FAILURE PROBABILITY OF GEAR TEETH WEAR

Milosav Ognjanovic
University of Belgrade
Faculty of Mechanical Engineering

ABSTRACT

In extreme gear service conditions some of the tooth damages such as pitting are not the main type of teeth flank failure any more. The hypothesis concerning infinite fatigue endurance of teeth flanks is without support now. Abrasive wear and squeeze at local points of contact eliminate and/or stop pitting from developing. Three types of surface damages (abrasive wear, squeezing and pitting) occur simultaneously and contribute to each other. In that way, teeth flank failure accelerates and gets more intensive and progressive. Infinite flank endurance does not exist. Besides this, the process of simultaneous (progressive) teeth flank damage is stochastic. Statistical approach to failure intensity evaluation is the only possibility. For certain wear limits of teeth flanks, experimental results are presented by statistical parameters. Those statistical models and statistical parameters are suitable for the development of reliability models of gear and gear drives.

Introduction

Intensive research in the area of the gear damage resistance is resulted with standard DIN 3990 part 5. This standard defines gear testing procedure and endurance limits for different kinds of materials and gear heat and mechanical treatments. Research in this direction is continued [1], [4], but many questions in that very complex area are still without answer. Gear calculation according to the mentioned standard is based on teeth pitting resistance. Fatigue of surface layer (pitting) is the most suitable for the load capacity calculation. In the service conditions and in the testing using FZG gear tester (DIN 51 354), it is not possible to extract fatigue (pitting) damages separately from the others surface damages (sliding wear, surface squeezing, etc.). Besides this, the processes like sliding wear (scoring and scuffing) and surface squeezing obstruct a pitting process. In these conditions, the gear teeth failure process can be slowed down (weakened) or accelerated. For this interaction, it is necessary to research and separately test a pitting process, for example, by using the ZF roller test rig [5] or perform especially those tests which can extract separate (not mixed) types of teeth failure [6]. Detailed research of teeth sliding wear is presented in the paper [2]. The wear depth of the teeth flanks is calculated by using a developed mathematical model.

Complex teeth surface failure is not possible to be defined in a deterministic way. Interaction of individual damage processes is not the same for different stress levels, for different materials, heat and mechanical treatment or lubrication. This interaction is stochastic and can be presented by statistical models and parameters. In this paper, a suggestion in that sense is presented. It is not possible to define complex teeth surface failure in a deterministic way.

Types of Teeth Wear and Wear Components Separation

The gear load capacity is limited by different kinds of teeth flanks wear: pitting, abrasive and adhesive wear (scoring and scuffing) and squeezing. These flank damages are parallel or complementary. For pitting development, it is necessary to start the crack and grow it up along with incrcreatesd high stress cycles number. In the meantime, by sliding or squeezing it is possible to eliminate cracks in the very initial period and slow down the pitting process (especially micro pitting). Each of the mentioned damages can be disturbed or supported by some of the others. Pitting is the damage which corresponds to the gears with surface hardened teeth, at surface stress close to surface endurance limit. Sliding wear (scoring) is characteristic for the gears with non-hardened teeth and with high surface stress. The process of sliding wear is not limited by surface endurance limit. There is no stress level which cannot make surface damage along unlimited stress cycles number (teeth mesh revolution). Scuffing is damage characteristic for highly loaded gears with a very high speed of rotation. Squeezing of gear teeth flanks can arise with not hardened materials caused by a very high flank stress level, especially at a low speed of rotation. More details for each of the mentioned types of teeth flank wear are as follows. The mentioned types of teeth flank wear will be considered in detail.

Conditions for Teeth Pitting

Pitting is the result of the fatigue process in the teeth surface layer. Cracks (Fig. 1) can start between roughness of the surface layer or under the surface layer. According to the Hertzian pressure, the stress maximum is below the surface layer (Fig. 1a). The oil layer affects the reduction the Hertzian pressure and allows to displace point of maximal pressure to the surface (Fig. 1b). It is possible to conclude that in the case of better lubrication the cracks initiate between surface roughness. For this phenomenon, it is necessary to have a high number of stress cycles, i.e. a high level of teeth mesh revolution. The roughness and profile deviation, by micro pitting (Fig. 1b), firstly increase and then some of them grow up and divide (fractured) smaller or larger pieces from the flank. This process can be stopped or slowed down by elimination of micro pitting by sliding wear. In the case of poor lubrication (Fig. 1a), the cracks initiate under the surface layer and need a lesser number of stress cycles (teeth mesh revolution). These cracks can grow up till the very large size and it is difficult to eliminate them by sliding wear. This kind of pitting (Fig. 1a) can occur after a relatively small number of teeth mesh revolutions (mild materials) and after a much higher number of teeth mesh revolutions for surface hardened steels [3][9][10].

