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Gears — Wear and damage to gear teeth —

Part 2: Supplementary information

Engrenages — Usure et défauts des dentures —

Partie 2: Informations supplémentaires

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 60, *Gears*, Subcommittee SC 1, *Nomenclature and wormgearing*.

This first edition of ISO/TR 10825-2, together with ISO 10825-1, cancels and replaces ISO 10825:1995, which has been technically revised.

The main changes are as follows:

— ISO 10825:1995 has now two parts: ISO 10825-1 and ISO/TR 10825-2 that gives additional information on failure modes.

A list of all parts of the ISO 10825 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document has been developed to assist readers in identifying possible causes of gear tooth damage and potential ways to avoid future damage. However, it is not intended to give a definitive reason for the damage observed. Some causes that are included are still a topic of research and discussion but are presented with the intent to provide possibilities. Also, in some cases, steps taken to reduce the risk of one type of damage can increase the risk of another type of damage.

This document is intended as a supplement to ISO 10825-1. To facilitate the correlation of the information in the two parts, both documents have the same structure. Some sections in this document are mainly place holders to keep the structures parallel.

Gears — Wear and damage to gear teeth —

Part 2:
Supplementary information

1 Scope

This document provides information on gear tooth wear and damage. The material contained herein is intended to help the user better understand damage to gear teeth, but the potential reasons for damage and preventive measures discussed are not definitive. Also, for individual cases, other reasons for damage or measures can exist that are not mentioned in this document. At the same time, reasons for damage or measures mentioned in this document are not always of importance. In many cases, damage can be the result of multiple interacting factors. Some causes that are included are still a topic of research and discussion but are presented with the intent to provide possibilities.

The solution to many gear problems involves detailed investigation and analysis by specialists; this document is not intended to replace such expert knowledge.

2 Normative References

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10825-1, *Gears — Wear and damage to gear teeth — Part 1: Nomenclature and characteristics*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10825-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org

4 Overview and warnings

4.1 Overview

Gears can be damaged by a wide variety of mechanisms. Damage can range from insignificant damage that can be ignored to damage that makes the gearset unusable. The term “gear failure” is subjective and a source of considerable disagreement. In the case of flank surface damage, there is no single definition of gear failure, since whether a gear is considered to have failed depends on the specific application. When there are only small changes to the surface, such as gear teeth that have a bright, mirrorlike appearance, by observing them, one can think the gears have “run-in” properly. However, another observer can think the gears have failed by polishing wear. There are numerous ways that the tooth surface can change over time. Whether the gears are considered failed or not depends on how much change is tolerable.

Fracture, where part or all of a tooth or teeth breaks off, can occur as a result of flawed material, as a result of a single application of high stress, as the result of fatigue which initiates a crack at the tooth surface, or as the result of fatigue which initiates a crack below the tooth surface. These cases are treated separately.

Load is a crucial factor for gears, so all influence factors increasing either the local or global load of a gear are important. Some examples are torsional vibrations, external forces transmitted through gear shafts, acceleration and overload.

The statements on what can be done to mitigate the chance of wear and damage to gear teeth that are given in this document are not recommendations or requirements, since the application determines what is appropriate. If a gearset has an extremely low chance of damage from a particular cause, then it makes no sense to try to reduce the chance of failure from that cause. There are a number of clauses in this document that contain a summary of methods that in some cases have been observed to reduce the risk of wear or damage. Depending on the situation, it can be that none is appropriate and rarely, if ever, would all of them be followed. The statements in this document are often based on experience, and many are not covered by the respective standards or calculation methods.

4.2 Warnings

The methods given for reducing the risk of a given damage or failure mode are specific to that mode, and implementation can sometimes worsen or create other damage or failure modes. Changes can have unintended consequences, both on the gears and other components in a gearbox, so it is prudent to thoroughly evaluate any proposed remedy prior to implementation and then test and evaluate after implementation.

This document is based on experience with steel gears; however, many of the damage and failure modes discussed apply to gears made from other materials.

This document is not intended to be used in determining blame for a failure. In many cases, blame is impossible to determine. A gear failure can be caused by events completely outside of the gears, by the interaction of the gearbox with the connected equipment, by gearbox systems or components other than the gears, by the materials used, by the manufacturing process (including heat treatment) or by the design of the gears. For example, an "overload" failure can be due to an insufficient gear design or to power above the gear rating being imposed on the gears, and it cannot be possible to conclusively determine the root cause.

NOTE "gear" throughout this document means gear wheel or pinion unless the gear is specifically identified.

