Engineering Failure Analysis 62 (2016) 276–286

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Fatigue of gears in the finite life regime — Experiments and probabilistic modelling

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ARTICLE INFO

Article history:
Received 2 December 2015
Received in revised form 18 January 2016
Accepted 23 January 2016
Available online 27 January 2016

Keywords:
Fatigue life
Finite element analysis
Gear-tooth failures
S–N curves
Probability

ABSTRACT

Fatigue of case hardened gears is investigated experimentally and numerically with focus on the finite fatigue life regime. Pulsating tooth bending fatigue experiments are performed at different load levels on two types of gears of different sizes to determine load–fatigue life relations. The experiments are compared with a probabilistic model for the finite life regime based on weakest-link theory. The stress fields, needed in the evaluations, are obtained by finite element simulations taking residual stresses, both due to case hardening and plastic deformation, into account. The stress history at each element is summarized into two different effective fatigue stress measures; one based on the largest principal stress and the Findley multiaxial fatigue stress. The material parameter needed in the Findley stress is determined by a linear correlation of the parameter with the Vickers hardness of the material using multiaxial fatigue data found in the literature. Both equivalent stress measures show equal behaviour and the probabilistic model shows good agreement with the experimental data in the finite fatigue life regime.

1. Introduction

The probably most important failure mode for industrial products is fatigue; one often stated number is that 90% of all failures are related to fatigue. When designing against fatigue, it is common to design either against finite fatigue life or infinite fatigue life. In the latter case, the component is assumed to survive an infinite number of load cycles as long as the load is below a critical value, the fatigue limit. In the finite fatigue life regime, there is a differentiation between the Low Cycle Fatigue (LCF) regime where the fatigue processes are controlled by alternating plastic strains on the macroscopic scale and High Cycle Fatigue (HCF) where stress based design methods are commonly used. For the present application, fatigue of small spur gears used in the transmission of pneumatic handheld nut drivers, the finite life regime is relevant as each gear is only experienced to high torques during short time intervals and only a few teeth are experiencing the highest loads during tightening of one nut.

One of the most common failure modes for gears is tooth bending fatigue failure [1], often immediately leading to subsequent failure of more teeth and thus, in this case, an unusable nut driver causing costly production stops. It is important to reduce the weight of transmission components to reduce material consumption and for the present application, for ergonomic aspects. In order to limit costly experimental investigations, models utilizing the fatigue properties for one type of gear to predict the properties of another gear are needed.

One issue when dealing with fatigue is its probabilistic aspects, i.e. that it is just meaningful to discuss the probability that a component will fail at a certain load and after a certain number of cycles. For instance, the fatigue limit is usually, and in this paper, defined as the load giving 50% failure probability. Another aspect is the fact that there is a higher probability that a larger

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http://dx.doi.org/10.1016/j.engfailanal.2016.01.012
1350-6307/

component contains a critical defect than a smaller component and thus the fatigue limit (and fatigue life) will decrease with the size of the component. Models based on weakest-link statistics have been used successfully to design against fatigue at the fatigue limit and several such models exist in the literature starting with the work by Weibull [2]. For example, during the recent years, the predictability capabilities of the weakest-link model has been critically investigated by Norberg and Olsson [3] and later Karlén and Olsson [4]. Modifications of the theory, based on highly loaded regions, have been performed by Sadek and Olsson [5].

Probabilistic models for the finite fatigue life regime are less developed in the literature. Pascual and Meeker [6] presented a random fatigue limit model for the entire HCF domain by assuming that the fatigue life and the fatigue limit are either normally distributed or following the standardized smallest extreme value probability density function. A more recent statistic approach, based on the Weibull distribution was presented by Castillo and Fernandez-Canteli [7]. The more physically motivated model, based on damage on the grain level, by Morel and Flacelière [8] should also be mentioned in this context. Karlén and Olsson [9] proposed a probabilistic model for the entire HCF domain which accounts for inhomogeneous stress fields by defining different equivalent stress measures for the fatigue specimens and fitting the outcome to a log-normal distribution in fatigue life. This model is the one most similar to the model presented in this article which will be derived from the original weakest-link model for infinite fatigue life by having the parameters be dependent on the number of cycles to failure. One benefit with the present approach, compared to the other models, is that no underlying assumption about the probability distribution for the number of cycles has to be made.

In summary then, this paper focuses on modelling of one of the most important failure modes for gears, tooth bending fatigue, by accomplishing the following three steps:

- Investigate experimentally the fatigue properties in the finite life regime of two types of small spur gears of different sizes.
- Determine if there is a statistic volume effect upon the fatigue life in tooth bending of the gears.
- Propose a probabilistic model for the fatigue life that incorporates the possible volume effect.

The model will use stress histories obtained by the finite element method and account both for plastic deformation and residual stresses due to case hardening.

2. Experiments

2.1. Test objects

The experimental part of the work is focused on two types of small spur gears, Gear A and Gear B, with different geometry. The smaller gear, Gear A, has 16 teeth and the larger gear, Gear B, has 22 teeth. The two gears are pictured in Fig. 1 and the dimensions of the two gears are given in Table 1. The module of the gears, i.e. the reference diameter divided by the number of teeth is the same for the both gears, 0.6 mm.

The gears were manufactured of a carburizing steel named Ovako 253C with material composition given in Table 2. After manufacturing, the gears were case hardened giving a martensitic microstructure in the case hardening layer. The surface hardness after hardening was measured at the gear flank to 704 HV for Gear A and 742 HV for Gear B. The case-hardening depth at the gear flank was 0.25 mm for Gear A and 0.23 mm for Gear B.

2.2. Fatigue experiments

The fatigue experiments were performed using a servo-hydraulic testing machine from MTS with a load capacity of 100 kN. The testing machine was controlled by the control electronics Instron M8500+. The test was performed in load control with a sinusodal waveform. Testing frequency was 30 Hz. The investigated load case was gear tooth bending aiming at fatigue failure at the tooth root. A photograph of the test setup is seen in Fig. 2 (a). The loading was applied using two hardened steel plates

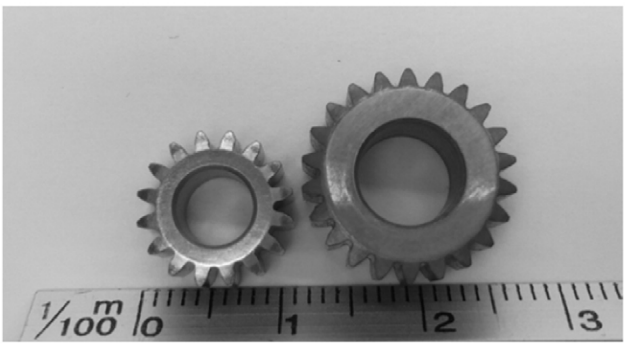

Fig. 1. Photograph of the two studied spur gears. To the left is the smaller gear with 16 teeth (Gear A) shown and the larger gear with 22 teeth (Gear B) is shown to the right.