahl and Osterlund *(28)* conducted $2\frac{1}{2}D$ transmission electron microscopy for the phase changes observed in ball bearings. The motivation behind using this technique was to study the crystal lattice of the transformed microstructure. They reasoned that for cases where the crystal structure and orientation relationships are similar to the matrix, the diffraction pattern is often complex and exhibits dense clusters of spots. By employing the $2\frac{1}{2}D$ technique, the correlations between the image features and the object lattice structure are transformed to a stereoscopic effect by using defocused dark-field image pairs (Lindahl and Osterlund *(28)*). The results indicated that the microstructural transformation involves a redistribution of excess carbon from the body-centered tetrahedral martensite matrix and forms decayed primary carbides. Short-range migration of the excess carbon takes place by dislocation core diffusion in preferred directions. Thereby, a carbon concentration in the interfaces might be created. Localized

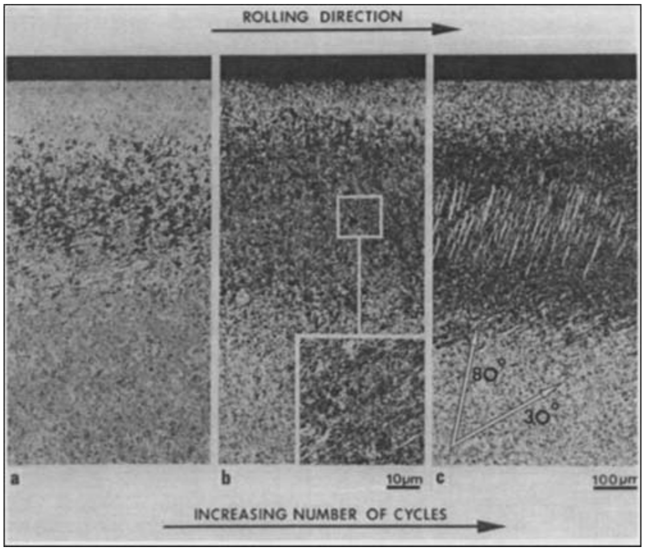

Fig. 4—Microstructural alterations with contact cycling: (a) dark etching region in early stages, (b) fully developed dark etching region and 30° bands, and (c) dark etching region, 30 and 80° bands (Swahn, et al. *(15)*).

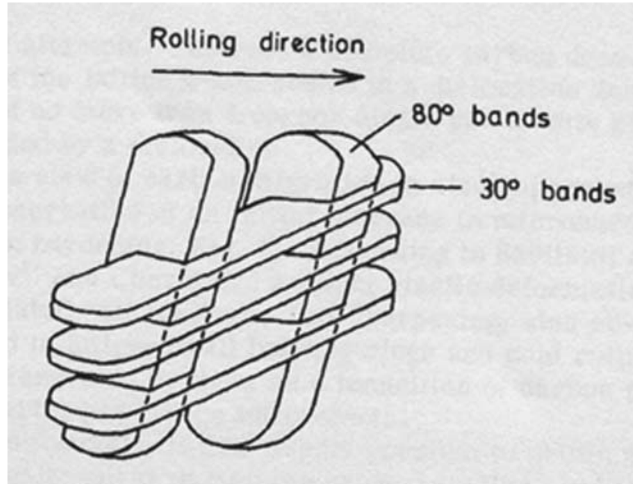

Fig. 6—3D schematic representation of the 30 and 80° bands (Swahn, et al. *(15)*).

agglomerates of carbon atoms constitute the nucleation sites. These sites serve as microprecipitation sinks for additional carbon atoms at further cycling. The white etching bands are three-dimensional in nature as depicted schematically in Fig. 6.