5 Tribological damage (non-fatigue)

5.1 General

Non-fatigue tribological damage is often referred to as wear. It can occur as the result of particles entrained in the lubricant, particles embedded in the teeth of the mate, insufficient oil film thickness, or loss of lubricant. Wear is the removal of material from the tooth surface and, as described in ISO 10825-1, it can range from mild polishing to destruction of the gear teeth.

In some applications, no wear is acceptable. However, in other applications, mild wear is considered normal. Moderate and sometimes even severe wear are acceptable in some applications.

5.2 Polishing

5.2.1 General

Polishing is fine-scale abrasion (see Reference [22]) that causes gear teeth to have a bright mirrorlike finish. Based on the severity, polishing can be categorized as mild, moderate or severe. If extreme, polishing can reduce tooth thickness to where the top land of teeth is a knife-edge.

When a hard surface mates with a soft surface, polishing can preferentially occur on the hard surface because the abrasives embed in the soft surface and create two-body abrasion on the hard surface.

Polishing can be promoted by chemically aggressive additives when the lubricant is contaminated with fine abrasives (see Reference [22]). Although the polished gear teeth can look good, polishing wear can be undesirable if it reduces gear accuracy by wearing the tooth profiles away from their ideal form. Antiscuff additives that contain sulfur or phosphorous are used in lubricants to prevent scuffing, see 4.5.1. They function by forming iron-sulfide and iron-phosphate films on areas of gear teeth where high temperatures occur. Ideally, the additives 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, polishing wear can become excessive (see Reference [22]).

Polishing can be prevented by using less chemically active additives (see Reference [23]) and clean oil. Antiscuff additives that are appropriate for the service conditions can reduce polishing. When dispersed material, such as some antiscuff additives is used, monitoring can be used to detect if this beneficial material is precipitating or being filtered out. Abrasives in the lubricant can be removed by using fine filtration or frequent oil changes.

5.2.2 Summary of methods that have been observed to reduce the risk of polishing

The following methods can be considered for reducing the risk of polishing:

— using a less chemically aggressive additive system;

— removing abrasives from the system;

— case hardened surfaces for pinion and gear;

— sufficient lube oil film thickness (e.g. viscosity, speed).

5.3 Scratches

Scratches can be caused by improper handling or assembly procedures, or by a piece of hard or abrasive material going through the mesh.

5.4 Abrasive wear

5.4.1 General

Abrasive wear, also known as abrasion, is the removal or displacement of material due to the presence of hard particles (such as metallic debris, scale, rust, sand or abrasive powder) in the gear unit. The particles can be loose (suspended in the lubricant) or embedded in the surface of the gear teeth.

Abrasive wear causes scratches or gouges on the tooth surface that are oriented in the direction of sliding. Under magnification, the scratches appear as parallel furrows that are smooth and clean.

Two-body abrasion occurs when embedded particles or asperities on one gear tooth abrade the opposing tooth surface. Abrasion due to loose contaminants is called three-body abrasion. Generally, two body abrasion is more damaging than three-body abrasion because the abrasive is fixed in one body and it abrades directly on the other body. Three-body abrasion is generally much less severe because the abrasive can roll, slide and vary its approach angle.

NOTE Abrasive wear is not limited to gear teeth; it can also severely degrade bearings, seals and other components. Abrasion of bearings can promote damage to gear teeth by causing misalignment.

5.4.2 Sources of particles that cause abrasive wear

Contamination can enter gear units by being present at assembly, internally-generated, ingested through breathers and seals, carried by the lubricant from an improperly cleaned lubrication system or inadvertently added during maintenance.

Sand, scale, rust, machining chips, grinding dust, weld splatter or other debris can find their way into new gear units.

Internally generated particles are usually wear debris from gears, bearings or other components due to Hertzian fatigue, adhesive wear and abrasive wear. The wear particles can become more abrasive as they become work hardened when they are trapped between the gear teeth. Internally-generated wear debris can be minimized by using accurate, surface-hardened gear teeth (with high macropitting resistance), smooth tooth surfaces and clean appropriate viscosity lubricants.

5.4.3 Methods for reducing abrasive wear

5.4.3.1 General

Clean lubricant is essential to prevent abrasive wear. Foreign particles in the lubricant are damaging to gears, bearings and seals and can cause a decline in the integrity of the geared system.

Magnetic plugs can be used to capture ferrous particles that are present at start-up, or are generated during operation. Periodic inspection of the magnetic plug can be used to monitor the development of ferrous particles during operation. Magnetic wear chip detectors with alarms are also available.

