Wear on Gears: Calculation of Progression of Wear and Forecast of Worn Tooth form

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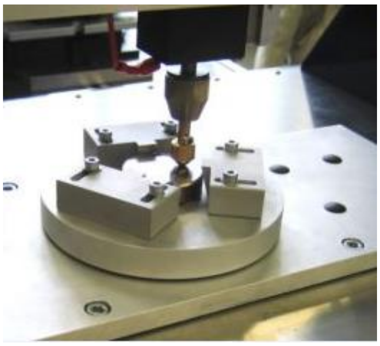
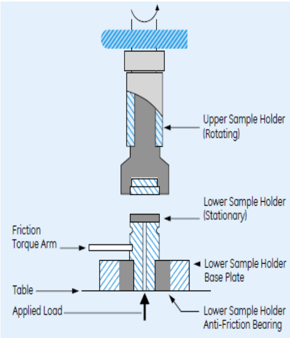
Wear is a very important topic for dry running plastic gears. Over the past few years, the authors have worked closely with a number of manufacturers of plastic gears to investigate the problems of gear wear in detail. Together they have developed a calculation method that can be used to predict where and when local wear will occur on a tooth flank. Their findings have also just been published in the final version of VDI 2736.

Theory of wear and wear coefficient

The term "wear" is used to describe the progressive removal of surface material due to mechanical and/or chemical stress. The four main wear processes defined in DIN 50320 are adhesion, abrasion, surface break-up and tribochemical reaction.

The simplest method of measuring wear is to press a pin made of the material being investigated against a rotating ring (Figure 1). In the plastics industry this method is known as the "pin and disk test rig" test. When investigating plastics, this ring is usually made of metal with a low surface roughness R_z.





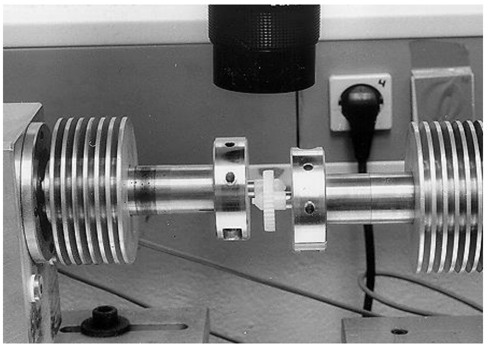


Figure 1. Left: pin and disk test rig. Middle: "thrust washer" test rig. Right: gear testing apparatus.

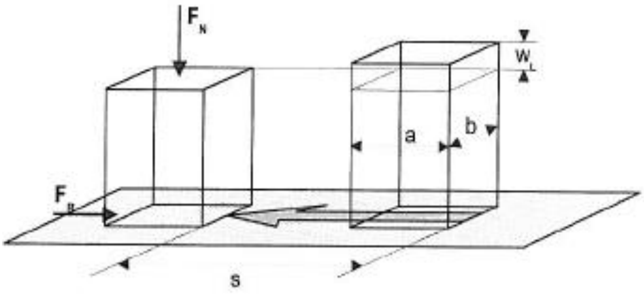


Figure 2. Diagram showing how wear rates are determined (pin and disk test).

The wear coefficient k_w derived using the pin and disk test rig (Figure 2) –
is defined as follows:

$$W = k_w \cdot p \cdot v \cdot t \quad (1)$$

Wear removal	W	mm
Surface pressure	p	N/mm^2
Sliding velocity (pin and disk test rig)	v	m/s
Time	t	s
Wear coefficient	k_w	mm^3/Nm*1e-6
Tooth normal force	F_n	N
Supporting width	b	mm
Sliding velocity (tooth flank)	v_g	m/s
Speed in direction of tangent	v_p	m/s
Specific sliding	ζ	-
Number of load cycles	N	-

The wear formula (1) can be modified for use in the tooth flank:

$$W_{lokal} = \frac{F_{n.lokal}}{b} \cdot N \cdot \zeta \cdot k_w \quad (2)$$

This determines the local wear in each point of the tooth contact area on the gear. At the suggestion of the authors, this formula has been included in VDI 2736 [1]. Another confirmation of the formula's effectiveness is that Feulner [2] derived the same formula on the basis of measurements.

