FRACTURE MECHANICS AND MODELING OF CONTACT FATIGUE

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Contents

Summary

Moving surfaces in various machines exposed to external loading are subjected to cyclic normal and frictional stresses which cause fatigue damage and limit their useful life. In addition to that, due to various technological operations including tempering and finishing operations (such as grinding, honing, polishing etc.) machine parts acquire some residual stresses. In properly treated and finished machine parts these residual stresses are usually relatively high compressive near surfaces and low tensile at subsurface part locations. In most cases these joints are lubricated one way or another. Therefore, it is important to understand the possible interaction of lubricant with solid containing cracks. There are a number of damage mechanisms caused by cyclic stresses such as pitting, wear, abrasive wear, delamination, scuffing, etc. Usually all these mechanisms of damage take place simultaneously and compete with each other. Due to the fact that each of these mechanisms has its own scale and origination depth in material different contact parameters affect these damage mechanisms differently. For example, surface roughness and other near surface material parameters have the most effect on delamination and wear and the scale of the damage is relatively small. On the other hand, pitting is usually a subsurface originated phenomenon unless there are significant surface defects which may change its origin. This essay treats some aspects of fracture mechanics based modeling of contact fatigue, i.e. pitting. First, a theoretical analysis of subsurface and surface cracks behavior is proposed. Under certain conditions

it is possible to apply perturbation methods and obtain relatively simple analytical expressions for the stress intensity factors at the crack tips. That provides the basis for fatigue modeling. The essay establishes the essential modules/elements of such modeling and provides the analysis of the resulting relationships of fatigue life versus applied normal and frictional contact stresses as well as residual stress. The analysis of fatigue life on the initial material defectiveness is also provided.

1. Introduction

Cyclic loading is a typical regime of operations various machine elements are subjected to. There are a number of processes associated with cyclic loading which limit the useful life of machine parts. Among them there are a number of surface related damage mechanisms such as pitting, fatigue and abrasive wear, corrosion, pealing, scuffing, etc. Each of these damage mechanisms has its own scale and depth of penetration. The damage mechanism with the largest scale is pitting which is caused by material accumulated fatigue. The scale of wear, corrosion, pealing etc. is usually significantly smaller. This essay is concerned with analyzing and modeling of pitting mechanism of fatigue failure.

Historically, the first approach to fatigue is based on SN curves which represent the inverse relationship between fatigue life N (measured in number of loading cycles) and some positive power of the applied stress S. Due to the complexity of fatigue phenomena fatigue modeling of construction (structural) fatigue and contact fatigue were considered as separate phenomena and developed differently. Even in contact fatigue, modeling of pitting in bearings and gears is historically done differently. It was understood that pitting is a very complex phenomenon and it is affected by various operational and material parameters. Among these parameters are the applied load and lubrication, material elastic and fatigue properties, initial material defectiveness and surface properties, material crystalline structure and residual stresses. It is very hard to keep track of all these parameters experimentally and, at the same time, it is possible model the effect of many of these parameters analytically. Therefore, it is important to determine which parameters are affecting pitting/contact fatigue the most. To do that a review of some existing experimentally and numerically obtained data will be conducted which will reveal these most important for contact fatigue parameters. That will allow to review some of the well known models of contact fatigue and their ability to adequately take into account the established most important for contact fatigue parameters. After that a contact fatigue will be developed to include these parameters as its essential part.

Any pitting phenomenon culminates in a surface spall which is cased by fatigue crack propagation. Therefore, the question is how long does it take for the crack(s) leading to a spall to propagate and to be initiated. Assuming that crack propagation stage in contact fatigue is important it is necessary to know whether fatigue cracks coalescence or propagate alone, what is the direction and rate of fatigue crack propagation and which parameters affect them. The answers to these questions lie in the analysis of the available experimental and numerical data. It will be shown that it is reasonable to assume that the crack initiation period is much shorter than the crack propagation stage. Therefore, with low error it can be assumed that the useful fatigue life of a machine element is practically completely controlled by the crack propagation stage. That creates the necessity to characterize stress intensity concentrations in the vicinity of cracks. Also, it will be shown that for the most of their lives fatigue cracks are located far away from each other and practically do not feel the presence of the neighboring cracks. Taking into account the fact that for properly designed and operated machine elements the location of contact fatigue origination is usually relatively far away from the contact surface and from other cracks allows for simple analytical solution of complex equations controlling stress intensity factors at the tips of fatigue cracks. That by itself opens a great opportunity to easily model the fatigue behavior of machine elements subjected to cyclic loading which is done in two- and three-dimensional cases.

In addition to that the interaction of lubricant usually present at the joint surfaces with surface cracks is considered. The comparison of the stress intensity factors for surface and subsurface cracks allows to understand the difference between fatigue lives of drivers and follows as well as the location of contact fatigue origination: surface or subsurface.

2. Review of Experimental and Numerical Contact Fatigue Data, Identification of the Parameters Most Strongly Affecting Fatigue. Review of Some Existing Contact Fatigue Models

To make an objective conclusion on which parameters are affecting contact fatigue the most there is a need to analyze the response of contact fatigue to variations in external and residual stresses, the effect of material cleanliness, lubricant nature and its contamination, surface topography, material structure, elastic and fatigue properties, and the relationship between the durations of the crack initiation and propagation stages.

