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Investigations on Tooth Root Bending Strength of Case Hardened Gears in the Range of High Cycle Fatigue

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Tooth root load-carrying capacity is one of the determining factors in gear design. In addition to the strength of the material itself, the existing state of stress significantly influences tooth root load-carrying capacity.

Based on extensive experimental investigations of gears, the beginning of the fatigue strength range is generally set 3×10^6 load cycles, which common calculation methods, like ISO 6336, also take into account. According to this, standard test methods for tooth root bending endurance strength usually assume a load cycle limit of $3-6 \times 10^6$. However, current as well as completed studies on tooth root load-carrying capacity show tooth root fractures with relatively high numbers of load cycles in a range of general fatigue strength and above. Analysis of these fracture surfaces shows that these late breakages are often initiated by small inclusions or microstructural defects in the material. These tooth fractures that initiate with cracks under the surface have a negative effect on the tooth root load-carrying capacity in the range of high cycle fatigue.

Therefore, experimental investigations regarding high cycle fatigue have been carried out in a pulsator test rig on gears of various sizes, materials and residual stress conditions. As a result, depending on the existing residual stress condition, there are different levels of tooth root load carrying capacity, different failure behaviors in high cycle fatigue and different types of damage. Especially for test variants with high residual stresses, the size of the gear and the cleanness of the material have an impact on the tooth root load-carrying capacity and the damage pattern.

This paper discusses the different fracture modes by means of examples. Furthermore, it presents the influence of residual stresses, size and material cleanness on the tooth root load-carrying capacity and on the type of tooth root fractures with crack initiation on and under the surface. These influences will be additionally confirmed by examples of experimental test results.

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Introduction

Gears are one of the critical components which determine the capability and reliability of drive systems. Thus the tooth root load-carrying capacity is one of the determining factors in gear design. Continuous demand for higher efficiency, increased load-carrying capacity and endurance life, while at the same time, ensuring smaller size and low costs, increasingly often make the solid expertise of fatigue mechanisms of gears indispensable. In addition to the strength of the material itself, the existing state of stress can significantly influence the tooth root load-carrying capacity and the associated fracture mode.

According to the current state of the art, case hardened gears for industrial gear box applications often are peened for the cleaning process. Along with the effects of cleaning, peening processes also substantially affect the tooth root load-carrying capacity. Additionally, controlled shot-peening processes lead to an increase of the tooth root load-carrying capacity up to more than 15% [3] compared to blast cleaned gears. Based on extensive experimental investigations on gears different kinds of fracture modes can be observed depending on the present state of stress. According to the current state of knowledge it must be distinguished between breakages with an initiation of fatigue cracks on and under the surface. Especially those breakages with an initiation of cracks under the surface have a negative effect on the tooth root load-carrying capacity in the range of high cycle fatigue.

The scope of this research project was to increase the knowledge of the tooth root load-carrying capacity of cylindrical gears with different residual stress conditions, especially in the range of high numbers of load cycles up to 100×10^6 . Therefore, an extensive program of gear tests in pulsator test rigs has been carried out to verify on the one hand the different types of tooth root fracture modes and, on the other hand, the associated dominating influences on high cycle fatigue of gears.

Internal fracture mode in the tooth root

Due to common experience of tooth root bending tests in pulsator test rigs, the endurance limit of the tooth root fatigue strength is usually considered to be 3×10^6 load cycles. As a result, suitable standard tooth root bending tests set the endurance limit at which a test is meant to be graded as fatigue resistant to $3\text{--}6 \times 10^6$ cycles. In current and completed studies on tooth root load-carrying capacity at FZG, especially on case hardened gears, more and more frequent tooth root breakages were found that occurred in and above the range of these ultimate numbers of cycles. Analysis of corresponding fracture surfaces show that these damages in the range of high numbers of load cycles often initiate from small inclusions or microstructural defects in the material. Similar damage patterns determined on simple specimens exhibiting a small bright spot at the crack origin are well known from technical literature, the so called “fish-eye” (Figure 1).

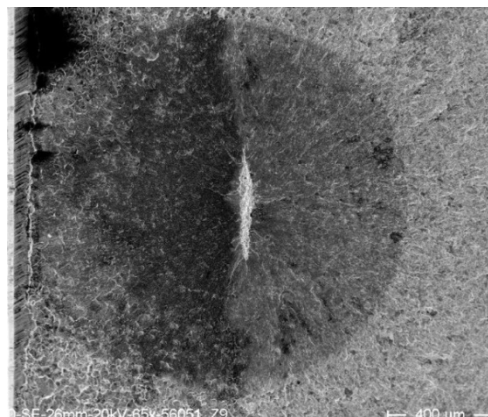


Figure 1. Example of tooth root breakage with “fish-eye” failure

Extensive studies [8], [9] on the initiation and propagation of internal cracks in gears or simple specimens already exist. Most of them describe the same propagation process of fatigue crack initiation and essentially specify the three different areas of the fish-eye failure according to Figure 2 [9]. The inclusion in the center surrounded by the GBF (Granular Bright Facet), an area of multiple microcracks, and the surface crack, as a result of the subsurface cracks, form the typical appearance of these failures. Surface crack initiation occurs at high stress levels and relatively low numbers of load cycles, whereas subsurface crack initiation is mainly observed at lower stress levels and in the high cycle range. As a consequence, failures with a crack initiation under the surface tend to decrease the tooth root load-carrying capacity in regions of high numbers of load cycles. As a result, the normally applied S-N curve has to be converted schematically to a stepwise S-N curve (Figure 3), which takes into consideration the possible reduction in load-carrying capacity in the high cycle range.

