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SELECTION OF THE GEAR MATERIALS BASED ON TRIBOLOGICAL ASPECTS

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Abstract: *The aim of this paper is to determine the problems of selecting gear materials due to tribological aspects.Gear performance if profoundly influenced by tribology. Gears are such common machine components they may be taken for granted. It is not generally appreciated that they are complex systems requiring knowledge from all the engineering disciplines for their successful design. Gear design is a process of synthesis in which gear geometry, materials, heat treatment, manufacturing methods and lubrication are selected to meet the requirements of a given application. The constructor must design the gear with adequate strength, wear resistance and scuffing resistance thus gear tribology must be considered. The gear design is responsible for the initial selection of material and heat treatment but the finalization of both material and thermal processing must be a joint effort. This paper will give some answers to these questions and will show how the gear design first approaches the problem of material selection and heat treatment technology, as influenced by the performance, life requirements of the gear set and tribology aspects. The research shown in the paper will also enhance the ability of both the gear design engineer and the gear metallurgist to better grasp their relative, related critical roles in the exciting world of gear processing, heat treatment and inspection. Interspersed of the research shown in the paper will be examples of gear related problems, failures, and improved processing procedures. Analyses and comments on a number of relevant failures is given.*

Keywords: *gear materials, tribology, pitting, abrasive wear, scoring, plastic deformation*

1. INTRODUCTION

Basic task of the gears sets are to transmit rotation and torque from one to another using a so called form connection which is in this case represented by the teeth in contact. Gear power transmitter can be used in a wide diapason of speeds and loads, thus ensuring high kinematic accuracy, working continuance, and reliability needed in different exploitative conditions. They are the widest spread elements of power transmitters, and they are a part of many machines and devices, and reliability of the whole systems depend largely on theirs characteristics. The development of transmission is characterized by continuously increasing levels of torque and power, lightweight design, increasing life, improved efficiency and low noise requirements. These demands altogether with tribological aspects make selection of the gear materials complex element of the gear design. In order for gears to achieve their intended performance, life and reliability, the selection of a suitable gear material is very important. Gears are made of various materials depending upon their usage in diverse applications. The final selection should be based upon an understanding of material properties and application requirements. If you are looking for a high performance gear with reliable operation, the selection of suitable material is very important. Based on applications, gears for high load capacity require a tough and robust material like carbon steel etc. Whereas, high precision gears require materials having lower strength and hardness rating.

To reduce wearing and damaging of transmission elements they have to be oiled. The lubricant may be considered as constructive element and thus it is very important to know the composition of lubricants, their properties and effects.

Dissipative processes occurred in that way are demonstrated in unwanted effects which can be identified in loss of material, energy, moving, functionality and reliability, reduce of life and increase of maintenance coasts.

1.1 Lubricants as constructive elements

Choice of lubricants for gear power transmitter is a very complex work and depends on a large number of parameters. The highest influence to choice of lubricant quality is requirements on various lubricant characteristics meeting specific aspects of design and results of gear power transmitter. [1]

Reduce of friction on contact surfaces and its consequences may be reached by use of adequate lubricant formulation also. [1]

The aim is to define a connection between properties of contact surfaces and lubricant oil characteristics as well as to recognize their effect to tribological characteristics of contacts at various lubricating conditions. Thus, model test results of various material variants of contact pairs and the lubricant should enable to make choice of optimal combinations which are to be tested on real parts in the transmission of power. [1]

It has already been said that use of a quality lubricant is necessary but not a sufficient condition to reach a reliable and a long work life of a gears. One of a principal condition is coordination and optimization of materials, heat and other treatments of surfaces with characteristics of lubricants at load conditions.

Such standpoint brought a definition of the research methodology that has an aim to define a connection between characteristics of the contact surfaces (type of a material, heat treatment, roughness...) and characteristics of the lubricants and to recognize their influences on contact tribology characteristics. This includes model test and tests on real systems. [1]

For investigations of the power loss and measuring of the gear bulk temperatures the test rig has to be fitted with the relevant measurement devices. These are a torque load and a torque loss sensor, a revolution sensor, an oil temperature sensor and gear bulk temperature sensors for pinion and wheel. Gear bulk temperature is measured with PT 100 temperature sensors, which are mounted approximately 6 mm below the tooth tip of the low-loss gears. Figure 1 shows a drawing of the modified FZG gear test rig. [7]

