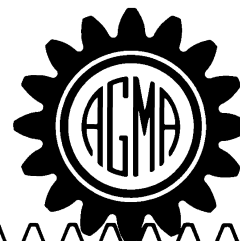


Estimation of Lifetime for Plastic Gears

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American Gear Manufacturers Association



TECHNICAL PAPER

Estimation of Lifetime for Plastic Gears

Dr. Stefan Beermann, KISSsoft AG

[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

The importance of plastic gears for modern industry is growing every year. The engineer sizing plastic gears has a very difficult task. There is no international standard available for the strength analysis. The only method publicly accepted is the German guideline VDI2545. In addition to a lack of calculation methods there is a need for measuring material properties.

This paper shall give an overview over the current situation and will provide some guidelines how to rate plastic gears, how to handle the lack of material data available and how to conduct measurements of material properties to make them suitable for the available calculation methods.

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500 Montgomery Street, Suite 350
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October, 2007

ISBN: 978-1-55589-905-9

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Introduction

The number of gears produced out of plastic is getting dramatically larger. This is primarily due to the improvement of plastic materials strength. The properties of plastic can be varied in a large range, especially when compared to steel. It is now possible to select an optimal material for a specific task based on the following properties: strength, wear, stiffness, damping and noise production.

In spite of the growing use of plastic gears the scientific research is astonishingly low, especially compared to the resources used for research on metal gears. A mirror of this situation is the availability of standards. The standard used for the strength analysis of cylindrical plastic gears is the German guideline VDI 2545 and is poor compared to the respective standards AGMA 2001 and ISO 6336 for metal gears. AGMA 909-A06, ANSI/AGMA 1006-A97 and ANSI/AGMA 1106-A97 address plastic gears, but only the geometry. ANSI/AGMA 920-A01 offers much general information about the applicability of plastic material for gears and presents the typical test procedures. The VDI 2545 is currently invalid and fits into the overall lack of research into plastic gearing.

One of the major restrictions of the VDI 2545 is the availability of data for only three different materials (PA12, PA66, POM). Currently several groups are attempting to produce reliable data for modern materials. These experiments have proven to be expensive and are very time consuming. A design engineer therefore needs to know how he can design new plastic gears successfully without the use of a valid standard and without scientific materials research data. The engineer must rely on knowledge gained from past experience.

Usually metal gears are produced in a generating process. Plastic gears most often are injection molded. If the insert for the mold is manufactured with EDM (e.g. wire erosion) the tooth form can be optimized without additional costs. For generated gears this is only possible with special tools, which increases the costs. On the other hand, typical

injection molded gears have a relatively low quality (ISO 9-10), a problem, however, which can be handled with special arrangements. Optimized plastic gear tooth forms are also designated "hybrid toothing" in literature.

Strength analysis

Material data for plastic gears (Wöhler curves or S-N curves)

For the sizing and optimization of gears, the calculation of root, flank and wear strength for the prescribed lifetime are of large importance.

In the same way as with steel gears, for plastic materials the specific parameters (root pulsating strength and flank strength) are dependant on the number of load cycles. For plastic gears these parameters depend strongly on temperature and the type of lubrication (oil, grease or dry running). Where one value for the tooth strength calculation is sufficient for steel, a plastic material requires the necessity of several S-N curves (e.g. for POM figure 1).

The method according to VDI 2545 [1] for the strength analysis of cylindrical gears made of plastic is the only worldwide known method for the calculation solution. Even though it was cancelled some years ago it is still in common use due to the lack of a replacement. Currently Prof. Werner Krause and Dr. Jürgen Wassermann in Germany along with their associates have plans to develop a replacement for the guideline but it is in the very early stages of development.

Today's materials are much more numerous than the materials mentioned in the VDI 2545. Some of them show a significantly higher strength, e.g. reinforced material. Typically, the producer of the material will only provide values for the tensile strength, the aforementioned data for a gear calculation is not known and can not be derived from the tensile strength. Changing the recipe of a plastic might lead to higher ultimate strength, thus increasing the root strength, while the flank or wear resistance is decreasing at the same time due to tribological effects.