2.1. Crack Initiation versus Crack Propagation

In most cases researchers categorize crack initiation period as the period during which fatigue cracks are smaller than a certain small size. Often fatigue cracks are initiated somewhere beneath the surface and cannot be observed until they grow to the surface. The latter and the fact that the value of this small crack size is very subjective make the definition of the crack initiation period itself also subjective which creates some ambiguity. Nonetheless, in some experimental studies researchers were able to register and somehow distinguish between the periods when fatigue cracks are small and the rest of crack lives until a pit is formed. In the experimental study of Clarke et al. (Clarke et al., 1985) it has been observed that microcracks which eventually produce micropits are present as early as 5% of the sample fatigue life. In studies of ceramics Kapelski et al. (Kapelski et al., 1988) observed that microcraking occurs in the very beginning of cyclic loading. Nisitani and Goto (Nisitani and Goto, 1984), Tanaka et al. (Tanaka et al., 1984), and Wu and Yang (Wu and Yang, 1987) experimentally determined that the crack initiation period is much shorter than the crack propagation period. That can be clearly seen in Figures 1 and 2. The data in Figures 1 and 2 show that the crack propagation period represents at least 80%-90% of contact fatigue life. Shao et al. (Shao et al., 1988) reported that the subsurface crack growth period lasted 89% of the contact life.

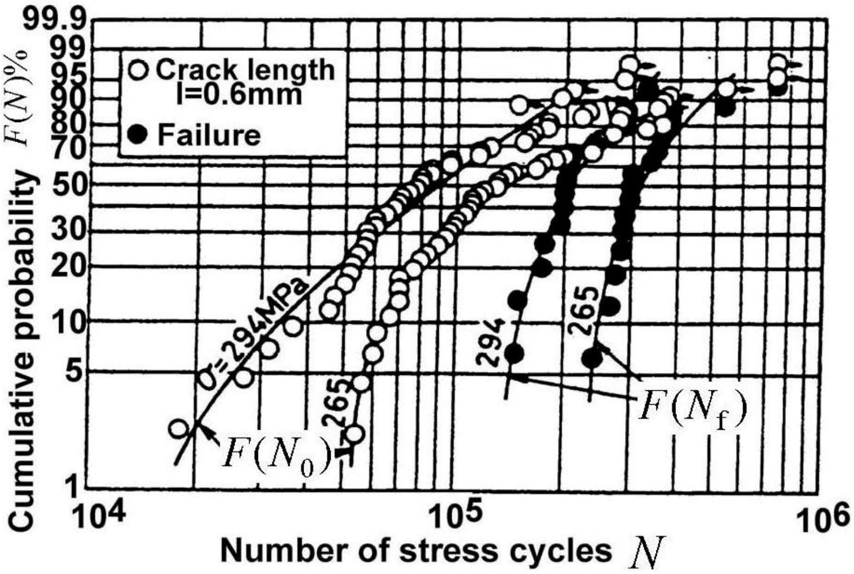

Figure 1. Distributions of lives for crack initiation and for final failure (after Tanaka et al. (Tanaka et al., 1984)). Reprinted with permission from the JSME.

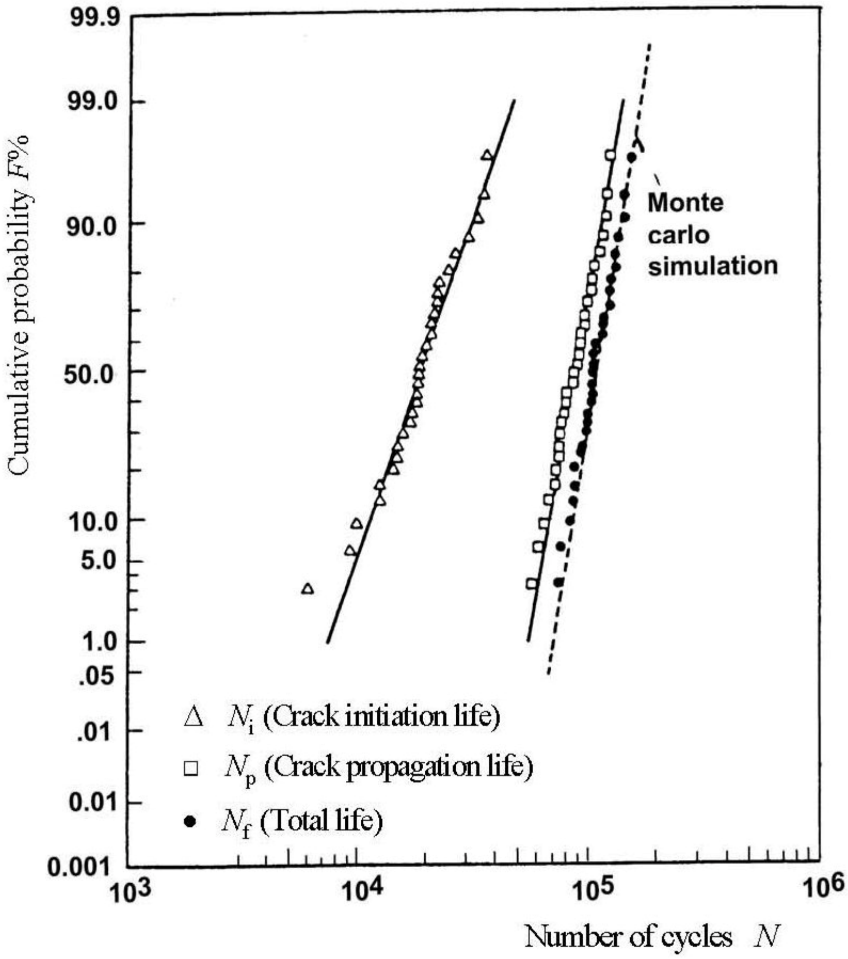

Figure 2. Cumulative probability of failure versus number of load cycles (after Ishikawa (Ishikawa, 1984)). Reprinted with permission of JSME.

