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Lifetime prediction for the subsurface crack propagation using three-dimensional dynamic FEA model

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ABSTRACT

The subsurface crack propagation is one of the major interests for gear system research. The subsurface crack propagation lifetime is the number of cycles remaining for a spall to appear, which can be obtained through either stress intensity factor or accumulated plastic strain analysis. In this paper, the heavy loads are applied to the gear system. When choosing stress intensity factor, the high compressive stress suppresses Mode I stress intensities and severely reduces Mode II stress intensities in the heavily loaded lubricated contacts. Such that, the accumulated plastic strain is selected to calculate the subsurface crack propagation lifetime from the three-dimensional FEA model through ANSYS Workbench transient analysis. The three-dimensional gear FEA dynamic model with the subsurface crack is built through dividing the gears into several small elements. The calculation of the total cycles of the elements is proposed based on the time-varying accumulated plastic strain, which then will be used to calculate the subsurface crack propagation lifetime. During this process, the demonstration from a subsurface crack to a spall can be uncovered. In addition, different sizes of the elements around the subsurface crack are compared in this paper. The influences of the frictional coefficient and external torque on the crack propagation lifetime are also discussed. The results show that the lifetime of crack propagation decreases significantly when the external load T increasing from 100 N m to 150 N m. Given from the distributions of the accumulated plastic strain, the lifetime shares no significant difference when the frictional coefficient f ranging in 0.04–0.06.

1. Introduction

Gear system is a critical subsystem in any machinery products and the gear wear is the most common failure mode [1,2]. Wear means that the surface deterioration on the active contact profiles of machine components, e.g. gearing. Hence, the performance of gearing highly depends on the durability of tooth surface. In general, there are four basic wear modes: contact fatigue, adhesion, abrasion and corrosion, and contact fatigue is the most common mode of failure for gears under normal operating conditions.

Generally, pitting and spalling are two types of surface contact fatigue. According to [3,4], pitting and spalling can be distinguished from two aspects: appearance and mechanism of the crack generation. With respect to the appearance, pitting appears as shallow craters at contact surfaces with the maximum depth of a pit around 10 μm, while spalling appears as deeper cavities (typically 20–100 μm) at contact surfaces. The appearances of a pit and a spall are illustrated in Fig. 1. For the generation mechanism, Ding, et al. [3] believed that pitting results from the surface crack propagation, while spalling from the subsurface cracks that are initiated parallel to the contact surface. However, they indicated that the subsurface crack propagation will not lead to

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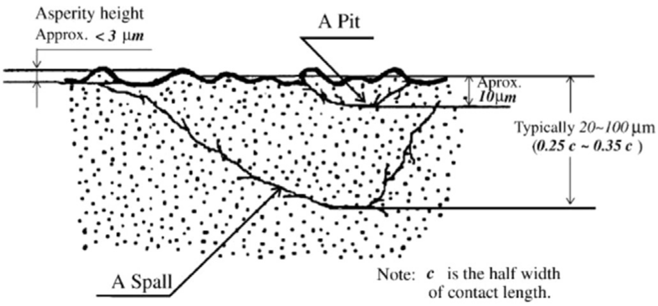

Fig. 1. The appearances of a pit and a spall [3].

failure, and the possible reason for spalling formation is the ligament collapse spalling mechanism. The region between the crack tip and the contact surface is called ligament where the material can no longer hold its designated strength. As a result, catastrophic failure occurs with a deep cavity.

Despite of a pit or a spall, the crack propagation and fatigue lifetime are always the main concern. The lifetime prediction model estimates the remaining cycles for pits or spalls to appear. The surface or subsurface crack grows with the cyclic contact loadings. Eventually, a crack becomes large enough to produce unstable growth, allowing material to break away from the surface, which results in a gradual deterioration of the surface. Failure occurs either when the surface deteriorates that the component cannot function as designed, or when the damage becomes severe enough that leads to another failure mechanism, e.g. tooth breakage [5]. Based on the stress intensity factor (SIF) and Paris law, the crack propagation rate and fatigue lifetime of gearing can be given as [6]

