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Experimental and analytical study of gear micropitting initiation and propagation under varying loading conditions

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ABSTRACT

Micropitting damage is one of the failure modes commonly observed in gears leading to destructive failures, which in turn results in unplanned shutdown and expensive replacement, such as those observed in wind turbine gearboxes. This study investigates gear micropitting initiation and propagation when subjected to varying torque loads under a constant rotational speed. The study employs both experimental gear testing and analytical evaluation based on the ISO Technical Report of Gear Micropitting, ISO/TR 15144-1:2010 and the recently revised ISO/TR 15144-1:2014. Initiation and propagation of micropitting are assessed in testing by quantifying the development of micropits and their progressive rate after specific numbers of running cycles at step-up torque levels. The analytical study is conducted to validate the prediction of micropitting using the ISO/TR recommended procedures by comparing the results with the occurrence of micropits in the tested gears.

The gear test results show that micropitting initiates at the pinion dedendum but escalates at the addendum, because of the greater severity of progressive micropitting at the dedendum of the mating wheel where the tip relief area first comes into mesh. The analytical results, based on varying surface roughness measurements obtained from the tested gears, confirm that the maximum contact stresses and minimum specific lubricant film thicknesses occur in these regions. The specific lubricant film thickness varies considerably because of changes of surface roughness after gears are subjected to various running cycles under varying torque levels. It has found that the excessive loading, gear tooth micro-geometry, surface roughness and lubricant film thickness are the main factors affecting micropitting.

1. Introduction

Gear design and analysis methods are standardised by many international committees and manufacturing organisations, such as AGMA 2001-D04, ISO/6336 and DIN 3990, to guide the various aspects of gear design and industrial applications. The methods have been developed to investigate and eliminate gear tooth failures such as tooth breakage, surface micropitting, scuffing, sliding wear and spalling (ISO 10825, 1995 and BS 7848, 1996). Gear tooth flanks are subjected to varying loading and relative sliding conditions when the tooth pair engages along the line of action because of changes of the radii of tooth profile curvature at different contact points and varying load sharing factors at the single/double tooth contact regions. These cause variations of some key parameters such as gear tooth contact stresses and sliding velocities between two mating teeth during each engagement cycle, especially when subjected to variable loading and variable rotational speed conditions in operation. Although gear design and failures are well studied, however, prediction of initiation and propagation of gear tooth micropitting to accurately estimate gear service life under complex operational condition is still a challenging problem. It contributes to considerable costs due to early replacement of gears, unplanned shutdowns for carrying out maintenance procedures, such as for wind turbine gearboxes.

During gear engagement, gear teeth experience a complex combination of surface rolling and sliding contact which varies along the tooth flank [1,2], as shown in Fig. 1. When used as a driving gear, the pinion sliding direction is away from the pitch line, whereas the driven wheel gear slides towards the pitch line [3]. For the pinion gear, this makes the sliding motion apt to pull the material away from the pitch line. At the pitch line of the wheel gear, however, the material is compressed by the sliding motion. The dedendum of both gears has a relatively short contact length and negative sliding as the direction of the sliding velocity is in the opposite direction of the rolling velocity. Furthermore, the contact stress changes continuously throughout the meshing process and high contact stresses can occur at the single tooth contact region where the load is supported by single pair of gear teeth. The variation of contact stresses and sliding directions can cause

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Nomenclature

Symbol Description Units

b	Face width mm
C_a	Tip relief μm
C_{eff}	Effective tip relief μm
F_t	Tangential load N
G_M	Material parameter
h_Y	Local lubricant film thickness μm
K_A	Load application factor
$K_{H\alpha}$	Transverse load factor
$K_{H\beta}$	Face load factor
K_v	Load dynamic factor
$p_{dyn,Y}$	Local Hertzian contact stress N/mm^2
R_a	Effective arithmetic mean roughness value μm
R_z	Mean of the height of five peaks to valleys μm
$S_{GF,Y}$	Local sliding parameter
U_Y	Local velocity parameter
W_Y	Local load parameter
Z_E	Elasticity factor, (N/mm^2)$^{0.5}$
α_t	Transverse pressure angle degree
β_b	Base helix angle degree
$\lambda_{GF,min}$	Minimum specific lubricant film thickness
$\lambda_{GF,Y}$	Local specific lubricant film thickness
λ_{GFP}	Permissible lubricant film thickness
$\rho_{n,Y}$	Normal radius of relative curvature at point Y mm

high temperatures and mixed lubrication conditions at contact surfaces, or even break down the lubrication film along the tooth flank. In addition, the surface roughness of meshing gear teeth will change after certain running cycles under loading. This leads to variations of lubrication condition between asperities of gear contact surfaces contributing to the initiation of micropitting. Gear tooth flank micropitting is characterised by a continuous surface deterioration, owing to various operational and loading conditions. Compared to the size of the contact zone, the micropits are small and shallow, with a size of about 5–10 μm long and 5–20 μm deep [4].