2.2. Material Microstructure versus Contact Fatigue

A number of researchers Drul' et al. (Drul' et al., 1987), Rodriguez and Sevillano (Rodriguez and Sevillano, 1984), Schaper and Bosel (Schaper and Bosel, 1985) indicated that the austenite grain size either does not affect fatigue life or the increase of austenite grain size leads to slow increase in fatigue life. There was not observed any appreciable change in crack propagation direction due to austenite grain boundaries (Kunio et al., 1982). There is practically no knowledge on how doping elements affect contact fatigue.

2.3. Normal, Frictional, and Residual Stresses versus Contact Fatigue

It is well known that as the normal load/stress increases contact fatigue life decreases. It is not that well known that the other two stresses, i.e. the frictional stress applied to the contact and the residual stress occurring below surface also have a significant impact on fatigue life. The appreciable influence of traction on contact fatigue has been demonstrated in (Soda and Yamamoto, 1981). Another clear indication of the strong relationship between the frictional stress and contact fatigue was demonstrated in experiments of Pinegin et al. (Pinegin et al., 1972) and Orlov et al. (Orlov et al., 1980). Most researchers (Mattson, 1961; Serensen, 1952; Scott et al., 1962; Almen and Black, 1963; Averbach et al., 1985; Voskamp, 1985; Sveshnikov, 1964) agree that tensile residual stresses and conducive to developing contact fatigue while compressive residual stresses retard fatigue failure. However, the increase of the compressive residual stress beyond a certain level does not produce any additional positive effect on contact fatigue life (Kepple and Mattson, 1970). The experimentally obtained data by Averbach et al. (Averbach et al., 1985) indicate that the rate of fatigue crack growth and, therefore, fatigue life are related not to material hardness but to the residual stress distribution versus depth below the surface.

2.4. Material Defects versus Contact Fatigue

Most researchers observed experimentally fatigue crack initiation in the vicinity of a material defect such as a nonmetallic inclusion (Murakami et al., 1989; Nishioka, 1951; Yokobori, 1961; Watanabe, 1962). Moreover, it has been concluded that nonmetallic inclusions have a strong influence of contact fatigue life (Murakami et al., 1989). That was clearly explained by the study of Brooksbank and Andrews (Brooksbank and Andrews, 1972) (see Figure 3) based on the difference between the values of the temperature expansion coefficient of an inclusion and the steel matrix. A number of experimental sources indicate that oxides and alumina inclusions are the most detrimental for contact fatigue while sulfides are harmless (Kinoshi and Koyanagi, 1975). It was determined directly from bearing testing and usage of nondestructive ultrasonic method of measuring of steel cleanliness (Stover and Kolarik, 1987) that there is an inverse power relationship between bearing contact fatigue life and the measured oxide stringer length where stringers are represented by clusters of individual oxide particles (see Figure 4). It can be shown that the replacement of these stringers by single cracks of the same size introduces just a small error in the stress field caused by the stringers.

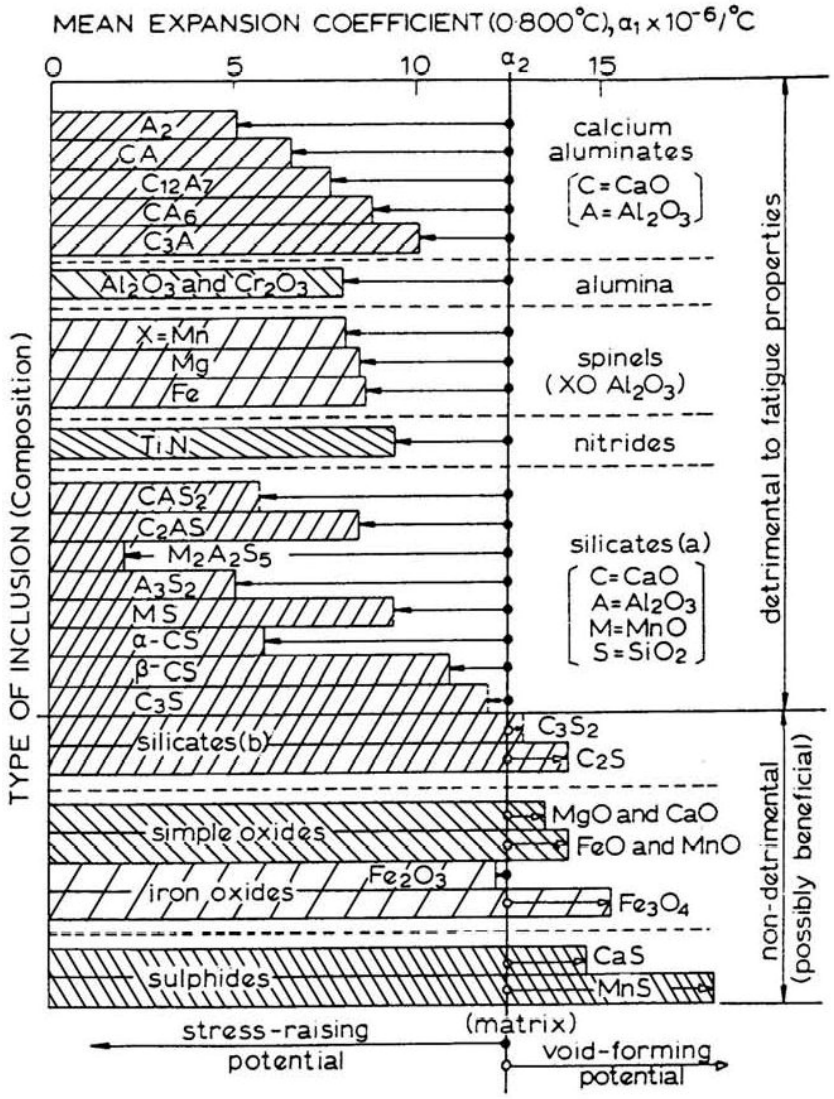

Figure 3. Stress-raising properties of inclusions in 1% C-Cr bearing steel (after Brooksbank and Andrews, 1972). Reprinted with permission from the Elsevier Science Publishing.

