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INFLUENCE OF LOW CIRCUMFERENTIAL SPEEDS ON THE LUBRICATION CONDITIONS AND THE DAMAGE CHARACTERISTICS OF CASE-HARDENED GEARS

CATEGORY
Gears

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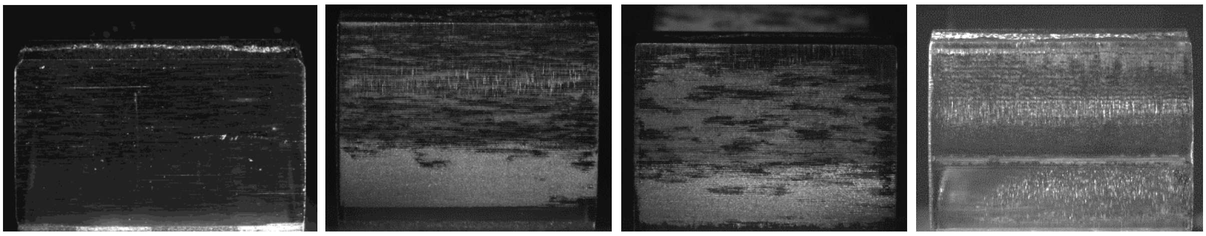
INTRODUCTION
The load carrying capacity of gears can be limited by a number of different failure modes which themselves depend on a variety of parameters, e.g. gear material, gear lubricant, operating conditions and surface roughness. Modern high-performance gearing systems often have one or more gear stages that are operated at small circumferential speed. Due to the challenging lubrication conditions, life-limiting tooth flank phenomena such as micropitting and sliding wear may occur, even if a sufficient pitting resistance is assured.
The failure mode of micropitting is decisively influenced by the minimum specific lubricant film thickness λ_{min} in the gear contact. So far, most experimental investigations on case-hardened gears regarding micropitting were undertaken at medium to high pitch line velocities ($v_t \geq 7$ m/s). Existing calculation models based on these investigations, e.g. [4] and [8], are not limited to higher pitch line velocities. However, for gears operated at lower pitch line velocities, there is only limited experimental validation.
Further on, for gears running at very low pitch line velocities ($v_t \leq 0.5$ m/s), the damage type of sliding wear often is the most common one. Based on the research work of e.g. the projects FVA 10 I+II [6, 7], an approach to calculate the wear amount for very low speeds has been proposed.
However, for the area of low to medium pitch line velocities (7 m/s $\geq v_t \geq$ 0.5 m/s), only limited knowledge of the relevant failure modes, their possible superposition and the applicability of the calculation models exists. Therefore, as part of a current research project (FVA 482 III [5]), the lubrication conditions and resulting damage characteristics of case-hardened gears operated at low to medium circumferential speeds have been investigated both theoretically and experimentally.

EXPERIMENTAL INVESTIGATIONS

In order to determine the effect of low to medium pitch line velocities, extensive gear running tests in the area of 7 m/s ≥ v_t ≥ 0.1 m/s were performed on standardized FZG back-to-back gear test rigs [1]. The gear geometry and test conditions were chosen according to the standard ISO 6336 [2] and are documented in the final report of the research project FVA 482 III [5]. Figure 1 shows exemplary tooth flank pictures of the pinion after completion of single load stage tests at different pitch line velocities.



New condition | 4.0 m/s | 1.0 m/s | 0.2 m/s

Figure 1: Exemplary pictures of the pinion tooth flanks of single load stage tests performed at different pitch line velocities v_t [5]

As expected, gears running with higher pitch line velocities failed due to micropitting. As seen in Figure 1 on the second picture (v_t = 4.0 m/s), for higher pitch line velocities, the micropitting is limited to the area below the pitch circle. The variants running with a reduced pitch line velocity of 1.0 m/s showed extended micropitting on most of the tooth flank, both above and below the pitch circle.

By decreasing the pitch line velocity even further to 0.2 m/s, the gears were suffering from sliding wear. This is in accordance with the expectations, since these variants were running at conditions critical to sliding wear. Further investigations by means of a scanning electron microscope (SEM) did prove that the tooth flanks on the right picture of Figure 1 did not show any micropitting anymore, but sliding wear only.

EXTENSION OF CALCULATION MODELS

The results of the performed research work show that some operating conditions are clearly critical towards micropitting, while others are critical towards sliding wear. This is mainly depending on the minimum specific lubricant film thickness in the gear contact λ_{min}, which itself is depending on the pitch line velocity, among other factors. It can be further stated that micropitting only occurs if sliding wear is not the dominant type of damage.

Based on the experimental results, a limitation of the applicability of the existing calculation models for micropitting and sliding wear is proposed. As shown in Figure 2, several areas of expected flank conditions can be determined based on the minimum specific lubricant film thickness calculated according to ISO TR 15144 [3]. The following operating ranges can be distinguished:

<u>a) $2\cdot\lambda_{GFP} \leq \lambda_{min}$ (full film lubrication):</u>

For applications operated at a sufficiently high specific film thickness, no micropitting and no sliding wear is expected. According to test experience micropitting and wear will not occur if the safety factor against micropitting according to ISO TR 15144 [3] is $S_\lambda \geq 2$. This means that the minimum specific lubricant film thickness in the gear contact λ_{min} is more than double the critical/permissible specific lubricant film thickness λ_{GFP}.