$$\frac{da}{dN} = C(\Delta k)^m \tag{1}$$

Given from (1), the driving force behind crack growth is the cyclic change in stress intensity at the crack tip. Keer et al. [7] proposed a line contact pitting model by assuming an initial crack with an initial angle relative to the contact surface. Mode II shear loading is used to represent the propagation driving force, and the fatigue life is given through calculating the SIF at the crack tip. Ding et al. [8] studied the SIFs ΔK_{I}, ΔK_{II} at both the leading and trailing tips of the subsurface cracks at different depths and lengths. The results show that ΔK_{I} has not exceed the threshold of crack propagation, which indicates that a subsurface crack under compressive contact loading could not be propagated in Mode I. On the contrary, ΔK_{II} is generally greater than the threshold $\Delta K_{\mathrm{II},th}$, meaning that the subsurface cracks will be propagated in Mode II. However, the highest value of ΔK_{II} is less than the critical SIF of crack failure, which demonstrates that a subsurface crack will not fail through Mode II propagation. The experimental results also show that the subsurface cracks propagating in Mode II are approximately parallel to the contact surface. Komvopoulos et al. [9] selected linear elastic fracture mechanics and finite element simulations to analyze subsurface cracking in a homogeneous half-space due to a moving asperity. The focus is on the direction and the rate of crack propagation due to indentation and sliding contact. The crack propagation directions in shear and tensile mode can be predicted based on the maximum range of the shear and tensile SIF. The results show that the maximum values of shear SIF ΔK_τ at both crack tips occurs at θ=0°, whereas tensile SIF ΔK_σ at the left and right tips occur at θ=70.5° and −70.5° respectively, where θ is the polar coordinate at the crack tips. The results demonstrate the horizontal subsurface crack would exhibit in-plane growth when the shear mechanism is dominant, which is in accordance with Ding et al. [3]. In addition, if the tensile mechanism is responsible for the commencement of crack growth, propagation from the left tip would tend to occur toward the surface and from the right tip downward into the half-space.

Besides the studies on single SIF, efforts have been devoted to the mixed mode SIFs. In Aslantas et al. [10], $\Delta K_{eff}^4 = \Delta K_I^4 + 8\Delta K_{II}^4$ is defined to evaluate mixed mode SIFs K_{I}, K_{II} at the subsurface crack tip, and then propagated to crack extension with Paris-type equation. The results show that the values of K_{I} are always negative under all load positions. Thus, the negative K_{I} is assumed to be zero since that it has no effect on crack growth. So the subsurface crack growth is dominated by K_{II} and $\Delta K_{eff}^4 = 8\Delta K_{II}^4$. However, the maximum tangential stress criterion is used to determine the crack growth direction, and the results indicates that subsurface crack could grow toward the surface and form a pit (spall) eventually.

The above mentioned studies are proposed under two-dimensional finite element simulation. Recently, special attentions are given to the three-dimensional finite element simulations [11,12]. Ural et al. [13] applied three-dimensional finite element analysis (FEA) model to predict crack shape for a spiral bevel pinion gear based on linear elastic fracture mechanics, combining with finite element method and incorporating plasticity-induced fatigue crack closure and moving loads, where K_{I} is that of interest. Lin et al. [14] established a three-dimensional boundary element model of cylindrical gear with crack in tooth root, and calculated the SIFs K_{I}, K_{II}, K_{III} using the opening displacement, sliding displacement and tearing displacement of the crack tip.

Despite of that utilizing the SIF and Paris law to determine the crack growth rate and fatigue life, extensive works have applied plastic deformation to study the crack propagation and fatigue life. A Hertzian pressure profile is generally used to determine the SIF. However, the pressure distribution in lubricated contacts is significantly different from that of the Hertzian. In addition, during heavily loaded lubricated contacts, high compressive stress in the contact zone virtually suppress Mode I stress intensities, and severely reduce Mode II stress intensities through the action of high friction between the crack faces [15]. Hence, the stress intensity factors based on the linear elastic fracture mechanics is not applicable for the situations of heavy loads that may result in plastic deformation. Bower et al. [16] proposed that the fatigue spall initiation and propagation are due to the accumulated plastic strain