OCCURRENCE AND CHEMICAL COMPOSITION OF MATRIX AND BANDS

The development of the altered microstructure below the bearing raceway is a function of the load carried by the contacting surfaces. Most researchers have reported that there exists a threshold load level below which no structural alterations are observed. Figure 7 illustrates a compendium of data collected from different sources plotted on a *P-N* diagram. The results in this figure represent the timeline for the different phases that develop within the bearing microstructure with contact cycling. It can be observed that first the dark etching region appears followed by the 30 and 80° white etching bands. The cycle number for the occurrence of these different phases is a function of the contact load. In addition, it can be observed that below a contact load of 2.5 GPa, no structural alterations were observed. This load matches closely with the minimum load required for the onset of plastic deformation of bearing steel under Hertzian contact. This suggests that the altered microstructure is closely related to the plastic deformation of the material during rolling contact fatigue. One interesting anomaly reported by Mitamura, et al. *(29)* was that for contact load of 5.5 GPa, the 80° bands appeared before the 30° bands. This condition, however, appears to be overload, because the stresses generated due to the contact load of 5.5 GPa were in excess of the ultimate compressive strength of the material. Thus, more experimental data are needed at these higher loads in order to explain the occurrence of this inconsistency.

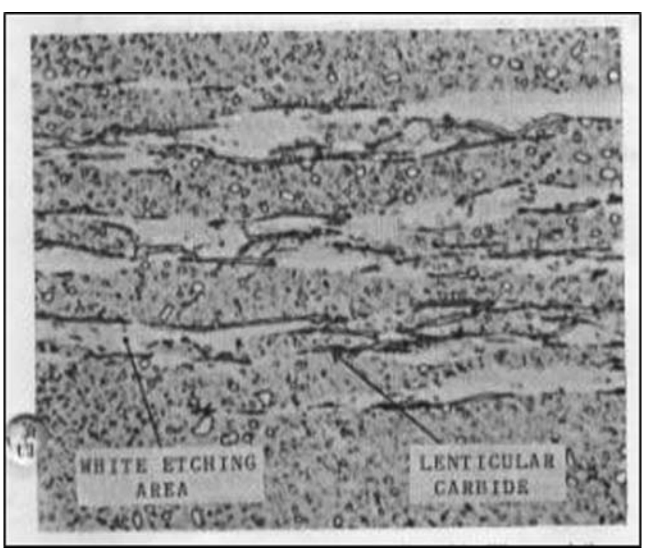

Fig. 5—Optical micrographs of axial section of bearing raceway showing white etching regions and lenticular carbides (Martin, et al. *(7)*).

The typical composition of bearing steel AISI 52100 is presented in Table 1. The most critical component from the point of view of microstructural alterations is percentage of carbon concentration, which is around 1 wt% in the pristine bearing steel microstructure. The 1 wt% carbon concentration in the different phases that evolve with contact cycling was first measured by Beswick *(14)* in 1975 by employing microprobe analysis technique. Later, Osterlund and coworkers *(27)* used high-resolution autoradiography and $2\frac{1}{2}D$ transmission electron microscopy to determine the amount of carbon present in the dark etching region and the white etching bands. Muroga and Saka *(30)*