The load level affects the surface pressure value. High flank pressure can succeed pitting cracks. At the same time, high pressure can eliminate lubricant between the flanks and succeed sliding wear, which can eliminate initial cracks. For this reason, better conditions for pitting development exist if the contact stress is not much higher than the endurance limit σ_{Hlim}. Pitting test planning has to include the stress levels lower than the endurance limit, stress levels in the endurance limit range and in the stress ranges not much higher than the endurance limit.

Thermal treatment of the teeth surface layers is an important condition for intensity of pitting development. The teeth without surface heat hardening are exposed to sliding wear from the beginning of the service. This wear reduces roughness and pitting cracks in the initial period of micro pitting development. In addition to this, the gear service life is limited by sliding wear. The teeth mesh revolutions during this short service life are not sufficient for the occurrence of fatigue cracks and their development. If the load (surface stress) is higher the sliding wear are more intensive. Conditions for the occurrence of pitting get worse and the pitting probability is smaller. On the other hand, hardened surfaces, for example, carburized teeth are very resistant to sliding wear, the stress cycles number in the service life is very high. This high stress cycle number is enough for pitting development. The pitting probability gets higher if the flank stress level is about the endurance limit. This is an additional condition for pitting development. Taking all this into consideration, pitting probability of hardened teeth is much higher in comparison with not hardened teeth.

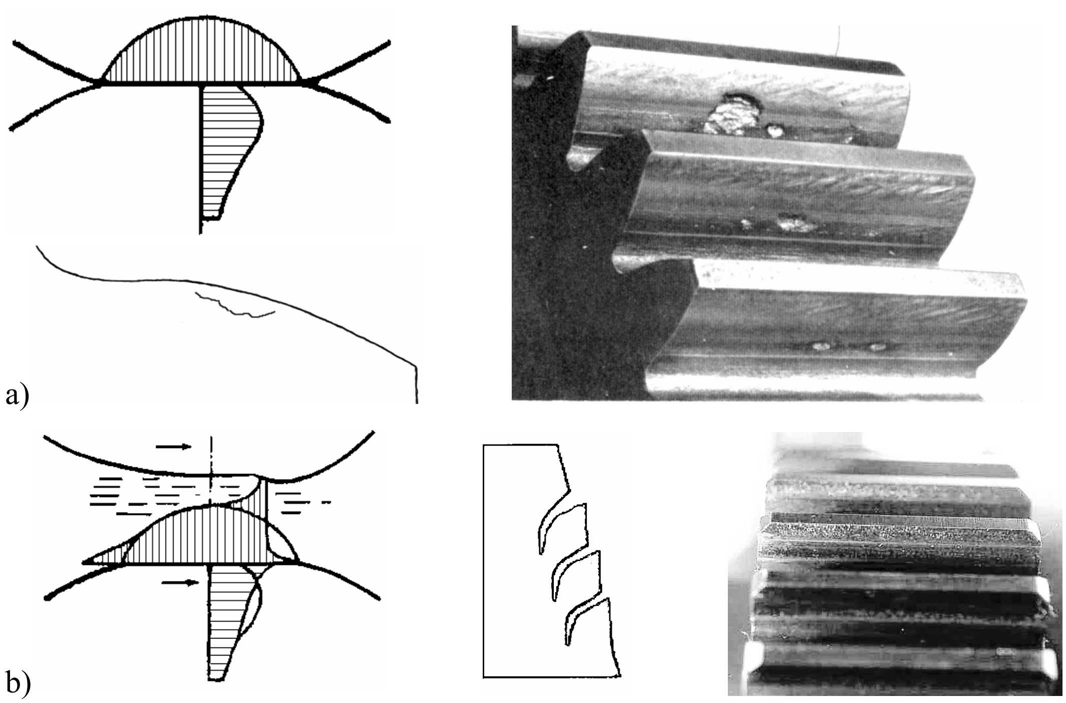


Figure 1. Teeth pitting:
a) Hertzian stress distribution and pitting development
b) Lubricant effect at stress distribution and pitting development