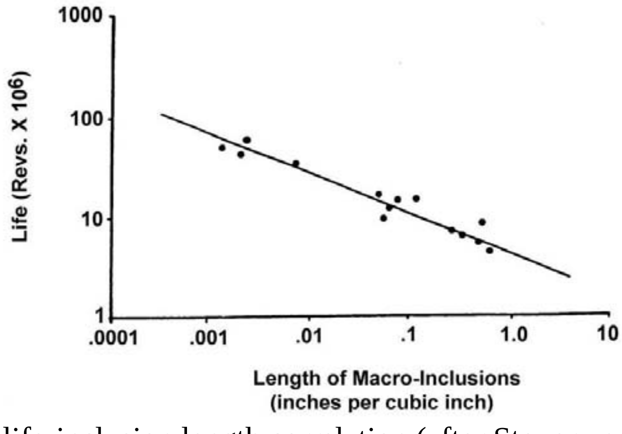

Figure 4. Bearing life-inclusion length correlation (after Stover and Kolarik II (Stover and Kolarik, 1987), Copyright The Timken Company 2009).

Bokman et al. (Bokman et al., 1986) and Bokman and Pershtein (Bokman and Pershtein, 1984) experimentally studying aluminum alloys concluded that the nonmetallic inclusion and crack size distributions are close to a lognormal probabilistic distribution.

Experimental studies of fatigue crack propagation showed that at its initiation at an inclusion surface or in its closest proximity crack propagation may initially be driven by shear stresses. However, soon after initiation these cracks turn and propagate perpendicular to the maximum of the local tensile stress (Wu and Yang, 1987; Kapelski et al., 1988; Kitagawa et al., 1981). A typical fatigue crack orientation near nonmetallic inclusions is shown in electron micrographs in Figure 5. It is clear from Figure 5 that all cracks initiated in the vicinity of an inclusion eventually become practically perpendicular to tensile stresses the direction of which indicated in the photographs by arrows.