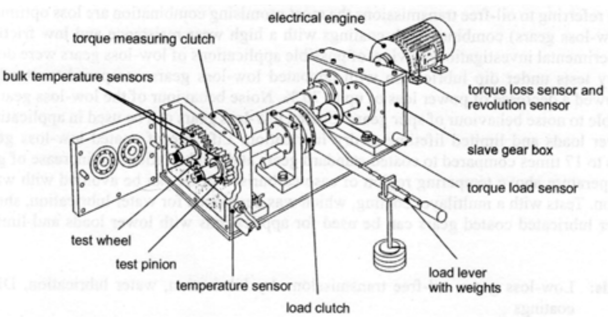

Figure 1. Modified FZG gear test rig [7]

1.2 Coatings

To avoid wear and damaging the low-loss gears were coated with different coatings. The used coating process for all investigated coatings was a PVD-process (Physical-vapour-deposition process). A PVD-process allows coating temperatures below or near the tempering region of a case carburised steel and therefore tempering of case carburised gears during the coating process can be avoided. Table 1. show the main properties of the coatings, which were used for the investigations at dry lubrication. [7]

Table 1. Main properties of coatings investigated at dry lubrication [7]

Parameter	Unit	Diaraor®	Balinit C®	Dynamant®
Coating material	-	ta-C	a-C:H:W	a-C:H:X
Microhardness	HV	5500-6000	1000	3000
Coating thickness	µm	≈ 5	1-4	≈ 2,5
Coating process temperature	°C	< 150	180-200	150-250

The coatings Balinit C® and Dynamant® are commercial coatings, the coating Diamor® was developed [7]. Diamor® is the hardest coating with a microhardness of 5500 HV to 6000 HV. It is a hydrogen-free tetrahedral amorphous carbon coating. Coating thickness is about 5 µm and coating process temperature is below 150 °C. To get a sufficient coating adhesion an ultra-thin adhesion layer was deposited on the bulk material. Balinit C® is the coating with the lowest hardness; the microhardness is about 1000 HV. The coating is an amorphous hydrogenated carbon coating with tungsten as a metallic part. Thickness is between 1 µm and 4 µm and the coating process temperature is between 180 °C and 200 °C. For a sufficient coating adhesion a chromium adhesion layer is used. The hardness of Dynamant® is with 3000 HV between the Diamor® and Balinit C® coating. It is also an amorphous hydrogenated carbon coating with additional elements. Coating thickness is about 2.5 µm and coating process temperature is between 150 °C and 250 °C. [7]

The main advantage of water lubrication is the avoidance of a temperature increase in the tooth contact due to the cooling effect of water. Table 2 shows the main properties of the developed multilayer coating for water lubrication.

Table 2. Main properties of coating for water lubrication [7]

Parameter	Unit	IWTid819
Coating material	-	CrN + a-C:H
Plastic ultra-microhardness	GPa	13
Coating thickness	μm	≈ 5,5 (CrN) + ≈ 5 (a-C:H)
Coating process temperature	°C	< 140

The coating consists of a chromium adhesion layer, a chromium-nitride transition layer and an amorphous carbon layer with an amorphous hydrogenated carbon top layer. Between the amorphous carbon layer and the amorphous hydrogenated carbon top layer there is a gradient transition. Plastic ultra-microhardness is about 13 GPa, coating thickness of the chromium-nitride transition layer is about 5.5 μm and of the amorphous carbon layer with the amorphous hydrogenated carbon top layer is about 5 μm. Coating temperature is below 140 °C. [7]

2. CLASSIFICATION OF GEAR TOOTH FAILURE MODES

To obtain optimum minimum weight gear-sets, the gear constructor must be aware of the intricate details of many competing modes of failure as non lubrication - related failure and lubrication-related failure

Nonlubrication-related failures include both overload and bending fatigue types of failure. Lubrication-related failures include fatigue caused by Hertzian contact stresses, wear, and scuffing. Many gear failures are known by several names and qualifying terms, such as initial, moderate, destructive, and so on.

This chapter is concerned with gear tooth failures that are influenced by friction, lubrication, and wear as tribology aspects. Pitting or scuffing may cause the gear teeth to decline and generate dynamic forces, which in turn cause the gear teeth to fail by bending fatigue. In these cases, the bending failure is secondary and not directly related to lubrication, whereas pitting or scuffing are the primary failure modes, and both are definitely influenced by lubrication.