TABLE 1—CHEMICAL COMPOSITION (WT%) OF AISI 52100 BEARING STEEL

	C	Cr	Fe	Mn	P	Si	S
AISI 52100	0.98–1.1	1.45	97.0	0.35	≤0.025	0.23	≤0.025

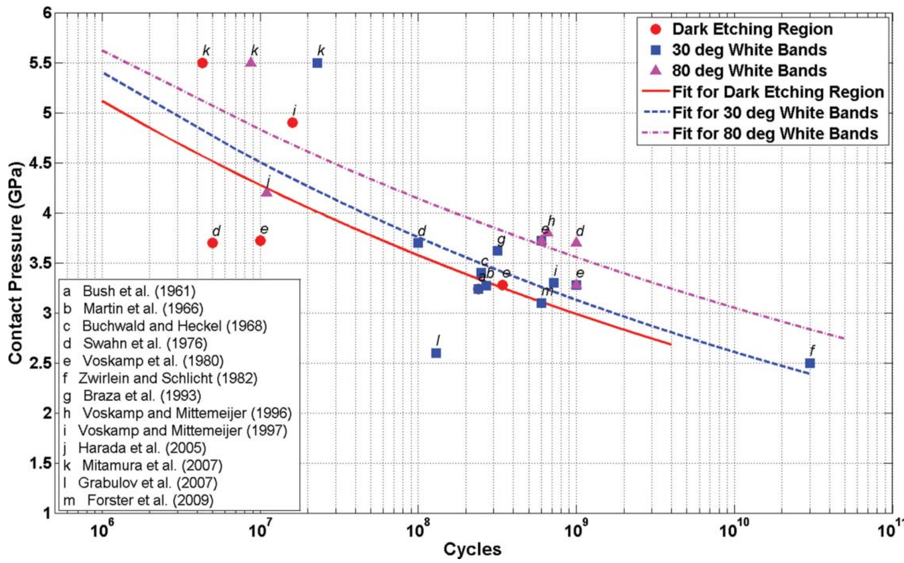

Fig. 7—Historical data on microstructural alteration (color figure available online).

performed focused ion beam sputtering and TEM analysis on fatigued bearings. Their analysis reported the concentration of main alloying elements in the matrix and white etching bands. The results are summarized in Table 2. From the table it can be deduced that the amount of carbon present in the dark etching region was nearly the same as in the parent microstructure. With contact cycling, carbon starts diffusing out of the martensite matrix along specific orientations. This leads to the formation of 30° bands that have a carbon concentration of about 0.2 wt%. Further, with continued contact cycling, more carbon diffuses out of the martensite matrix, leading to the formation of thicker 80° bands, which have almost 0 wt% carbon content.

DARK ETCHING REGION

As discussed in the Introduction, the dark etching region was first reported in 1947 by Jones *(4)*, who called this region troostite or tempered martensite. Dark etching region is typically observed after a few million cycles depending on the operating Hertzian pressure. The average depth of the dark etching region is also dependent on the contact load of the bearing operation. However, optical microscopy suggests that the depth of the dark etching region closely corresponds to the depth of the maximum unidirectional shear stress. Electron diffraction patterns show that the original plates of martensite are deformed and that each plate then contains significant misorientations almost in the form of a cell structure (Mitamura, et al. *(29)*; Sugino, et al. *(31)*). This is consistent with the observed change in electron diffraction pattern. Sugino, et al. *(31)* reported that the large cementite particles present due to incomplete austenitization are not significantly affected at this stage in damage evolution, but the fine carbide particles introduced during low-temperature tempering apparently dissolve in the process of cyclic deformation. However, the carbon must precipitate elsewhere because the region was observed to be softer than the virgin material. Aoki, et al. *(32)* used TEM to suggest that there is reprecipitation of ε-carbide in the bearing microstructure. The tendency to etch dark is a consequence of the deep grooves produced from carbide discs sandwiched between the ferrite-like phase as proposed by Osterlund and Vingsbo *(25)*, together with the heterogeneous deformation of the initial structure.

Bush, et al. *(5)* suggested that the dark etching region is an overtempered form of martensite with hardness of about 53 HRC (compared to 61 HRC for a virgin microstructure). There may or may not be adiabatic heating associated with localized plastic deformation. The mechanism of tempering is not clear in the literature on bearing steels, given that the damage arises during rolling contact (Bhadeshia *(33)*). Nakashima, et al. *(34)* proposed that dynamic creep induced by fatigue loading, accompanied by carbon migration and microscopic stress relief, results in alteration of the bearing steel microstructure during contact cycling. However, in general it is possible to rearrange

TABLE 2—METALLURGICAL PROPERTIES OF THE ALTERED MICROSTRUCTURE AFTER CONTACT CYCLING FOR AISI 52100 STEEL (BESWICK *(14)*; MUROGA AND SAKA *(30)*)