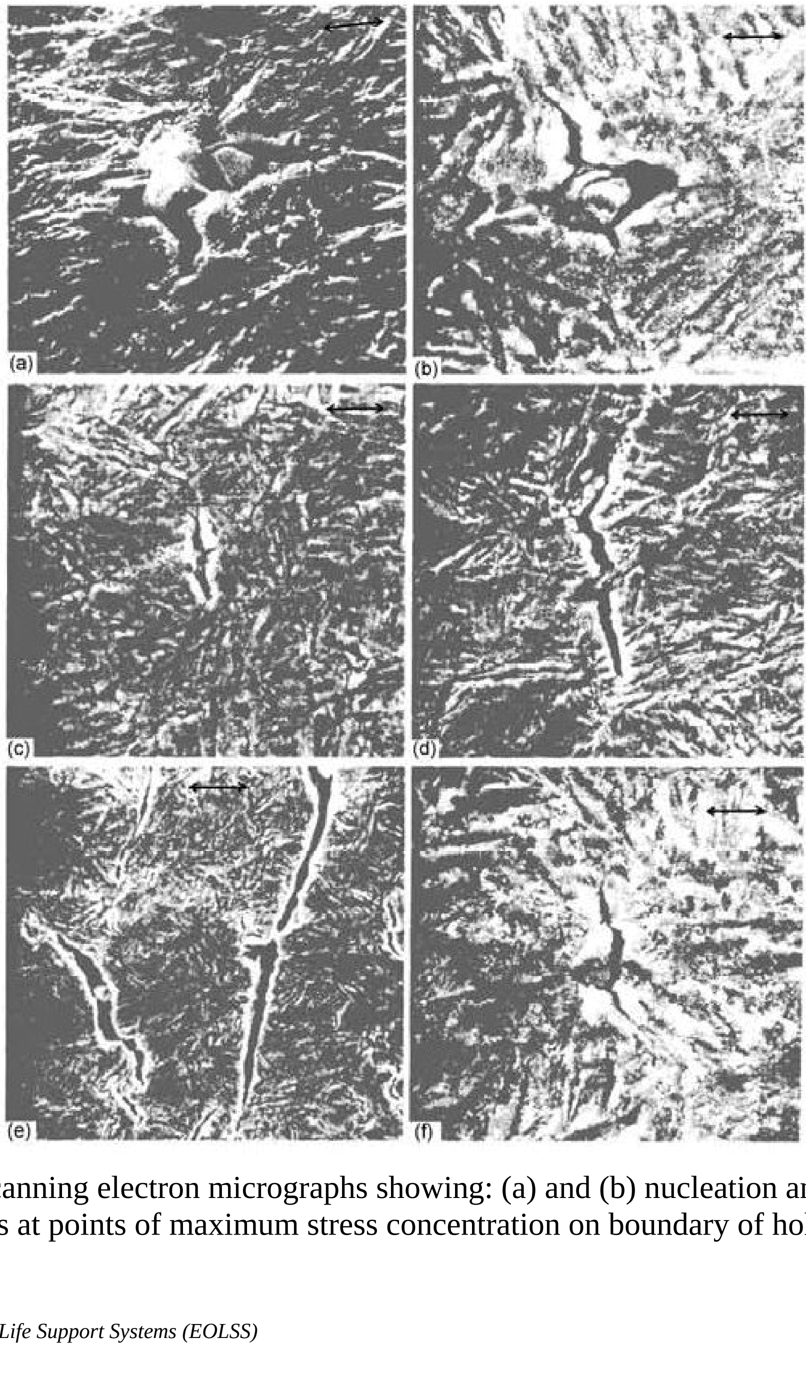

Figure 5. Scanning electron micrographs showing: (a) and (b) nucleation and growth of microcracks at points of maximum stress concentration on boundary of hole formed at

damaged alumina inclusions, 4×10^6 cycles ($\times3000$) and 4.3×10^6 cycles ($\times3200$), respectively; (c) fatigue crack nucleation away from inclusion sites at 4.5×10^6 cycles ($\times1600$); (d) and (e) propagation of microcracks from alumina nucleated holes and subsequent linking to form macrocracks, 4.7×10^6 cycles ($\times1650$) and 5×10^6 cycles ($\times790$), respectively; (f) surface of specimen, having failed at 5.5×10^6 cycles, with no evidence of crack nucleation due to the highly elongated manganese sulfide inclusions ($\times3300$). Arrows indicate direction of cyclic bending stress (after Eid and Thomason (Eid and Thomason, 1979)). Reprinted with permission from the Elsevier Science Publishing.

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Bibliography

Clarke, T.M., Miller, G.R., Keer, L.M., and Cheng, H.S. (1985). The Role of Near-Surface Inclusions in the Pitting of Gears. *ASLE Trans.* 28, No. 1: 111-116. [Experimental test results and microphotographs of fatigue failure are presented. A model of fatigue phenomenon consistent with test observations is proposed. Some recommendations on material selection are given.]

Kapelski, G., Platon, F., and Boch, P. (1988). Unlubricated Wear and Friction Behavior of Alumina and Silicon Carbide Ceramics. Proc. 15th Leeds-Lyon Symp. on Tribology, University of Leeds, UK, Tribological Design of Machine Elements, Eds. D. Dowson, C.M. Taylor, M. Godet, and D.Berthe.: 349-354. [The experimental study of different ceramics is focused on the initial stage of fatigue cracking.]

Nisitani, H. and Goto, M. (1984). Effect of Stress Ratio on the Propagation of Small Crack of Plain Specimens Under High and Low Stress Amplitudes. *Trans. Jpn. Soc. Mech. Eng.* Ser. A, 50, No. 453: 1090-1096. [Fatigue tests under axial load are conducted on specimens with a preexisting crack. Different stress ratios are considered.]

Tanaka, T., Sakai, T., and Okada, K. (1984). A Statistical Study of Fatigue Life Distribution Based on the Coalescence of Cracks from Surface Defects. *Trans. Jpn. Soc. Mech. Eng*. Ser. A, 50, No. 454: 1166-1173. [An experimental statistical study of crack propagation and coalescence is conducted.]

Wu, Han C. and Yang, C.C. (1987). On the Influence of Strain-Path in Multiaxial Fatigue Failure. *ASME J. Eng. Materials and Techn*. 109, No. 2: 107-113. [The fatigue experiments are conducted under axial-tortional conditions. For all specimens tested cracks initiation is driven by tensile stresses. Direction of cracks initiation is observed.]

Shao, E., Huang, X., Wang, C., Zhu, Y., and Chen, Q. (1988). A Method of Detecting Rolling Contact Crack Initiation and the Establishment of Crack Propagation Curves. *ASLE Tribology Trans*. 31, No. 1: 6-11. [The paper describes a new method for observing fatigue cracks at their initiation as well as stable and rapid growth under rolling contact conditions.]

Ichikawa, M. (1984). Some Problems in Probabilistic Fracture Mechanics. *Trans. Jpn. Soc. Mech. Eng*. Ser. A, 50, No. 456: 1435-1442. [A statistical study of fatigue crack initial size and consequent growth is considered. The model is validated by a comparison with experimental data.]

Drul', O.R., Levitsky, M.O., and Brodyak, D.I. (1987). The Influence of the Austenite Grain Size on the Cyclic Crack Resistance of the 40X Steel. *Physical-Chemical Mech. Materials*. Moscow: 116-118. [The effect of residual austenite on fatigue crack growth is considered.]

Ibale Rodriguez, J.M. and Sevillano Gil, J. (1984). Fatigue Crack Path in Medium-High Carbon Ferrite-Perlite Structures. Proc. 6th Intern. Conf. Fract. (ICF6), New Delphi, 4-10 Dec, 1984, Vol. 3, Oxford: 2073-2079. [The stage II fatigue crack propagation trajectories are investigated experimentally in ferrite-pearlite carbon steel.]

Schaper, M. and Bosel, D. (1985). Rasterelektronenmikro-skopische in-situ-Untersuchungen der Ermudungsribausbreitung in Metallishen Werkstoffen. *Prakt. Metallogr*. 22, No. 4:197-203. [The authors study the influence of the size of austenite grains on contact fatigue.]

Kunio, T., Shimizu, S., Yamada, K., Sakura, K., and Yamamoto, T. (1981). The Early Stage of Fatigue Crack Growth in Martensitic Steel. *Intern. J. Fract*. 17, No. 2:111-119. [The study concentrates on the differences in the fatigue crack initiation and early growth in martensitic steels and ordinary ductile materials.]