Gear surface failure of micropitting is affected by many factors including gear design, material, surface treatment and finishing, lubricant, and operational conditions such as loading and velocity, and lubrication condition. The following section will briefly review the published research in micropitting and effects of these key factors.

2. Review of recent micropitting research

Using a back-to-back gear test rig, surface durability of treated and untreated gear surfaces loaded under different torque levels was tested by Krishnamurthy and Rao [5]. The treated gears endured higher contact stresses and had a longer service life than that of untreated gears. Brechot et al. [6] tested many types of gears under different load levels. The main goal of these tests was to detect the occurrence of micropitting when using different industrial lubricant oil samples. Zhang and Shaw [7] used a back-to-back gear test rig to investigate two pairs of spur gears made from the same material, but with a different surface finishing. It concluded that the superfinished gears performed better against micropitting with smaller tooth profile deviation than the ground gears. Predki et al. [8] investigated micropitting of big spur gears with profile modification. Some of their key findings were that the higher surface roughness was related to wider micropitting zone, and the micropitting was influenced greatly by the amount of tip relief. Muraro et al. [9] experimented with spur gears of two different surface finishes, shaving and milling, to observe the wear mechanism. Two torque levels were implemented in their tests and it was observed that the wear was lower for the shaved gears due to the effect of the lubricant film thickness. Moorthy and Shaw [10] experimentally tested helical gears with different coating compared with as-ground (uncoated) gears, using a back-to-back test rig. The authors studied the micropitting propagation and profile deviation at different torque levels and cycle numbers. Evans et al. [11] analysed micro-elastohydrodynamic lubrication of two helical gears to investigate gear micropitting, using a gear test rig and predicted subsurface damage by accumulation analysis.

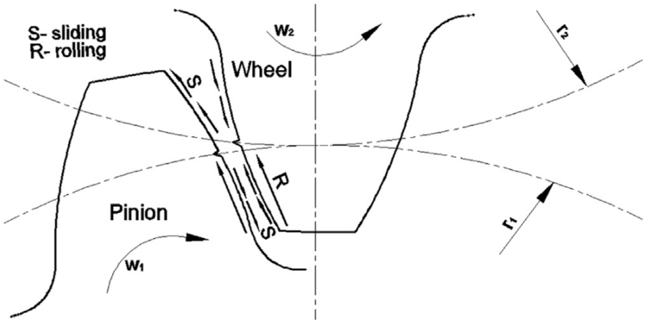

Fig. 1. Gear tooth surface rolling and sliding.

Hohn and Michaelis [12] tested different lubricants under different oil temperatures, and found that higher levels of micropitting were related to high contact stress and oil temperature as thin lubricant film thickness and low viscosity took place at high oil temperature. Oila and Bull [13] investigated micropitting using a two-disc machine and two different lubricant oils. One of their important conclusions was that the plastic deformation boundaries were preferred regions for micropitting initiation. Lainé et al. [14] experimentally tested carburised steel rollers; one of their main findings was that the micropitting was influenced by the surface roughness and lubricant film thickness. The micropitting may be exacerbated by the use of different types of anti-wear additives. Kleemola and Lehtovaara [15] developed a twin-disc test device to investigate the effects of three parameters, friction coefficient, temperature and lubrication conditions, on micropitting. Their results showed that higher sliding led to a higher temperature increase and lower film thickness.

Holmes et al. [16] used a transient analysis method to analyse lubricant film thickness in elliptical point contact, in the transverse direction. One of their key results was that the lowest film thickness occurred because of surface valleys, which helped the lubricant oil to escape between the contact surfaces in the transverse direction. Brandão et al. [17] presented a numerical model and compared with a FZG testing of gear surface-initiated damages, to predict the micropitting and gear tooth wear loss. The predictions and measurement of wear losses were correlated, but the surface roughness results did not match well. Zhu and Wang [18] used different types of contact geometry and three types of contact surfaces which were transverse, longitudinal and isotropic, to study the effect of surface roughness orientation on the EHL (elastohydrodynamic lubrication) film thickness.

Through the continuous research, the understanding of the mechanism of micropitting has been improved. However, the prediction of initiation and propagation of gear tooth micropitting to accurately estimate gear service life is still a challenging problem. This study combines the experimental and analytical studies to