Region	Metallurgical Composition	% C	% Fe	% Cr	% Mn
Dark etching region	Ferrite + Retained martensite	Nearly the same as the base microstructure	96.5–97.0	1.9–2.1	0.4–0.5
30° Bands	Ferrite with some carbide	~0.2	96.3–96.5	1.9–2.3	0.6–0.8
80° Bands	Purely ferrite	~0.0	96.3–96.5	1.9–2.3	0.6–0.8

dislocations into cell structures (or subgrains) under the influence of cyclic deformation. Cyclic softening in quenched and tempered martensite steels occurs when these arrangements of dislocation substructures lead to a reduction in overall dislocation density (Ritchie *(35)*). There is in effect a mechanical removal of excess dislocations. Thielen, et al. *(36)* suggested a kind of softening similar to the well-known Bauschinger effect wherein the dislocations may become unpinned from the localized "atmosphere" of carbon concentration. The dark etching region is not observed if the steel is first tempered to a hardness of 57 HRC (Bhadeshia *(33)*); this observation led to the conclusion that the dark etching region is effectively an overtempered region of martensite. The white bands appear later during rolling contact cycling, the mechanism for which is presented in the following sections.

30° AND 80° WHITE ETCHING BANDS

Jones *(4)* was the first to report the existence of grey lines or white etching bands in the structurally altered region below the bearing raceway. These bands develop within the dark etching region after prolonged contact cycling. The two most striking features of these bands are (1) they display no internal contrast using optical microscopy and hence appear white or grey in color and (2) their peculiar orientation. The lack of contrast under optical microscopy is due to the fact that the scale of the structure is very fine and hence the resolution of the optical microscope is not enough to differentiate the region, making them appear as solid bands (Bhadeshia *(33)*). However, recent high-magnification SEM/TEM analyses have revealed that the white bands consist of nanosized ferrite grains (on the order of 20 nm; Bhadeshia *(33)*). As Lund *(13)* pointed out, the white etching bands can be categorized into 30 and 80° bands. The 30° white etching bands appear earlier in the altered microstructure than the 80° bands. In addition, the 30° bands are thinner and deeper compared to the 80° bands. The average thickness of the 30° bands is about 3 μm and their depth is about 100 to 200 μm. The length of the 30° bands is usually greater than 50 μm, which is quite large compared to the prion austenite grain size. Similarly, the 80° bands are about 10 μm in width and can span up to 100 μm. Thus, it can be concluded that the formation of 30 and 80° bands is independent of the existence of the preexisting crystallographic orientation. This observation is further bolstered by the fact that if the direction of the rolling contact is reversed, the bands are found to form in the opposite direction, as reported by Forster, et al *(23)*. Thus, the anisotropic response of the material is not a contributing factor in the development of the white etching bands. In addition, Voskamp and Mittemeijer *(37)* concluded that the development of the white etching bands does not necessarily strengthen the crystallographic texture that develops under rolling contact cycling. Harada, et al. *(38)* found that acicular structures formed in the initial stages of white etching band formation. This acicular structure has a dislocation cell structure and a fine granular structure, which is formed due to shear deformation of martensite. They further concluded that the formation of a white etching region is due to the plastic deformation of the material. Electron diffraction patterns have revealed rings corresponding to a variety of orientation of the fine grains within the white etching region. This structure can also have layers embedded inside it or can have amorphous regions due to severe deformation. Harada, et al. *(38)* also reported the presence of cracks at the interface between the amorphous-like structure and fine granular area in the white etching region. They suggested that crack formation is related to the amorphous phase transformation.