Soda, N. and Yamamoto, T. (1982). Effect of Tangential Traction and Roughness on Crack Initiation/Propagation During Rolling Contact. *ASLE Trans*. 25, No. 2:198-206. [The paper considers experimentally the influence of friction on contact fatigue. Also, it demonstrates that fatigue life of drivers is significantly higher than the one of followers.]

Pinegin, S.V., Shevelev, I.A., Gudchenko, V.M., Sedov, V.I., and Blokhin, Y.N. (1972). In T*he Influence of External Factors on Rolling Contact Strength*. Moscow: Nauka. [Using arc bearings with different angles the paper provides an interesting study of the effect of frictional stresses on contact fatigue. The study shows that contact fatigue life is a decreasing function of the level of frictional stresses.]

Orlov, A.V., Chermensky, O.N., and Nesterov, V.M. (1980). *Testing of Design Materials for Contact Fatigue*. Moscow: Mashinostroenie. [The study is devoted to study of the effect of traction on contact fatigue.]

Mattson, R.L. (1961). Fatigue, Residual Stresses, and Surface-Layer Strengthening by Work Hardening. In *Fatigue of Metals*. Moscow: Inostrannaya Literatura. [The article provides experimental results indicating that compressive residual stresses prolong contact fatigue life.]

Serensen, S.V. (1952). Fatigue Resistance in Connection with Strain-Hardening and Design Factors. In *Increasing the Fatigue Strength of Machine Parts by Surface Treatment* Moscow: GNTI (State Scientific and Technical Publishing). [The experimental data presented in the paper show that compressive residual stresses are conducive for longer contact fatigue.]

Scott, R.L., Kepple, R.K., and Miller, M.H. (1962). The Effect of Processing-Induced Near-surface Residual Stress on Ball Bearing Fatigue. In Rolling Contact Phenomena Proc. Symp. held at the GM Research Laboratories, Warren, MI, October 1960, Amsterdam: Elsevier Publishing. [The study examines the effect of different machining operations on created residual stresses and the effect of these residual stresses on contact fatigue.]

Almen, I. and Black, P. (1963). *Residual Stress and Fatigue of Metals*. New York: McGraw-Hill. [The authors provide an experimental justification for the observed effect of fatigue retardation due to the presence of compressive residual stresses.]

Averbach, B.L., Bingzhe L., Pearson, P.K., Fairchild, R.E., and Bamberger, E.N. (1985). Fatigue Crack Propagation in Carburized High Alloy Bearing Steels. *Metallurg. Trans*. Ser. A, 16A: 1253-1265. [The paper studies experimentally the influence of material hardness and residual stresses on the rate of fatigue crack propagation. It is observed that material hardness practically does not affect crack rate propagation while the residual stress distribution is directly related to the rate of fatigue crack propagation.]

Voskamp, A.P. (1985). Material Response to Rolling Contact Loading. *ASME J. Tribology* 107: 359-366. [The experimental study is devoted to the analysis of the evolution of residual stresses due to cyclic contact loading.]

Sveshnikov, D.A. (1964). The Increase of Fatigue Strength of the Carburized and Cyanide Parts by Shot Peening. Phys. *Metallurgy and Thermal Treatment* 4: 47-49. [The paper provides an experimental evidence that an increase in compressive residual stresses leads to an increase in contact fatigue.]

Kepple, R.K. and Mattson, R.L. (1970). Rolling Element Fatigue and Macroresidual Stress. *ASME J. Lubr. Techn.* 92, No. 1: 76-82. [The authors show experimentally that large tensile residual stresses decrease fatigue life of specimens.]

Murakami, Y., Kodama, S., and Konuma, S. (1989). Quantitative Evaluation of Effects of Non-Metallic Inclusions on Fatigue Strength of High Strength Steels. I: Basic Fatigue Mechanism and Evaluation of Correlation Between the Fatigue Fracture Stress and the Size and Location of Non-Metallic Inclusions. *Intern. J. Fatigue* 11, No. 5: 291-298. [The paper studies how the size and location of non-metallic inclusions affect contact fatigue and provides some quantitative estimates for the stress intensity factors in the vicinity of cracks/inclusions.]

Nishioka, K. (1957). On the Effect of Inclusion upon the Fatigue Strength. Material Testing (Soc. Mater. Sci. Jpn.) 6, No. 45: 382-385. [The author considers experimentally the correlation between non-metallic inclusions and material fatigue.]

Yokobori, T. (1961). Fatigue of Metals and Fracture Mechanics. *J. Sci. in Machines* 13, No. 7: 973-976. [The author investigates how fracture mechanics material properties are related to material fatigue.]

Watanabe, J. (1962). How Does the Cleanliness Influence the Mechanical Properties of Metals. *Bull. Jpn. Inst. Metals* 1, No. 2: 129-133. [The paper studies the relationship between material cleanliness and its fatigue properties.]

Brooksbank, D. and Andrews, K.W. (1972). Stress Fields around Inclusions and Their Relation to Mechanical Properties. *J. Iron and Steel Inst.* 210, Part 4: 246-255. [The paper provides a clear and transparent explanation of the severity of various nonmetallic inclusions in steels based on the values of their temperature expansion coefficients.]

Kinoshi, M. and Koyanagi, A. (1975). Effect of Nonmetallic Inclusions on Rolling-Contact Fatigue Life in Bearing Steels. Bearing Steels: The Rating of Nonmetallic Inclusion, ASTM STP 575, ASTM: 138-149. [The study considers the influence of alumina and sulfur inclusions on contact fatigue. It is determined that alumina inclusions in steels decrease fatigue life while sulfur inclusion may increase it.]