Determining the progression of wear

The wear characteristics can be calculated by implementing the formula (2) for local wear on the flank in a gear contact analysis. This makes it possible to define the shape of the abraded tooth flank. Initially, this approach did not provide any usable results, if the wear – starting with a perfect tooth form – was determined in a single calculation step. The wear characteristics must be calculated step by step because the tooth form changes as it becomes worn, and therefore the load distribution moves across the meshing.

Very useful results can now be achieved by running the calculation at a sufficient number of small increments. The maximum permitted wear per iterative step must be predefined, so that the iterative progression of wear can be calculated. This predefined value is critical for achieving realistic results. This recently developed calculation method has been used to compare a range of gears that have been subjected to testing and then measured in 3D.

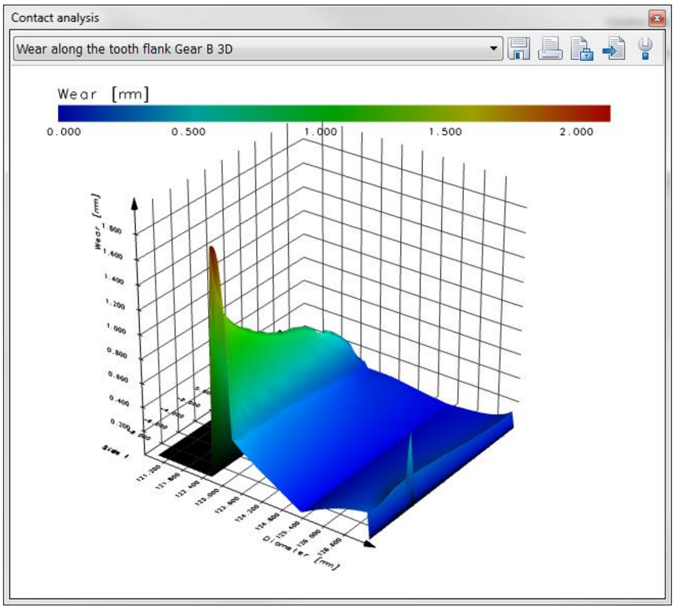


Figure 3. 3D display of the wear along the tooth flank in the contact analysis of KISSsoft.

Figure 4 shows this type of comparison using a pairing where the plastic output gear is badly worn (PBT). The difference between the arithmetical forecasts, with and without iterative calculation, clearly shows that the wear characteristics along the flank without iteration cannot be used and it displays quite a different trend to the measured progression. A maximum interval of 1µm wear per iterative step has been defined for the wear characteristics in a forecast with iteration. In this case, 146 iterations were calculated (the calculation took 2.5 min, using an Intel Core i7-3770). The result showed a relatively good match with the measurement.