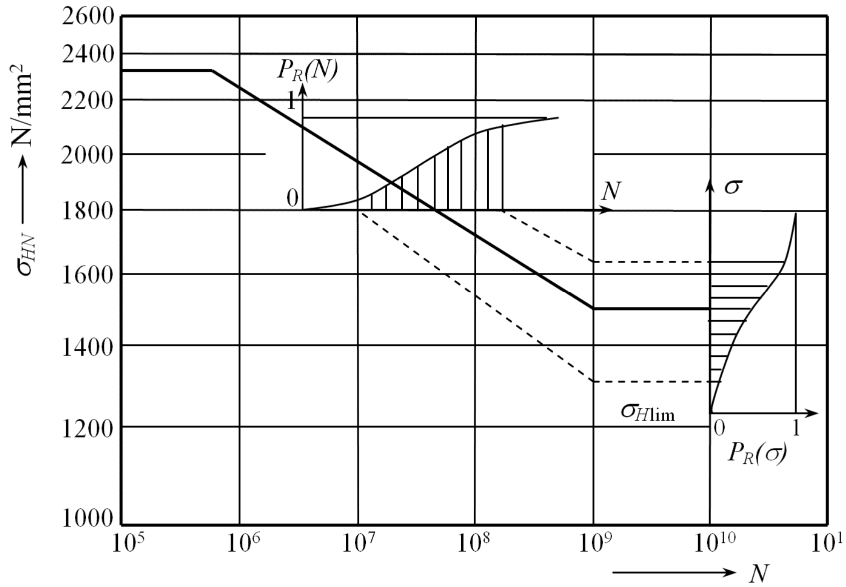
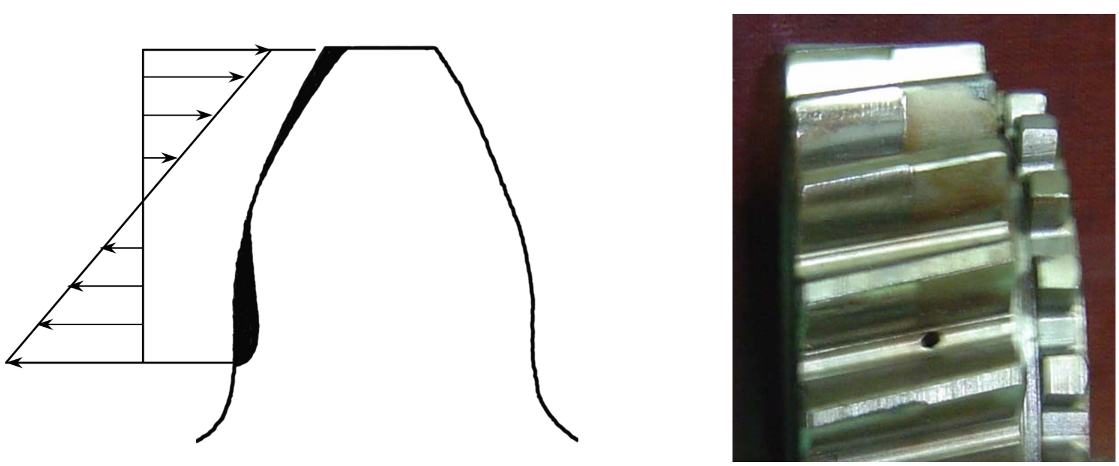


Figure 2. Failure probability distribution of the gears failed by pitting

Teeth Sliding Wear Conditions

The gear teeth sliding speed is depends on the contact point position. In the middle of the teeth flank, the speed is close to zero and at the ends of the flank it is maximal. Sliding wear is also proportional to the contact stress [2]. Surface hardened teeth are resistant to sliding wear, especially carbonized teeth. The effect of sliding wear in this case is very small. Not hardened teeth are not resistant to any type of wear. Sliding wear (especially scoring) is proportional to the sliding speed along the flank (Fig. 3a). The gears without surface hardening are not resistant to pitting wear either, but intensive sliding wear prevents development of surface cracks into full pitting. Figure 4 presents the results of gear flanks endurance based on pitting resistance of not hardened materials. These data can be obtained by the ZF rolling rig. As the sliding slows down the pitting process, not hardened teeth are predominantly damaged by sliding wear. Besides this, sliding resistance is not limited by the endurance limit. That is the reason why this presentation is without the horizontal part of the endurance line. Gear teeth made of not hardened steels are predominantly damaged by sliding wear.