Careful maintenance and monitoring of the lubrication system can ensure that the gears receive an adequate amount of cool, clean, uncontaminated lubricant. Contamination can be removed by draining and flushing the gearbox lubricant and changing the lubricant filter (if there is one) after an appropriate time of operation. Usually, the gearbox manufacturer recommends the appropriate time interval for changing the filter or changing the lubricant. For circulating-oil systems, fine filtration helps to remove contamination. Very fine filtration has been used to significantly increase gear life, however the finer the filtration the higher the pressure loss. Offline filters (kidney-loop type systems) can also be used to clean oil. They efficiently remove very small particles (finer than what is achievable with other filters) because they process only a small amount of the total flow rate. They can use electrostatic agglomeration systems to reduce the amount of very fine particles that normally would pass through filters. Other systems can be used to remove water from the oil. Fine filtration can remove some beneficial additives from some lubricants; the lubricant supplier can be consulted regarding the filtration level and filter type.

The lubricant can be changed or processed to remove contaminants and maintain additive levels. For mineral based lubricants, water is normally considered a contaminant. For oil-bath gear units, changing the lubricant is the only way to remove contamination, which is usually done frequently. The lubricant needs to be changed more frequently when the operating temperature is high. See ISO/TR 18792 for additional information. For critical gear units a regular program of lubricant monitoring can be used to assess lubricant condition. The lubricant monitoring can include such items as spectrographic and ferrographic analysis of contamination along with analysis of acidity, viscosity and water content. Used filter elements can be examined for wear debris and contaminants.

Breather vents are used on gear units to relieve internal pressure that occurs when air enters through seals or when the air within the gearbox expands and contracts during normal heating and cooling.

Locating a breather vent with a filter in a clean, non-pressurized area can prevent ingression of airborne contaminants. A desiccant in the vent can remove water. In especially harsh environments, the gearbox can sometimes be completely sealed, and the pressure variation can be accommodated by an expansion chamber with a flexible diaphragm.

Contamination of the gear unit can be minimized by providing an environment as clean as possible when performing any maintenance procedures that involve opening any part of the gear unit or lubrication system.

Unless the tooth surfaces of a surface-hardened gear are smoothly finished, they can act like files if the mating gear is appreciably softer. For this reason, a worm is polished after grinding before it is run with a bronze worm wheel.

5.4.3.2 Summary of methods that have been observed to reduce the risk of abrasive wear

The following methods can be considered for reducing the risk of abrasive wear:

- minimizing lubricant contamination by:
  - flushing unit thoroughly before initial operation;
  - removing built-in contamination from new gear units by draining and flushing the lubricant after an appropriate period of operation (per gearbox manufacturer and lubricant supplier), then refilling with clean recommended lubricant and replacing the filter if there is one;
  - minimizing internally generated wear debris by using surface-hardened gear teeth, smooth tooth surfaces and high viscosity lubricants with suitable additives;
  - minimizing ingested contamination by maintaining oil-tight seals and using filtered breather vents located in clean, non-pressurized areas;
  - minimizing contamination that is added during maintenance by using good housekeeping procedures;
- circulating-oil systems by:
  - using fine filtration in consultation with the gearbox manufacturer and lubricant supplier;
  - using an offline (kidney loop) filter to remove very small particles;
  - using an agglomeration system to remove very fine particles;
- maintaining the lubricant by:
  - changing or processing the lubricant to remove water contamination;
  - for oil-bath systems, changing the lubricant as recommended by the gearbox manufacturer, or as determined by lubrication sampling analysis;
  - monitoring the lubricant with spectrographic and ferrographic analysis together with analysis of acidity, viscosity and water content. Oil sampling is the best method for determining lubrication changing intervals.

5.5 Scuffing

5.5.1 General

Scuffing is severe adhesion that can occur in gear teeth when they operate in the boundary lubrication regime. If the lubricant film is insufficient to prevent significant metal-to-metal contact, the tribofilms and oxide layers that normally protect the gear tooth surfaces can be broken through, and the bare metal surfaces can weld together. The sliding that occurs between gear teeth results in tearing off the welded junctions, metal transfer from one tooth surface to another, and damage.