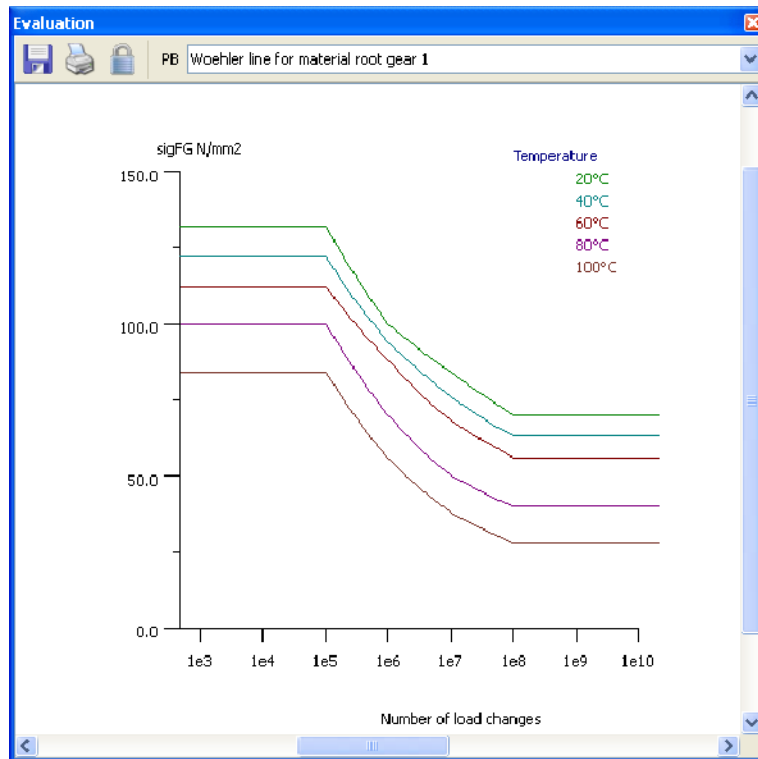


Figure 1. Temperature dependent Wöhler curves for POM.

A simple solution for the problem is not available. The material properties have to be verified using prototypes or by means of a long term test on a test rig. In most cases it is not necessary to conduct hundreds of measurements, to get enough data points for a diagram like in figure 1 but by determining some data points the diagram can be generated by interpolation with good accuracy. These data points can be derived from experience with produced gear boxes or experiments on test rigs. Still the effort is significant.

General layout of the strength calculation of plastic gears

The mechanical properties of plastic parts are strongly dependant on temperature. So for rating plastic gears first the relevant temperature has to be determined. This means that based on the environmental temperature, the local heat production in the meshing of the gear due to frictional and viscoelastic power losses and the dissipation of the heat, the final state of equilibrium must be searched. Figure 2 shows the general layout of the calculation procedure (according to Erhard [2]).

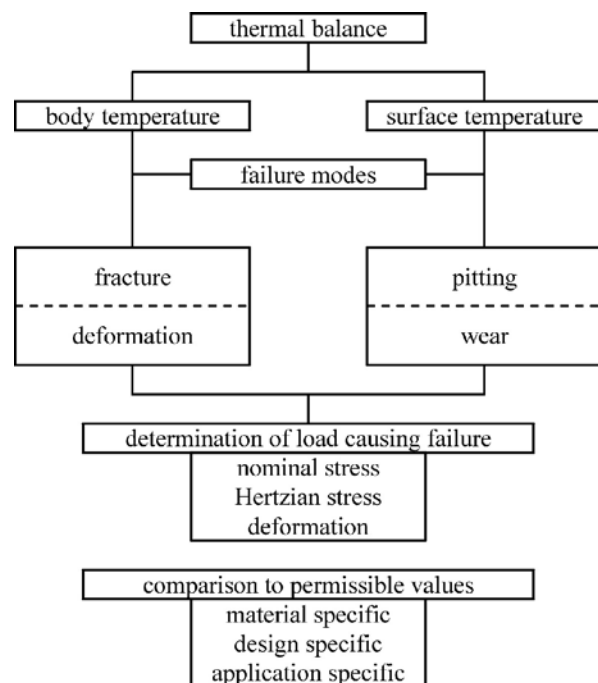


Figure 2. General layout of the strength calculation procedure for plastic parts.