Although corrosion, fretting - corrosion, cavitation, and electrical discharge damage are influenced by lubrication, occur relatively rarely in gear teeth. Hence, only the following failure modes are considered because of importance: fatigue caused by Hertzian contact stresses (including pitting and micropitting); wear (including adhesion, abrasion, and polishing); scuffing.

2.1 Pitting

Pitting is a common failure mode for gear teeth because they are subjected to high Hertzian contact stresses and many stress cycles. Pitting is a fatigue phenomenon that occurs when a fatigue crack initiates either at the surface of the gear tooth or at a small depth below the surface as shown in Fig.1.

Figure 1. Pitting of gear teeth [11]

The crack usually propagates for a short distance in a direction roughly parallel to the tooth surface before turning or branching to the surface. When the cracks have grown to the extent that they separate a piece of the surface material, a pit is formed. If several pits grow together, the resulting larger pit is often referred to as a "spall".

To extend the pitting life of gears the constructor must keep the contact stress low and the material strength and lubricant specific film thickness high.

2.2 Micropitting

Micropitting can be found on relatively soft gear tooth surfaces, fatigue caused by Hertzian contact stresses forms large pits. In many cases, micropitting is not destructive to the gear tooth surface (Figure 2.). It sometimes occurs only in patches and may stop after the tribological conditions have been improved by running. The micropits may actually be removed by mild polishing wear during running-in which case the micropitting is said to "heal".

The specific film thickness is the most important parameter that influences micropitting. Damage seems to occur most readily on gear teeth with rough surfaces, especially when they are lubricated with low-viscosity lubricants.

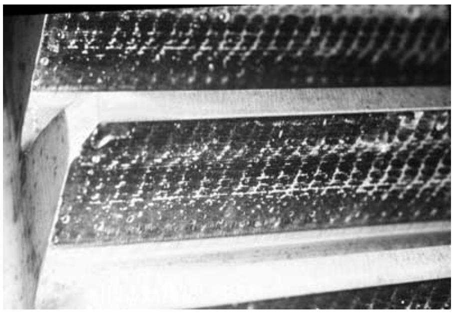

Figure 2. Micropitting of tooth surfaces [11]

To prevent micropitting the specific film thickness should be maximized by using smooth gear tooth surfaces, high-viscosity lubricants, and high speeds. Experiments have shown that flame-hardened and induction-hardened gears have less resistance to micropitting than carburized gears of the same hardness. This is probably due to the lower carbon content of the surface layers of the flame-hardened and induction-hardened gears.

2.3 Wear

Gears are susceptible to wear caused by adhesion, abrasion, and polishing.

Adhesive adhesion wear is classified as "mild" if it is confined to the oxide layers of the gear tooth surfaces. If, however, the oxide layers are disrupted and bare metal is exposed, the transition to severe adhesive wear usually occurs. Severe adhesive wear is termed scuffing. Here we assume that scuffing has been avoided through proper design of the gears, selection of the lubricant, and control of the running-in process.

When new gear units are first operated, the contact between the gear teeth is not optimum because of unavoidable manufacturing inaccuracies. If the tribological conditions are favourable, mild adhesive wear occurs during running and usually subsides with time, resulting in a satisfactory lifetime for the gears. The wear that occurs during running-in is beneficial if it smoothes the tooth surfaces (thereby increasing the specific film thickness) and if it increases the area of contact by removing minor imperfections through local wear as shown in Fig.3.

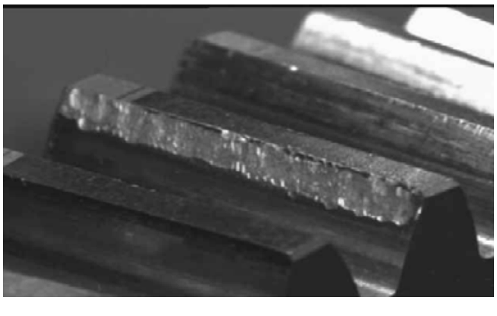

Figure 3. Wear as failure mode for gear teeth [11]

Wear is considered excessive when the tooth profiles wear to the extent that high dynamic loads occur or the tooth thickness is reduced to the extent that bending fatigue becomes possible.