a) b)

Figure 3. Teeth sliding wear:
a) Sliding speed and wear distribution
b) Sliding wear damage of a gear

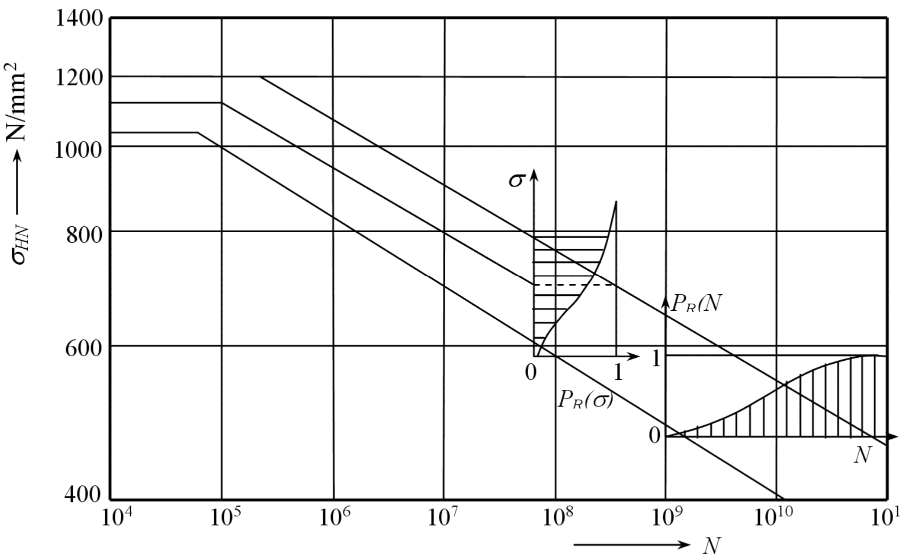


Figure 4. Failure probability distribution of the gear sliding wear

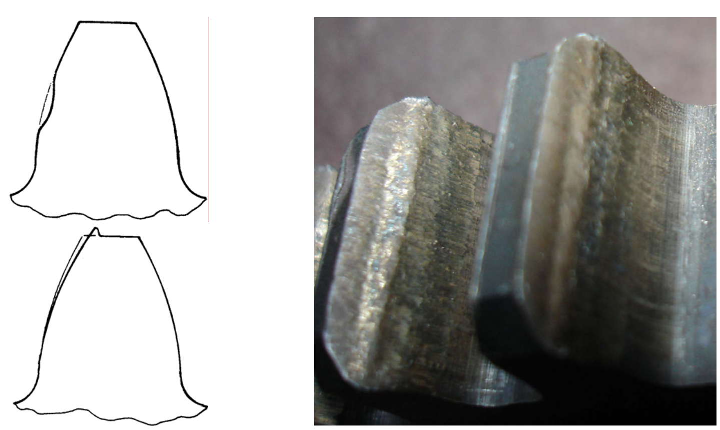
The conditions which can accelerate and succeed teeth sliding wear are lower flank hardness, higher sliding speed, poor lubrication and metal particles present in lubricant. Sliding wear is a continual process which starts from the beginning of the gear service. Surface fatigue cracks which can provoke pitting damage are eliminated by sliding and particles can succeed scuffing damage. The only cracks which can be developed and cause pitting damage are subsurface cracks which are peculiar to poor lubrication [7][8].