Mechanism of Band Formation

The exact mechanism for the formation of the white etching band has been a topic of much debate over the last 50 to 60 years. Bush, et al. *(5)* suggested an intrusion–extrusion mechanism for the formation of the white etching bands. They postulated that material is being transported from certain regions of the carbide particle into the adjacent matrix, thus creating an intrusion in the carbide and an associated carbide extrusion in the matrix, leading to the formation of the white etching bands. Martin, et al. *(7)* reported that white etching regions are populated in the areas corresponding to maximum shear stress and their formation is a direct consequence of the plastic deformation of the material brought about by the cyclic, reversed plastic strain in selected volume elements. Buchwald and Heckel *(11)* argued that the altered microstructure is a result of recrystallization, which involves diffusion, and hence it is possible that carbon would diffuse out of the martensite matrix into the adjacent dark etching regions to become trapped at dislocations or to precipitate as layers of cementite/lenticular carbides. They concluded that spherical carbides dissolve in the white etching areas as a result of the dilatational compressive strains in these areas, due to localized plastic deformation and the association of carbon with the increased dislocation density. The lenticular carbides grow bordering the white etching regions as a result of carbon migration out of the white etching region. Lund *(13)* also indicated that diffusion is the primary source of structural alterations. Becker *(39)* suggested an alternative mechanism wherein dislocations break away from their carbon atmosphere from the locally plasticized white region, leaving behind a supersaturation of carbon in the ferrite, which later partitions into surrounding regions to precipitate as lenticular carbides (cementite). Recent investigations by Ochi et al. *(40)* and Kino and Otani *(41)* using electron probe microanalysis and atomic emission spectroscopy, respectively, confirmed the redistribution of carbon from the white bands to the adjacent regions, where it precipitates in the form of lenticular carbides. Furthermore, microhardness tests have proved that the white etching regions are softer than the regions unaffected by contact cycling.

Orientation of the White Etching Bands

From the above reports, it can be inferred that carbon diffusion or carbon redistribution plays a key role in the development of white etching bands during rolling contact fatigue. However, the stress or a definitive mechanism that causes this diffusion along the 30 or 80° orientation still remains unknown. In 1970, Lyman *(42)* was among the first to present a theory for the orientation of white etching bands. This theory proposed that the orientation of the white etching bands is determined by a combination of the shear stress acting along the white etching bands and the maximum (extensional) normal strain at 45° to the white etching band. Their analysis considered only the 30° bands and neglected the 80° bands. Zwirlein and Schlicht *(17)* attempted an explanation for both the 30 and 80° white etching bands. According to their analysis, because plastic deformation is the key in explaining the white etching bands, the orientation of the bands is determined by the state of stress at the location of the maximum von Mises stress. They further proposed two different mechanisms for the formation of 30 and 80° bands: the 30° bands grow perpendicular to the direction of the highest (relative tensile) principal stress and the 80° bands develop in the direction of maximum shear stress (at the location of maximum von Mises stress). Zwirlein and Schlicht *(17)* also included residual stresses and surface friction in their calculation for explaining the orientation of the 30 and 80° bands. However, Polonsky and Keer *(22)* pointed out that this theory cannot be generalized because the hypothesis that surface friction affects the orientation of the white etching bands has been a subject of much dispute. Furthermore, the theory developed by Zwirlein and Schlicht *(17)* when applied to bainitic steel bearings (with residual stresses of 200–500 MPa) provides results that are inconsistent with the experimental observations. Johnson *(43)* also postulated that the orientation of the white etching bands is determined by the direction of maximum shear stress at the location of the maximum shear stress. He assumed that when 30° bands are formed the compressive residual stresses are moderate—that is, $P_r/P_h = 0.06$–0.08—but gradually increase to $P_r/P_h = 0.2$–0.25 later in the bearing life, leading to the formation of 80° bands. (Here, P_r is the compressive residual stress and P_h is the applied Hertzian pressure.) However, Voskamp, et al. *(44)* reported that higher amounts of compressive residual stresses can develop in the early life of bearing operation prior to the formation of 30° bands, thus identifying potential deficiencies in the theory provided by Johnson *(43)*. It can be concluded that the initial theories provided by these different researchers worked only for a few specific cases and have various lacunas. Polonsky and Keer *(22)* made a systematic study of these different theories and provided the following paradoxes:

1. The observed angles for the white etching bands are either 30 or 80°. These angles correspond to neither the direction of the maximum unidirectional shear stress (45° to the bearing raceway) nor the direction of the maximum alternating shear stress (0 or 90° to the bearing raceway), which are the general characteristics of Hertzian line contact in the absence of surface friction.
2. The contact stress is symmetric about the centerline of contact without the presence of any surface traction. Hence, if one particular direction is preferred for the formation of the white etching bands there is another direction available for the growth of these bands by symmetry. However, white etching bands lying in the symmetric directions are never observed unless the direction of the rolling contact is reversed.
3. Similarly, the white etching bands are not observed in the conjugate directions. Many investigators have postulated that the growth of the white etching bands is along the direction of the unidirectional shear stress or principal stress or principal plastic strains. However, each of these stress–strain quantities has a conjugate direction associated with them. This conjugate direction is never preferred for the growth of the white etching bands during microstructural alterations.

Polonsky and Keer *(22)* stated that a unified theory for the development of the white etching bands must answer all of the above three paradoxes.

Bhargava, et al. *(19)* developed a 2D elastic–plastic finite element model for rolling contact. They employed this model to tackle the issue of the peculiar orientation of the white etching bands. In their study, they found that the maximum equivalent cyclic plastic strain increment occurs twice during a contact cycle; during the first of these maxima the direction of the principal plastic shear strain makes an angle of 16° with the rolling direction and during the second one it makes an angle of 63°. They reported that these directions are responsible for the 30 and 80° bands, respectively. Furthermore, these plastic strain increment maxima are prominent only at the depth in the range of $0.2b$ to $0.5b$ and for depths below $0.625b$ the 30° bands disappear completely. However, there is evidence proving the presence of 30° bands at depths ranging from $0.2b$ to $1.5b$ (Voskamp, et al. *(44)*). Thus, it is apparent that these theories are inconclusive in explaining the peculiar orientation of the white etching bands. Polonsky and Keer *(22)* also proposed a theory for the directionality of the 30 and 80° bands while addressing all three paradoxes listed above. They considered carbon diffusion as the primary source for the formation of the white etching bands and related the carbon outflow from the bands as directly proportional to the quantity called *residual pressure*. This residual pressure (p^r) is given by Eq. [1]:

$$p^r = \frac{2(1+\nu)}{3(1-\nu)} G \varepsilon^p_{xx}, \quad [1]$$

where ε^p_{xx} is the plastic strain in the x direction with the coordinate system as indicated in Fig. 8 and G is the shear modulus of the material. This plastic strain is perpendicular to the white etching bands, thus assisting carbon outflow. They concluded that if $p^r > 0$, carbon outflow can be noticeably accelerated, whereas $p^r < 0$ hinders the process. Their model, however, was not based on solving the constitutive elastic–plastic relationships in order to determine the plastic strains generated during rolling contact. Instead, they developed an analytical tool to determine the magnitude of the ε^p_{xx} at different locations below the contacting surface. They recognized that there are two critical stress quantities that alternate as the load moves over the surface; that is, τ_{xz} (orthogonal shear stress) and s_{xx} (the x component of the deviatoric stress tensor). By observing how these two stress quantities evolve during a contact cycle they proposed that white etching band orientation is such that an extremum of τ_{xz} occurs just before the band exits from the contact stress field (i.e., if this extremum is the last among the four major extrema of τ_{xz} and s_{xx}). Hence, the criteria for white etching band orientation is that the main maximum of s_{xx} follows the extrema of τ_{xz} and the minimum of s_{xx} (thus being the last of the major stress extrema experienced by the white etching band during the contact stress cycle). If this criterion is met, then ε^p_{xx} will be positive, making $p^r > 0$ (according to Eq. [1]) and thus leading to carbon outflow from the white etching band. Although this theory addresses the three paradoxes listed above, it is very convoluted and challenging to comprehend. Using TEM, Swahn, et al. *(45)* showed that the parent lamellar structure is gradually decomposed inside a developing 80° band, rather than completely destroyed in some process zone

