FRACTURE MECHANICS AND MODELING OF CONTACT FATIGUE

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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 to 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 caused 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 coalesce 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 microcracking 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 (Kinoshiz 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, $4 \times 10^6$ cycles ($\times 3000$) and $4.3 \times 10^6$ cycles ($\times 3200$), respectively; (c) fatigue crack nucleation away from inclusion sites at $4.5 \times 10^6$ cycles ($\times 1600$); (d) and (e) propagation of microcracks from alumina nucleated holes and subsequent linking to form macrocracks, $4.7 \times 10^6$ cycles ($\times 1650$) and $5 \times 10^6$ cycles ($\times 790$), respectively; (f) surface of specimen, having failed at $5.5 \times 10^6$ cycles, with no evidence of crack nucleation due to the highly elongated manganese sulfide inclusions ($\times 3300$). 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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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.