Teeth Squeeze Conditions

Teeth squeezing is failure typical for the gears made of steels of small hardness and exposed to high surface stresses. Figure 5a shows squeezing damage in the middle of the teeth flank. At the end of the flank there is the action of strong friction forces which produce high shearing stress. A combination of a normal contact stress and a shearing stress creates more effective surface plastic deformation in this flank region (Fig. 5b).

a)

b)



c)

Figure 5. Teeth squeeze:
a) Squeeze in the middle of teeth flank,
b) Squeeze at teeth addendum area
c) Example of a gear damaged by squeezing

Progressive Teeth Wear

Combination of different kinds of teeth wear with very intensive metal losing (weight reduction), is progressive teeth wear. Intensive teeth scoring at the beginning of the work eliminates flank surface roughness and makes a very smooth flank. At the same time, this process eliminates micro pitting between the roughness. The pitting process is disturbed and the fatigue stress cycles number for high stresses is higher in comparison with pure pitting (compare diagrams in Fig. 7). For the lower stress levels, the fatigue process needs higher stress cycles numbers. Particles relished by pitting, make damage process more intensive (scuffing) in comparison with pitting produced by surface fatigue. This is a combination of pitting and scuffing which wears more material from gear flanks. A hardened layer can be partly or completely eliminated. The soft teeth inside the material and roughness made by pitting and scuffing are liable to squeezing, especially in the area of high stresses. The squeezing process slows down the fatigue (pitting) process and accelerates the scuffing process along the whole teeth flank (Fig. 6).

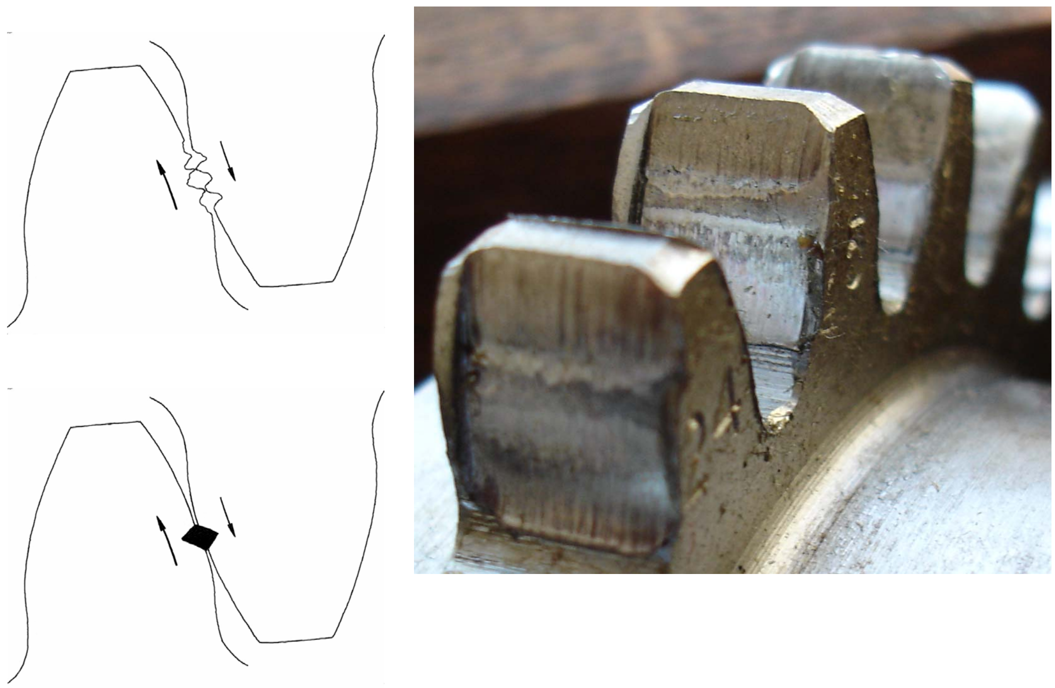


Figure 4. Progressive teeth wear – combination of pitting, scuffing and squeezing

Failure Probability and Reliability Modeling

The first feature of a progressive wear process is stochastic behavior combined of a few elementary wear processes. The second one is that in the service life very severe working conditions are not continual. Periodical service conditions may be presented by the probability of these conditions p. By combining the failure probability P_R of progressive teeth wear and the probability of service conditions p, it is possible to obtain the complex probability $F_p=pP_R$ which defines the probability of progressive wear in service life.