Stover, J.D. and Kolarik II, R.V. (1987). The Evaluation of Improvements in Bearing Steel Quality Using an Ultrasonic Macro-Inclusion Detection Method. The Timken Company Technical Note January 1987: 1-12. [The study employs the ultrasound technique to measure the size and the location of the original material defects and tracts the dependence of contact fatigue of bearings on the size of these inclusions.]

Bokman, M.A. and Pershtein, E.M. (1986). The Study of Microcrack Growth under the Plastic Strain Conditions. *Plant Laboratory*, Moscow, No. 2: 68-70. [The authors study experimentally the distribution of non-metallic inclusions and cracks in the process of their fatigue growth.]

Bokman, M.A., Pshenichnov, Yu.P., and Pershtein, E.M. (1984). The Microcrack and Non-Metallic Inclusion Distribution in the Alloy D16 after a Plastic Strain. *Plant Laboratory*, Moscow, No. 11: 71-74. [The paper offers an analysis of the distribution of non-metallic inclusions and cracks versus their size.]

Kitagawa Hideo, Yuuki Ryoji, and Tohgo Keiichiro. (1981). Fatigue Crack Growth Behavior From a K1 and K2 Mixed Mode Crack. *Trans. Jpn. Soc. Mech. Eng.* Ser. A, 47, No. 424: 1283-1292. [The authors experimentally observe and consider the mechanisms of fatigue crack nucleation near inclusions in high-strength steels. The observations show that predominantly fatigue cracks nucleate at inclusions debonded from the material matrix or at fractured alumina inclusions.]

Eid, N.M.A. and Thomason, P.F. (1979). The Nucleation of Fatigue Cracks in a Low-Alloy Steel Under High-Cycle Fatigue Conditions and Uniaxial Loading. *Acta Metallurgica* 27: 1239-1249. [An experimental study reveals the mechanisms driving fatigue crack initiation in high-strength steel under high-cycle fatigue. Specifically, it is determined that cracks nucleate near inclusions due to inclusion debonding from the steel matrix or due to rupture of an alumina inclusion and creation of a hole. It is found that manganese inclusions have practically no affect on fatigue.]

Keer, L.M., Bryant, M.D., and Haritos, G.K. (1982). Subsurface and Surface Cracking Due to Hertzian Contact. *ASME J. Lubr. Techn.* 104, No. 3: 347-351. [The authors numerically model the behavior of surface and subsurface cracks in an elastic half-plane under moving Hertzian contact.]

Kaneta, M., Yatsuzuka, H., and Murakami, Y. (1985). Mechanism of Crack Growth in Lubricated Rolling/Sliding Contact. *ASLE Trans*. 28, No. 3: 407-414. [A numerical study of a surface crack in a half-space loaded by moving Hertzian and shear stresses is conducted. It is shown that frictional stress is a controlling factor in lubricant seepage into the crack.]

Kaneta, M., Murakami, Y., and Okazaki, T. (1986). Growth Mechanism of Subsurface Crack Due to Hertzian Contact. *ASME J. Lubr. Techn*. 108, No. 1: 134-139. [A numerical study of a circular crack parallel to the half-space boundary loaded by moving Hertzian and frictional stresses is provided.]

Murakami, Y., Kaneta, M., and Yatsuzuka, H. (1985). Analysis of Surface Crack Propagation in Lubricated Rolling Contact. *ASLE Trans.* 28, No. 1: 60-68. [A numerical study of surface cracks in a lubricated loaded half-space is presented. The authors find that the lubrication "wedge effect" can be accepted as one of the mechanisms driving propagation of surface cracks.]

Kudish, I.I. (2002). Lubricant-Crack Interaction, Origin of Pitting, and Fatigue of Drivers and Followers. *STLE Tribology Trans*. 45, No. 4: 583-594. [The detailed formulation of the fracture mechanics problem for a cracked elastic half-plane loaded by normal and frictional stresses transmitted through the lubrication layer as well as by residual stress is given. A number of different examples of numerical solutions of the problem provided. Based on the analysis of the presented data a conclusion on fatigue crack initiation location is made. That, in turn, leads to the explanation of why contact fatigue life of drivers is usually significantly longer than the one of followers.]

Kudish, I.I. (1987). Contact Problem of the Theory of Elasticity for Pre-Stressed Bodies with Cracks. *J. Appl. Mech. Techn. Phys.* 28, No. 2: 295-303. [An asymptotic solution of a crack mechanics problem for a loaded half-plane is provided. The cracks are considered to be small in comparison with the distance between them and the distance from the half-plane surface.]

Kudish, I.I. and Covitch, M.J. (2010). *Modeling and Analytical Methods in Tribology*. Boca Raton, London, New York: CRC Press. [A monograph presents comprehensive approaches to modeling of lubricant degradation, contact fatigue based on fracture mechanics, and various steady and non-steady lightly and heavily loaded elastohydrodynamic problems for contacts lubricated with Newtonian and non-Newtonian fluids and greases under isothermal and thermal conditions. Mixed lubrication problems as well as problems for contacts lubricated by degrading lubricants are considered as well.].

Lundberg, G. and Palmgren, A. (1947). Dynamic Capacity of Rolling Bearings. *Acta Polytechnica* (Mech. Eng. Ser. 1), Royal Swedish Acad. Eng. Sci. 7: 5-32. [This the first attempt to model and predict contact fatigue life of bearings. The model is empirically based and served as the basis for a number of improvements. The basic premise of the model is that fatigue life is practically equivalent to the duration of crack initiation and the appearance of the first crack signifies fatigue failure.]