Relating to the different gear standards, ISO 6336 [7] takes a decrease of the tooth root load-carrying capacity in high cycle areas into account. The corresponding life factor is based on AGMA 2001 [1] standard and considers various influences, such as cleanness of material, residual stresses or signs of fatigue. This factor is the result of assessments and experiences and is insufficiently secured by systematic experimental results in the high cycle range.

Influence of the existing state of stress in the tooth root

Gears are exposed to different types of stresses during their manufacture, for example from milling, heat treatment, grinding, shot peening. These stresses in the material overlap with applied stresses caused by the existing load. The different states of stress affect the load-carrying capacity of gears in different ways. To evaluate the load-carrying capacity of gears it is necessary to know the local stress situation and the associated strength of the material itself. The local load induced stresses mainly depend on the current load situation and the size of the gear, whereas the local strength of the material is primarily affected by base material, previous heat treatment, peening conditions or irregularities in the material itself (according to Figure 4).

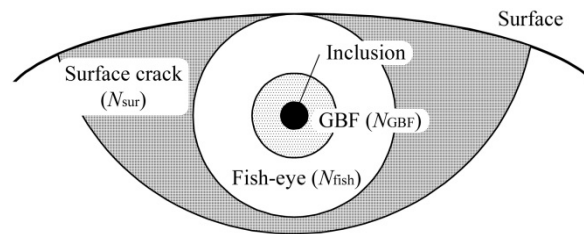


Figure 2. Schematic illustration of subsurface crack growth 9

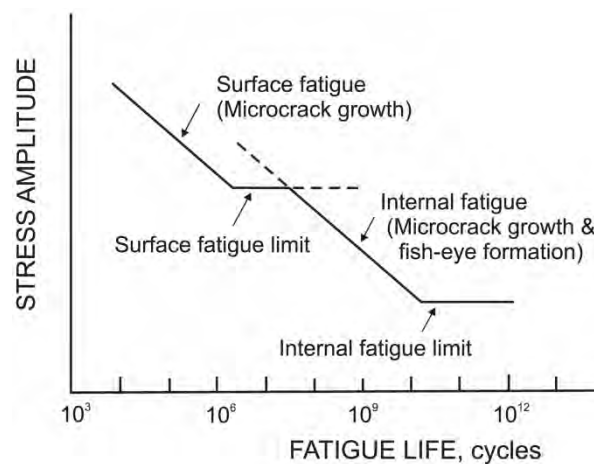


Figure 3. Schematic illustration of stepwise S-N curve 8

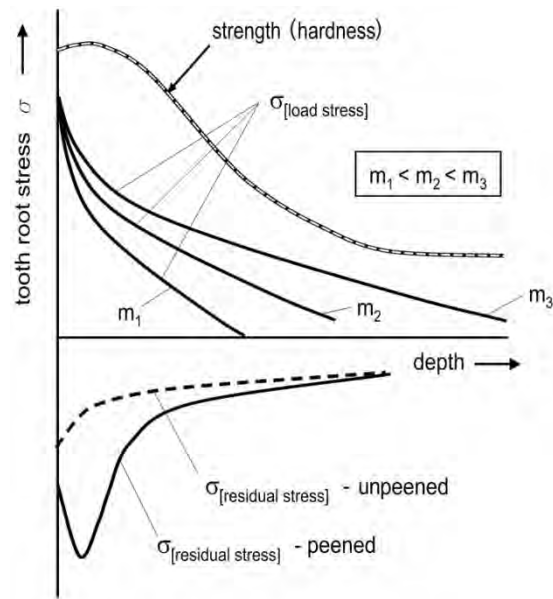


Figure 4. Schematic distributions of load stress, residual stress and hardness in tooth root area of case hardened gears depending on material depth

Common calculation methods for tooth root bending stress, such as ISO 6336-3 [7], apply the point of contact of the 30° tangent and the tooth root fillet to maximum local tooth root bending stress. The maximum local tooth root bending stress generally occurs on the surface of the root fillet due to slip deformations, surface defects and additional notch effects.

Depending on the current state of stress, different fracture modes can be determined on gears. Experimental investigations [3], regarding high cycle fatigue on gears of various sizes, materials and residual stress conditions showed that the main factors on high cycle fatigue of external gears are residual stresses, tooth size and the material cleanliness. These influences are regarded more closely in the following.

Residual stresses

The state of the art in industrial practice is often a cleaning process after previous heat treatment to remove scale layers and impurities of case hardened gears with the help of blast cleaning techniques. Besides the mentioned cleaning effects, an additional increase of the tooth root load-carrying capacity caused by residual compressive stresses can be noticed. This positive stress situation on and just below the tooth root surface counteracts the tensile load stresses and leads, especially on the surface and in the near surface layer, to an increase of the local fatigue strength. Therefore, the values of the tooth root load-carrying capacity for case hardened gears, material quality MQ, published in the standard ISO 6336-5 [7], depend on gears that have been professionally blast cleaned under industrial standards. Furthermore, ISO 6336-5 [7] attributes case hardened and shot-peened gears an increase of the tooth root load-carrying capacity of 10% compared to blast cleaning.

Concerning the major influence of peening in general, extensive experimental investigations in diverse studies [6], [10], [12] on gears and other components have been carried out. Figure 5 and Figure 6 contain exemplary test results of tooth root bending tests on unpeened and peened gears of different sizes and materials. The increase of tooth load-carrying capacity of peened gears can be observed. It should be noticed that these test results are based on standard tooth root bending test methods with an endurance limit of 6×10^6 load cycles.