As prevention of adhesive wear the following recommendations serve as guidelines: use smooth tooth surfaces; if possible, run-in new gears by operating the first 10 hours at one-half load; use high speeds if possible. Otherwise, recognize that highly loaded slow-speed gears are boundary lubricated and are especially prone to excessive wear. For these conditions, specify nitride gears and the highest permissible lubricant viscosity.

Abrasive wear on gear teeth is usually caused by contamination of the lubricant by hard, sharp-edged particles.

Abrasive wear due to foreign contaminants, such as sand or internally generated wear debris, is called three-body abrasion and is a common occurrence. Two-body abrasion also occurs when hard particles or asperities on one gear tooth abrade the opposing tooth surface.

Polishing wear is also one of the tooth failure modes. If the extreme-pressure (HP) antiscuff additives in the lubricant are too chemically reactive, they may cause polishing of the gear tooth surfaces until they attain a bright mirror finish. Although the polished gear teeth may look good, polishing wear is undesirable because it generally reduces gear accuracy by wearing the tooth profiles away from their ideal form. Antiscuff additives used in lubricants to prevent scuffing are sulphur and phosphorus. They function by forming iron-sulphide and iron-phosphate films on areas of the gear teeth where high temperatures occur. Ideally, the additives should react only at temperatures where there is a danger of welding. If the rate of reaction is too high, and there is a continuous removal of the surface films caused by very fine abrasives in the lubricant, the polishing wear may he excessive.

2.4 Scuffing

Scuffing is defined its localized damage caused by solid-phase welding between sliding surfaces. It is accompanied by the transfer of metal from one surface to another due to welding and tearing. It may occur in any sliding and rolling contact where the oil film is not thick enough to separate the surfaces. The symptoms of scuffing are microscopically rough, matte, and torn surface. Surface analysis that shows transfer of metal from one surface to the other is proof of scuffing (Fig.4.).

If the lubricant film is insufficient to prevent significant metal-to-metal contact, the oxide layers that normally protect the gear tooth surfaces may be broken through, and the bare metal surfaces may weld together. The sliding that occurs between gear teeth results in tearing of the welded junctions, metal transfer, and catastrophic damage.

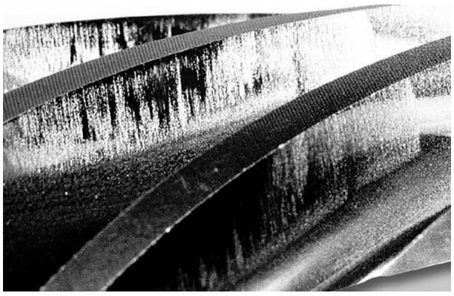

Figure 4. Scuffing of gear teeth surface [11]

In contrast to pitting and bending fatigue, which only occur after a period of running time, scuffing may occur immediately upon start-up. The gear constructor can maximize scuffing resistance by optimizing the gear geometry so that the gear teeth are as small as possible, consistent with bending strength requirements, to reduce the temperature rise caused by sliding. Nitride steels are generally found to have the highest resistance to scuffing, whereas stainless steels are liable to scuff even under near-zero loads. The thin oxide layer on stainless steel is hard and breaks up easily under sliding loads, exposing the bare metal and thus promoting scuffing. Hardness does not seem to be a reliable indication of scuffing resistance.

3. GEAR MATERIAL

Gear materials can be broadly classified as non metallic and metallic materials. Metallic gear materials can be further subdivided into ferrous, or iron-base alloys, and nonfenous alloys. The most commonly used ferrous alloys are the wrought surface-hardening and through-hardening carbon and alloy steels. Other ferrous alloys used for gears are cast irons, cast steels, powder metallurgy irons and steels, stainless steels, tool steels, and merging steels.

3.1 Wrought gear steels

Wrought steel is term applied to carbon and alloy steels which are mechanically worked into form for specific applications. In general, there are two types of wrought gear steels: surface-hardening and through-hardening grades. The surface-hardened steels are hardened to a relatively thin cast' depth and include carburizing, nitriding, and carbonitriding steels. Surface hardening steels include plain carbon and alloy steels with carbon content generally not exceeding 0.25% C.

Through-hardening steels may be comparatively shallow hardening or deep hardening, depending on their chemical composition and method of hardening. Through-hardening steels include plain carbon and alloy steels with carbon content ranging from 0.30 to approximately O.55% C.