<u>b) $\lambda_{GFP} \leq \lambda_{min} < 2\cdot\lambda_{GFP}$ (mixed EHL lubrication):</u>

In this operating range, a moderate risk of micropitting may be expected. The more the value of the minimum specific lubricant film thickness λ_{min} tends towards the critical specific lubricant film thickness λ_{GFP}, the more the risk of micropitting rises. In addition, the specific lubricant film thickness for sliding wear $\lambda_{C,wear}$ according to Plewe [6, 7], which determines whether a superposition of micropitting and wear occurs, must be checked in comparison with λ_{GFP}.

c) $\lambda_{C,wear} < \lambda_{min} < \lambda_{GFP}$ (severe mixed EHL lubrication):
In this operating range, a significant risk of micropitting is to be expected. The value of the critical specific lubricant film thickness for sliding wear $\lambda_{C,wear}$, which determines whether a superposition of micropitting and wear occurs, must be checked in comparison to λ_{GFP}.

For the areas b) and c), the following considerations must also be taken into account:
If $\lambda_{min} > 2 \cdot \lambda_{C,wear}$ is fulfilled, it can be assumed that the calculation of S_λ is providing accurate results. For $\lambda_{min} < 2 \cdot \lambda_{C,wear}$, it can be assumed in principle that a risk of micropitting is present, but the expected micropitting can be decisively influenced by sliding wear as main failure mechanism, so that the calculated safety factor against micropitting S_λ in this area only has a limited informational value.
It has to be noted that λ_{GFP} is depending on the micropitting performance of the lubricant and $\lambda_{C,wear}$ on the wear performance of the lubricant in use. Therefore, the relationship of both values is not a constant factor and absolute values as well as the ratio may be different for different lubricants and operating conditions.

d) $\lambda_{min} \leq \lambda_{C,wear}$ (boundary lubrication):
In this area, sliding wear can be expected to be seen as dominant type of damage. A calculation of a safety factor against micropitting S_λ is not recommended for applications operated under such critical lubricating conditions.

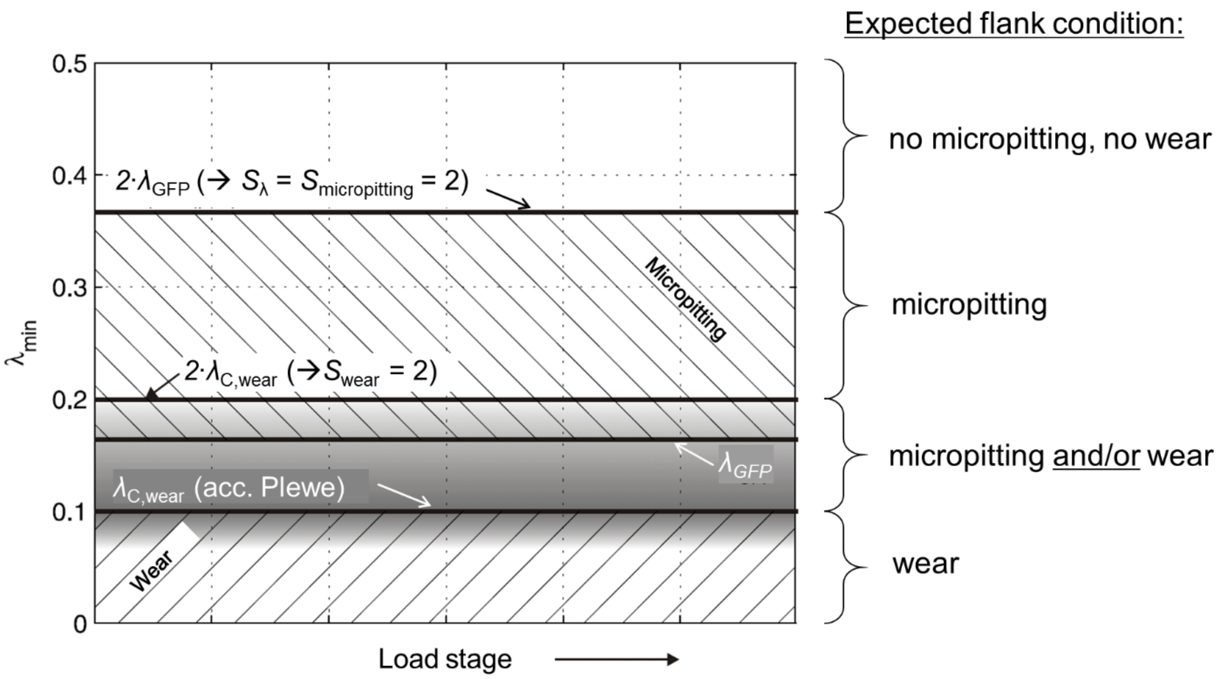


Figure 2: Risk zones depending on the minimum specific lubricant film thickness in the gear contact λ_{min} for a given lubricant (acc. to FVA 482 III [5])

CONCLUSIONS

Modern high-performance gearing systems often have one or more gear stages that are operated at small circumferential speed. Due to the challenging lubrication conditions, life-limiting tooth flank phenomena such as micropitting and sliding wear may occur, even if a sufficient pitting resistance is assured.
As part of the research project FVA 482 III [5], the lubrication conditions and resulting damage characteristics of case-hardened gears operated at low to medium circumferential speed have been investigated both theoretically and experimentally. As a result, characteristic parameters have been identified in order to evaluate whether micropitting or sliding wear will emerge and which of both will be the dominating damage mechanism.

Furthermore, based on the experimental results, the existing models (e.g. ISO/TR 15144 [3]) for the development of sliding wear and micropitting, respectively, have been validated and extended to gears operating at low to medium circumferential speeds.

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KEYWORDS
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