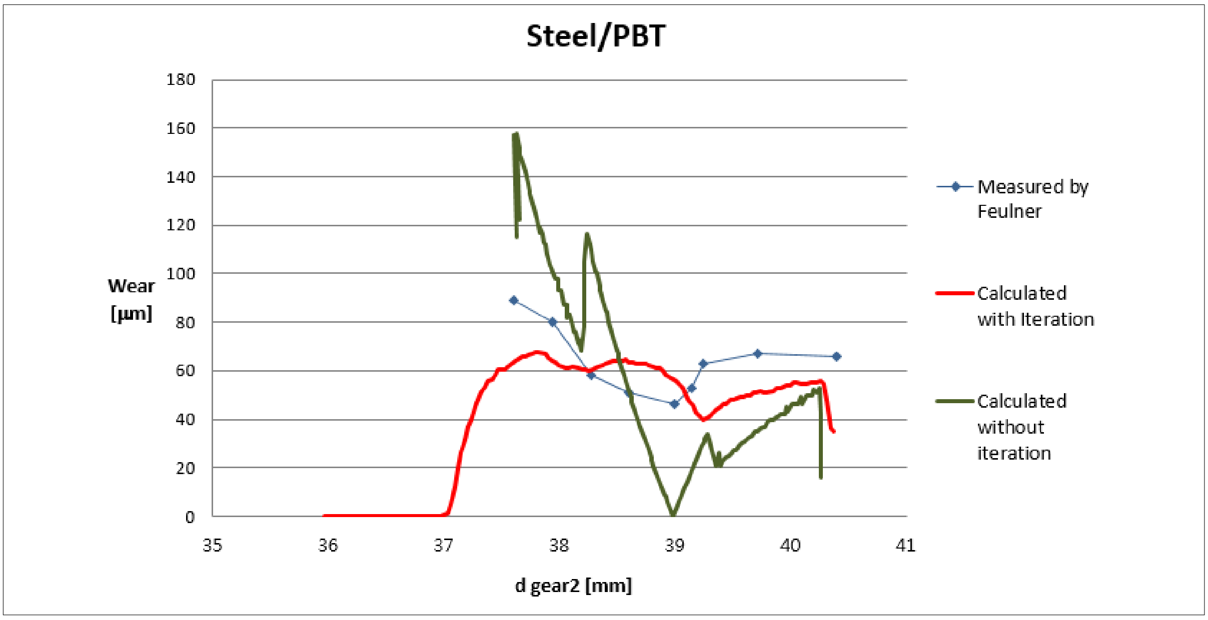


Figure 4. Wear characteristics on a dry-running PBT gear, in accordance with measurement [2] and in accordance with the calculation with and without an iterative definition of the progression of wear.

Influence on „Transmission Error“

As the tooth form can now be predicted with reasonable accuracy, more detailed analyses – for example, determining the change in load distribution or the increase in transmission error due to wear – can be defined. Increasing vibrations in the meshing over a long period of time can reduce the endurance limit. This is a recognized effect of frosting and a cause of concern wherever gears are used. For this reason, being able to predict the progression of transmission error in advance is a very interesting result.

Initial verifications performed on different pairs of gears have revealed that transmission error has a tendency to reduce in the first phase of wear ("running-in phase"), however as the amount of wear increases, this error also increases significantly to reach values that are 2 to 3 times greater.

Figure 5 shows results calculated using a steel/PBT gear pair (Figure 4). When the tooth flank calculated by wear iterations is verified with contact analysis, it is visible that the “Peak-to-Peak Transmission Error” (PPTE) is much greater when the wear has also progressed. Closer investigation of the development of transmission error over the operating time shows an initial improvement in the transmission behavior. It is generally accepted that gear units which have been properly run in have a better load capacity because the load distribution has a tendency to improve during the running-in period. This "running-in effect" obviously also applies to the transmission error.