Estimation of the temperature

Several models are available for the calculation of surface and body temperature. For metal gears the flash temperature concept of Blok is used for the calculation of the scoring safety factor. For plastic gears this model was adapted by Siedke [3]. Practical experience however shows that this model may not be appropriate for plastic gears. Takanashi developed equations with an approach containing a friction and a deformation part. The heat production out of the deformation part is based on the model according to Voigt (spring-damping-model). To balance the heat production the dissipation has to be calculated. The difference between heat production and heat dissipation then leads to surface and body temperature. The model according to Takanashi [4] proved to be precise enough for practical application. However, several of the parameters needed are hard to determine. For this reason another model prevailed, based on work of Hachmann and Strickle [5]. The calculation is also based on heat balancing. The assumption is, that the heat quantity Q_1 , which is produced by the power loss in the tooth meshing is equal to the heat quantity Q_2 that is dissipated to the inner space of the gearbox housing. This in turn is equal to the quantity Q_3 which is dissipated by the housing to the environment. This approach leads to a formula, which is also used in the VDI guideline. The factors in the formula differ slightly between original publication, the formula in the VDI guideline and other publications.

$$\delta_{1,2} = \delta_a + 136(P)(\mu) \frac{u + 1}{z_2 + 5} \times \left[\frac{17100}{b(z_{1,2})} \frac{k_2}{(v m)^\kappa} + 6.3 \frac{k_3}{A} \right]$$

Where

$\delta_{1,2}$ [°C] is the surface or body temperature of gear i , $i=1,2$,

δ_a [°C] is the ambient temperature,

P [kW] is the power transmitted,

μ [-] is a coefficient taking friction into account (**not** the friction coefficient!),

z_i [-] number of teeth of gear i , $i = 1,2$,

u [-] transmission ratio z_2/z_1 ,

b [mm] face width,

v [m/s] circumferential speed,

m [mm] normal module,

k_2, κ [-] factors described in the VDI2545, see below,

k_3 [-] takes the influence of the housing into account (none, open, partially open or closed),

A [m²] is the surface of the housing.

Comparison of the results of the temperature calculation according to Hachmann and Strickle and measured temperatures in tests show slightly lower calculated temperatures in the root area, and significantly higher calculated temperature of the flank surface. Frequently, the calculated temperature exceeds the melting temperature of the material, although the test showed no melting of the flank. Erhard and Weiss [6] proposed a modified calculation of the temperature, taking the ratio of the power-on-time into account. Based on measurements, they defined continuous power-on-time of 75 minutes to be permanent running. For all cases with shorter periods they introduced a factor f_{ED} to reduce the calculated temperature. Since this work was done after the publication of the VDI guideline, this correction factor is not included in the calculation formula of the temperature in the VDI 2545.

The factors k_2 and κ show up during the derivation of the formula. They take the material combinations and lubrication type into account. The factor k_2 also determines whether the calculated temperature is the body or the surface temperature. For k_2, k_3, κ and μ tables are provided in the guideline.

The temperature calculation is one of the critical points not only in the VDI 2545, but in the calculation of plastic parts in general. Due to the problems mentioned above it is recommended to use a fixed temperature whenever possible to supersede these problems. For slow running gears (circumferential speed <5 m/s) the guideline recommends the use of ambient temperature.

Most plastic gears are used for very short running period (less than 1% operating time per hour), so that for all these cases the ambient temperature equals to the operating temperature. However, for the ambient temperature a large range might be defined, for example for car applications from -20°C to 80°C.