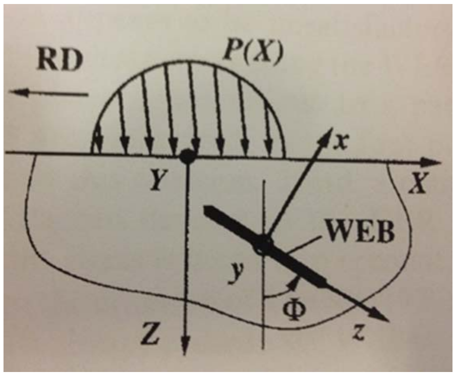

Fig. 8—Coordinate system adopted by Polonsky and Keer *(21)* (color figure available online).

at its ends. Hence, significant plastic shear concentrated in an 80° band generally involves plastic deformation of the lenticular carbides. Using this information, Polonsky and Keer *(22)* concluded that the 80° band formation is likely to be controlled by cyclic plasticity-induced dissolution of the lenticular carbides. Accordingly, the 80° white etching band can be expected to assume an orientation that maximizes the plastic deformation experienced by the lenticular carbides when plastic shear occurs in the white etching bands. In other words, along such a direction, the rate of lenticular carbide decay is maximized, leading to the development of the 80° bands. Polonsky and Keer *(22)* further concluded that the direction along which the lenticular carbides can decay the fastest is 45° to the direction of the 30° bands, which corresponds approximately to the 80° bands. This explanation satisfies paradoxes 1 and 2 listed above but fails to explain paradox 3. This is because the conjugate 45° orientation to the 30° bands also satisfies the condition for faster lenticular carbide decay; however, no 80° band is found to develop along this conjugate orientation.

Thus, it can be perceived that the tribology community still lacks a comprehensive theory or model that can accurately predict the occurrence of the white etching bands along with their orientation. It is important, especially to bearing manufacturers, to understand and model the development of these structures in bearing steel microstructure in order to continue optimizing bearing materials and designs in the future. This article presents the historical background on the topic of microstructural alterations. In the next article, an elastic–plastic finite element model is coupled with a diffusion-based model to predict the redistribution of carbon in the bearing steel microstructure, thus predicting the occurrence and orientation of white etching bands with good experimental corroboration.

CONCLUSIONS

The first work on microstructural alterations was performed by the seminal work of Jones *(4)* in 1947 when he first observed the occurrence of troostite type structure underneath the bearing raceway along with the grey lines interlaced within this structure. With time, the troostite-type structure came to be known as the dark etching region and the grey lines as the white etching bands. These bands were later categorized into 30 and 80° bands due to their characteristic orientation. Over the last half a century, significant work has been performed to better understand these phenomena and the mechanism of their formation. Though the topic has been subjected to much debate, there are certain commonalities that have now been accepted with good agreement. The structural alterations are caused due to the decay of the parent martensite structure due to contact cycling. These changes are not observed below a threshold contact load, indicating that plastic deformation at high loads is the root cause of these alterations. The dark etching region appears first in the altered microstructure and consists of a ferritic phase containing homogenously distributed excess carbon mixed with residual martensite. When etched with nital and observed under an optical microscope, this region appears dark and hence is called the dark etching region. With further contact cycling, another phase appears within the dark etching region. This phase is ferrite, which etches white and is inclined at 30° to the raceway sandwiched between carbon-rich discs known as lenticular carbides. During contact fatigue cycling, carbon diffuses out of the white etching region and precipitates at its edges, forming the white etching bands and the carbides discs. With further cycling, another structure appears in the altered region. This phase is similar to the 30° bands; however, it is thicker, longer, shallower, and inclined at an angle of 80° to the raceway. The white bands have lower hardness compared to the unaltered microstructure. The carbon content in 30° bands is about 0.2% compared to almost 0% in the 80° bands. Carbon diffusion is the most accepted mechanism for the development of the white etching bands. However, many researchers have presented alternative theories. Still, none of the theories can fully explain the formation of white etching bands and their characteristics orientation. In Part II of this article, we continue the discussion on the mechanism for the white etching band and develop an elastic–plastic finite element model coupled with a diffusion-based model to predict the formation of the white etching bands along with their distinctive orientation.

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