The failure probability is obtained by gear wear testing using the FZG gear tester (back to back system) or another similar system for gear loading and long time testing. Figure 7 presents the results of gear testing in planetary gear drive tested in a back to back system similar to the FZG gear tester. The lower boundary of failure probability distribution is defined by the visible flank failure beginning (10% failure). The upper boundary is defined by the thickness of the layer of teeth flank wear of 0,3 m (m – gear module). Gear teeth is surface hardened and the hardened layer is eliminated by a progressive wear process. Some of the points are obtained by the testing and some of them are defined by approximation. For a more precise definition, it is necessary to perform a number of tests, which will be done in the future. The results presented are compared with the gear endurance limits available in the DIN 3990 for the surface hardened and not hardened steels.

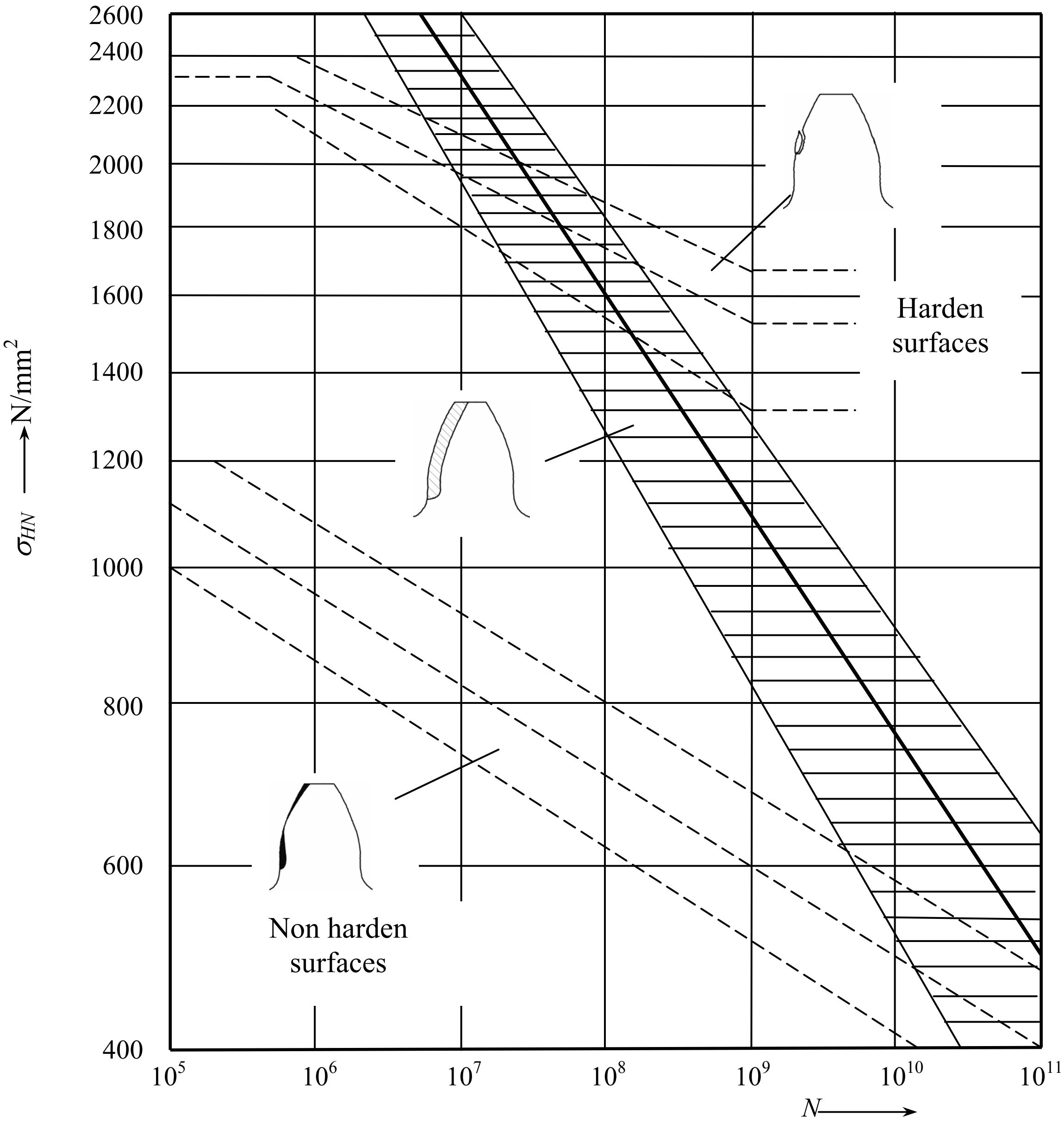


Figure 7. Failure probability of progressive teeth wear

By using the lines of lower and upper failure boundaries, it is possible to obtain Weibull's functions of the failure probability P_R. The function of the stress cycles number (teeth mesh revolution) $P_R(N)$ can be defined for every level of the stress σ_{HN}. For every stress cycle number N (teeth mesh revolution) it is possible to define the following function $P_R(\sigma_{HN})$