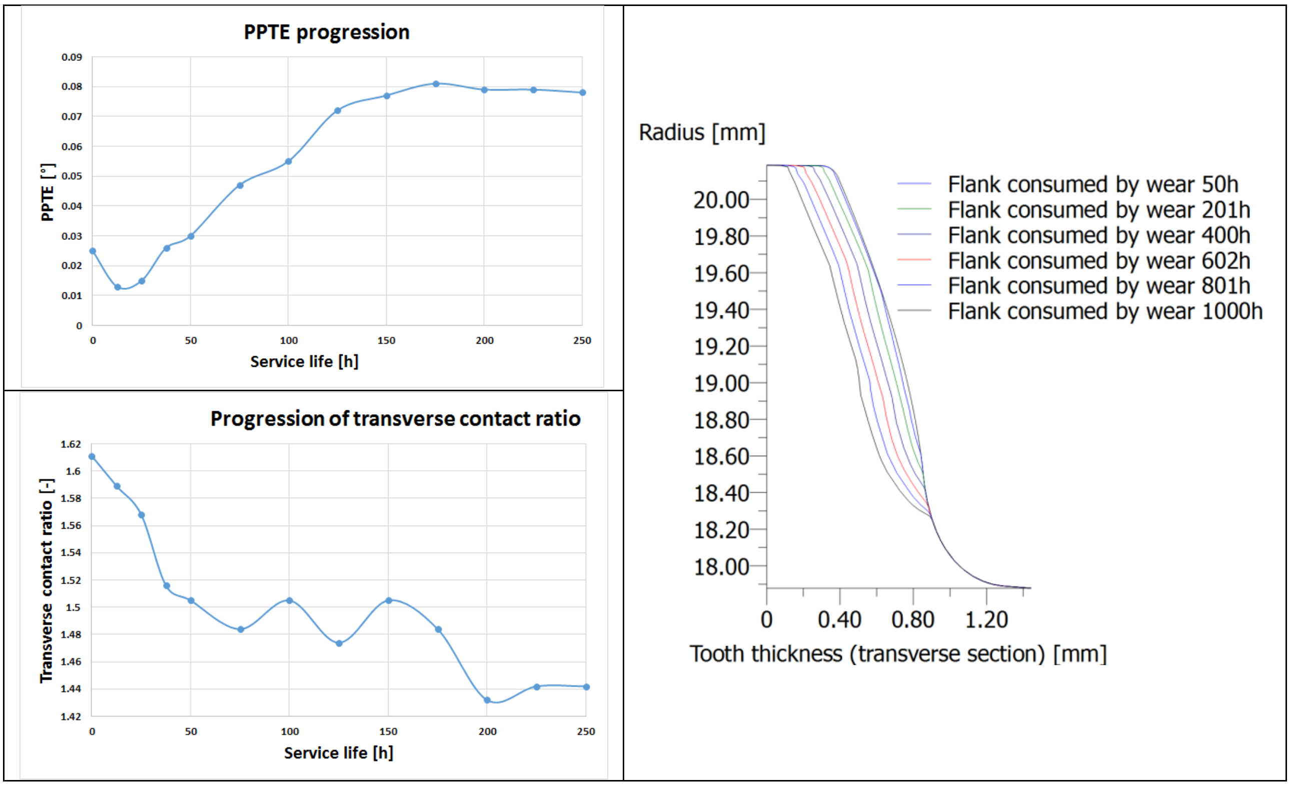


Figure 5. Left top: Progression of PPTE over the service life. Left bottom: Change in the transverse contact ratio. Right: Worn tooth flank in several steps up to 1000 h.

However, as the wear increases, the transmission error also increases sharply until it reaches a plateau. The fact that the transmission error does not then continue to increase, but remains at a specific, high level, can be explained as follows: a certain level of equilibrium is achieved where the tooth thickness continues to decrease but the tooth form no longer changes very much. This is illustrated by the worn flanks in Figure 5: after the green tooth form (operating time of approximately 200 h) the following tooth forms display a similar progression, where the thickness reduces at a constant rate.

Summary

Two calculation methods are now available for calculating wear: The first is an analytical method which uses simple formulae to determine the average wear when designing gear systems [1, 3]. The second, more complex method, is integrated in contact analysis and is used to ascertain the progression of wear.

When these calculation methods are compared with measurements taken by test rigs (plastic and metal) and with results from real life situations, it can be seen that these methods produce very usable, realistic results. Therefore, it is now also possible to predict the effect of a worn tooth form on the load distribution and transmission error.

Literature

[1] VDI 2736, Sheet 2: Thermoplastische Zahnräder – Tragfähigkeitsberechnung Stirnräder; VDI Düsseldorf, 2014.

[2] Feulner, R.: Verschleiss trocken laufender Kunststoffgetriebe; Dissertation, Erlangen, 2008.

[3] Kissling, U.; Hauri, S. Das Phänomen Kaltverschleiss von Stirnrädern – neu berechnet. Tagungsband SIMPEP, 2014.