3.2 Surface-Hardening Steels

Carbonized easy-hardened gears are best suited for heavy-duty service, for example, transmission gears, and offer high resist to wear, pitting, and fatigue. Surfaces must be sufficiently hard to resist wear and of sufficient depth to prevent case crushing. A rough rule for case depth is that it shall not exceed one-sixth of the base thickness of the tooth. A case-hardened gear provides maximum surface hardness and wear resistance and at the same time provides interior toughness to resist shock. In general, case-hardened gears can withstand higher loads than through-hardened gears, although they are lighter and less expensive because of the simpler heat treatment required. The following factors must be considered when selecting a case-hardened gear: high tooth pressures will crack a thin case; too soft a core will not provide proper backing for a hard case; compressive stresses in the case improve fatigue durability, and a high case hardness increases wear resistance; if the ratio of case depth to core thickness is too small excessive stresses in subsurface layers can produce poor fatigue life; residual tensile stresses are highest with low core hardness and increase with increasing case depth. These stresses can be relieved by tempering.

3.3 Carburizing Steels

Carburizing is a very important commercial heat-treating operation that is used to modify the surface chemistry of components manufactured from ferrous alloys by the processes of carbon absorption and diffusion. The process is carried out at a temperature sufficient to render the steel austenitic generally between 850 and 950 ^{0}C followed by quenching and tempering to form a high-carbon martensitic structure. The increase in carbon content of a carburized surface layer results in a substantial change in the properties of the effected volume of material. The carburized case will be harder, will be more resistant to abrasive wear and will exhibit improved fatigue properties compared with the unaffected core. These variations in properties are quite useful in applications where a hard, wear-resistant surface is needed and where a softer, more ductile core is required to prevent catastrophic failure.

3.4 Nitriding steels

Nitriding is a surface-hardening heat treatment that introduces nitrogen into the surface of steel at a temperature range of 500 to 550 °C while it is in the ferritic condition. Thus, nitriding is similar to carburizing in that surface composition is altered, but different in that nitrogen is added into fertile instead of austenite. Because nitriding does not involve heating into the austenite phase field and a subsequent quench to form martensite, nitriding can be accomplished with a minimum of distortion and with excellent dimensional control. Nitriding steels can be used in many gear applications where a hard, wear-resistant case, good fatigue strength, low score sensitivity and some degree of corrosion resistance are desired. In addition, nitriding steels make it possible to surface harden the teeth of large gears having thin sections that might be impractical to carburizing and quench. Nitride gears are relatively free from wear up to the load at which surface failure occurs, but at this load they become badly crushed and pitted. Thus, nitride gears are generally not suitable for applications where overloads are likely to be encountered.

3.5 Through-Hardening Steels

By benefit of their higher carbon content, through-hardening steel gears possess greater core strength than carburized gears. They are not, however, as ductile or as resistant to surface compressive stresses and wear as case-hardened gears. Hardness of gear surfaces may vary from 300 to 575 HB. Through-hardened steels may also be effectively surface hardened by induction heating or by flame hardening. When selecting a through-hardening steel, it should he considered that a higher carbon and alloy content is accompanied by greater strength and hardness (but lower ductility) of the surface and the core. Fully hardened and tempered medium-carbon alloy steels possess an excellent combination of strength and toughness at room temperature and at lower temperatures. Because of their good hardenability and immunity to temper brittleness molybdenum steels have been widely used for gears requiring good toughness at room and low temperatures.

4. CONCLUSIONS

Gear design is a process of synthesis in which gear geometry, materials, heat treatment, manufacturing methods, and lubrication are selected to meet the requirements of a given application. The constructor must design the gear with adequate strength, wear resistance, and sculling resistance. To do this, gear tribology must be considered. The choice of 1ubricant and its application method is as important as the choice of material and heat treatment. The interrelationship of the following factors must be considered: gear tooth geometry, kinematics, gear tooth forces (static and dynamic), gear tooth material and surface characteristics (physical and chemical), lubricant characteristics and environmental characteristics.

Gear material requirements are:
processing characteristics; response to heat; resistance to tooth bending fatigue, both low-cycle and high-cycle fatigue; resistance to surface-contact fatigue; resistance to rolling contact fatigue; resistance to wear; their hot hardness; their bending strength and bond ductility; their toughness, both impact toughness and fracture toughness.

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