ISO (1989). Rolling Bearings - Dynamic Load Ratings and Rating Life. Draft International Standard ISO/DIS 281, ISO, Geneva, Switzerland. [The standard provides bearing dynamic load ratings by introducing a number of adjustment coefficients describing steel cleanliness, lubrication quality, etc.]

Tallian, T.E. (1992a). Simplified Contact Fatigue Life Prediction Model - Part I: Review of Published Models. *ASME J. Tribology* 114, No. 1: 207-213. [The paper is concerned with the review of eleven published models for contact fatigue.]

Tallian, T.E. (1992b). Simplified Contact Fatigue Life Prediction Model - Part II: New Model. *ASME J. Tribology* 114, No. 1: 214-222. [The paper presents a new contact fatigue model based on crack propagation versus crack initiation. The model takes into account a number of factors relevant for contact fatigue.]

Ioannides, E. and Harris, T.A. (1985). A New Fatigue Life Model for Rolling Bearings. *ASME J. Tribology* 107: 367-378. [This the first in a whole series of authors' papers devoted to improving of contact fatigue modeling for bearing. The model differs from the Lundberg-Palmgren model only in two essential aspects: introduction of the stress threshold and using the effective stress.]

Coy, J.J., Townsend, D.P., and Zaretsky, E.V. (1976). Dynamic Capacity and Surface Fatigue Life for Spur and Helical Gears. *ASME J. Lubr. Techn*. 98: 267-276. [The authors extended the Lundberg-Palmgren contact fatigue model for bearings on gears. The assumptions of the model, its advantages, and shortcomings are the same as for the Lundberg-Palmgren model.]

Blake, J.W. (1989). A Surface Pitting Life Model for Spur Gears, Ph.D. Dissertation, Northwestern University. [The dissertation introduces a contact fatigue model for predicting fatigue life of gears. The model is based on the study of crack propagation under applied contact loading.]

Ioannides, E., Jacobson, B., and Tripp, J.H. (1989). Prediction of Rolling Bearing Life Under Practical Operating Conditions. In *Tribological Design of Machine Elements*, Eds. D. Dowson, C.M. Taylor, M.

Godet, and D. Berthe, Amsterdam: Elsevier Science Publishers B.V.: 181-187. [The authors extended the Ioannides and Harris model (see Ioannides and Harris, 1985) to studying effects of lubrication, surface roughness, contaminants and internal plastic stresses on contact fatigue life using various fatigue stress criteria. Some comparisons of these data with the ISO predictions and available experimental data are made.]

Dwyer-Joyce, R.S., Hamer, J.C., Sayles, R.S., and Ioannides, E. (1990). Surface Damage Effects Caused by Debris in Rolling Bearing Lubricants, with an Emphasis on Friable Materials. In Rolling Element Bearings-Towards the 21st Century, Seminar organized by the Tribology Group of the Inst. of Mech. Eng., November 16: 1-8. [The paper extends the model originally proposed by Ioannides and Harris on the case when a contact is contaminated with friable debris.]

Savruk M.P. (1981). *Two-Dimensional Problems of Elasticity for Bodies with Cracks*. Kiev: Naukova Dumka. [The book provides a systematic introduction to two-dimensional fracture mechanics. The author employs perturbation and direct numerical methods.]

Kudish, I.I. (2000). A New Statistical Model of Contact Fatigue. *STLE Tribology Transactions*. 43: 711-721. [A new two-dimensional model of contact fatigue is proposed and analyzed. The model is fracture mechanics based and it is validated by comparison with some experimental data.]

Handbook on Mathematical Functions with Formulas, Graphs and Mathematical Tables, Eds. Abramowitz, M. and Stegan, I.A., National Bureau of Standards, 55, 1964. [This is a very well known and widely used source of various mathematics formulas and facts.]

Stover, J.D., Kolarik II, R.V., and Keener, D.M. (1989). The Detection of Aluminum Oxide Stringers in Steel Using an Ultrasonic Measuring Method. Mechanical Working and Steel Processing XXVII: Proc. 31st Mechanical Working and Steel Processing Conf., Chicago, Illinois, October 22-25, 1989, Iron and Steel Soc., Inc.: 431-440. [The authors describe an experimental ultrasonic measurement technique which allows measuring the size and determining the location of nonmetallic inclusions in steels.]

Biographical Sketch

Ilya I. Kudish was born in Russia. In 1973 he graduated Moscow Institute of Physics and Technology and in 1981 he received his Ph.D. degree in Mathematics and Physics from St. Petersburg Polytechnic University, St. Petersburg, Russia. In 1991 I.I. Kudish and his family immigrated to the USA. Since 1994 he works at Kettering University first as an Associate and 2000 as Full Professor of Mathematics. In 2004 Ilya I. Kudish was elected Fellow of the ASME, in 2005-2011 served as an Associate Editor of the ASME Journal of Tribology. Also, over the years he served as a reviewer of several research journals in the field of tribology. Ilya I. Kudish published over 100 research papers in the fields of contact problems of elasticity, fracture mechanics, elastohydrodynamic lubrication, lubricant degradation, and fatigue modeling. He developed distinct asymptotic approaches to various problems tribology as well as the theory of lubricant degradation and some models of contact and structural fatigue. In 2010 he together with M.J. Covitch published a monograph “Modeling and Analytical Methods in Tribology”, CRC Press.