$$P_R(N) = 1 - e^{-\left(\frac{N}{\eta}\right)^{\beta}} ; \qquad P_R(\sigma_{HN}) = 1 - e^{-\left(\frac{\sigma_{HN}}{\eta}\right)^{\beta}} \tag{1}$$

The parameters of the Weibull's function η and β are defined by using a coordinate of the points from the boundary lines which include the failure probability 0.1 and 0.9. For example, at the stress level of 1421 N/mm^2, parameters η =2.5·10^8 and β=1.5, i.e.

$$P_R(N) = 1 - e^{-\left(\frac{N}{2.5 \cdot 10^8}\right)^{1.5}} \tag{2}$$

Opposite of this, for the number of cycles to failure N=1.197·10^8, using diagram in Fig. 7, η=1618N/mm^2 and β=8.51, i.e.

$$P_R(\sigma_H) = 1 - e^{-\left(\frac{\sigma_H}{1618}\right)^{8.51}} \tag{3}$$

In the same way it is possible of the every (each) stress level or failure cycle number to define the Weibull's functions of failure probability P_R

Conclusions

Gear load capacity calculation is defined according to the pitting of the teeth flanks. In service conditions, a failure process is combined of a number of damage processes. Which of them will be prevail depends on design parameters, technological and exploitation conditions. Periodically, for some of gears, extremely difficult service conditions exist, which creates a possibility for progressive teeth wear. A process of progressive teeth wear is presented in the paper.

Every type of flank failure corresponds to defined conditions (service, design, technology,…). Results of progressive wear are obtained by experiments. For these results, failure boundaries which can be used for parameters of Weibull's function definition, for different stress levels and for different stress cycles numbers (teeth mesh revolutions) have been defined. For a more precise failure probability definition, it is necessary to perform a great number of teeth failure tests.

References

1. Hohn B.R., Winter H., Laboratories at Work: Institute for Machine Elements, Gear Research Centre (FZG), Tribology journal 3-3, pp 325-340, 1997
2. Floding A., Andersson S., Simulation of Mild Wear in Spur Gears, Wear, Vol.207, pp 16-23., 1997.
3. James,Li. C., Limer J.D., Model-based Conditions Index for Tracking Gear Wear and Fatigue Damage, Wear 241, pp 26-32., 2000.
4. Hohn B.R. , Modern Gear Calculation, - Proceedings of the International Conference on Gears, VDI-Berichte 1665, pp 23-43., 2002.
5. Joachim F., Kurz N., Glatthaar B., Influence of Coatings and Surface Improvements on the Lifetime of Gears, - Proceedings of the International Conference on Gears, VDI-Berichte 1665, pp 565-582., 2002.
6. Podgornik B., Vižintin J., (2002), Wear Reaistance of Plasma and Pulse Plasma Nitrided Gears, - Proceedings of the International Conference on Gears, VDI-Berichte 1665, pp 593-601., 2002.
7. Weck M., Hurachy-Schonwerth O., Bugiel Ch., Service Behaviour of PVD-Coated Gearing Lubricated with Biodegradable Synthetic Ester Oils, - Proceedings of the International Conference on Gears, VDI-Berichte 1665, pp 677-690., 2002.
8. Ding Y., Rieger N.F., Spalling Formation Mechanism for Gears, Wear 254, pp 1307-1317., 2003.
9. Aslantas K., Tasgetiren S., A study of Spur Gear Pitting Formation and Life Prediction, Wear 257, pp 1167-1175., 2004.
10. Komuri M., Kubo A., Takahashi T., Tanaka T., Ichihara Y., Pitting, Chipping and Tooth Breakage due to Edge Contact, - Proceedings of the International Conference on Gears, VDI-Berichte 1904.2, pp 1309-1324.,2005.