In contrast to Hertzian fatigue and bending fatigue, which only occur after a period of running time, scuffing can occur immediately upon start-up. In fact, gears are most vulnerable to scuffing when they are new, and their tooth surfaces have not yet been preconditioned by running-in. To reduce the chance of scuffing, new gears can be run-in under partial load. In some cases, a gradual series of steps of increasing load and speed to reduce the surface roughness and allow the formation of tribofilms on the teeth before the full load is applied. There have been reports of substantial increases in scuffing resistance due to proper run-in. The gear teeth can be coated with iron-manganese phosphate or plated with copper or silver to reduce the risk of scuffing during the critical running-in period. The use of an oil with an antiscuff additive can be useful during running-in to both help prevent scuffing and to promote polishing. However, if a different oil is used for running-in, at the end of the running-in period, the gearbox is normally completely drained and flushed so only the recommended oil is present during normal operation.

The basic mechanism of scuffing is not fully understood, but there is general agreement that it is caused by frictional heating generated by the combination of high sliding velocity and intense surface pressure. Critical temperature theory (see Reference [27]) is often used for predicting scuffing. It states that scuffing occurs in gear teeth that are sliding under boundary-lubricated conditions, when the maximum contact temperature of the gear teeth reaches a critical magnitude.

For mineral oils without antiscuff additives, each combination of oil and gear tooth material has a critical scuffing temperature that is constant regardless of the operating conditions (see Reference [28]). The critical scuffing temperature is not always constant for synthetic lubricants and lubricants with antiscuff additives, and so needs to be determined from tests that closely simulate the operating conditions of the gears or with in-situ tests on the actual gears.

Most antiscuff additives are sulfur-phosphorous compounds, which form boundary-lubricating films by chemically reacting with the metal surfaces of the gear teeth at local points of high temperature. Antiscuff films help prevent scuffing by forming solid films on the gear tooth surfaces and inhibiting true metal-to-metal contact. The films of iron sulfide and iron phosphate have high melting points, allowing them to remain as solids on the gear tooth surfaces even at high contact temperatures.

The rate of reaction of the antiscuff additives is greatest where the gear tooth contact temperatures are highest. Because of the sliding action of the gear teeth, the surface films are repeatedly scraped off and reformed. In effect, scuffing is prevented by substituting mild corrosion in its place. Antiscuff additives can promote micropitting. Some antiscuff additives can be too chemically active and promote polishing wear (see 5.2). This can necessitate a change to less aggressive antiscuff additives that deposit a boundary film without reacting with the metal. Lubricant specialists can be consulted for further guidance.

Gear units that have friction plate clutches or backstops can, in some cases, be negatively affected if additives that change the coefficient of friction are used in the lubricant. The gearbox manufacturer and lubricant supplier can be helpful in determining if a change from one lubricant to another is advisable.

For mineral oils without antiscuff additives, the critical scuffing temperature increases with increasing viscosity and ranges from 150 °C to 300 °C. The increased scuffing resistance of high-viscosity lubricants is believed to be due to differences in chemical composition rather than increased viscosity. However, a viscosity increase also helps reduce the risk of scuffing by increasing elastohydrodynamic lubrication (EHL) film thickness and reducing contact temperature generated by metal-to-metal contact.

Methods to calculate critical temperature are given in ISO/TS 6336-20 and ISO/TS 6336-21. ISO 14635 gives test methods to determine scuffing resistance of gear lubricants.

Lack or loss of lubricant and insufficient cooling effect (quantity, direction of injection) can also cause scuffing.

In some cases, initial scuffing can occur but then stop developing during further operation.

Scuffing can change the material characteristics of a shallow layer near the surface, with rehardening and/or tempering, which can lead to other damage or failure modes.

Nitriding can lead to improved scuffing resistance due to the change in chemical composition of the surface layer, provided the white layer remains in place (i.e. it is not removed by grinding after the final nitriding process). Carburizing and induction hardening do not have the same effect as nitriding, but for some designs, these hardening methods are preferred.

5.5.2 Methods for reducing the risk of scuffing

Anything that reduces either the bulk temperature or the flash temperature reduces the total contact temperature and lessens the risk of scuffing. Higher viscosity lubricants or smoother tooth surfaces help by increasing the specific film thickness, which in turn reduces the frictional heat, and therefore the flash temperature. The lubricant coefficient of friction and additive package strongly contribute to scuffing probability.

The lubricant performs the important function of removing heat from the gear teeth. It can only do this effectively if it is supplied to the gear teeth in a manner that removes heat rapidly and maintains a low bulk temperature. A heat exchanger can be used with a circulating oil system to cool the lubricant before it is sprayed at the gears (see Reference [29]).

Scuffing resistance can be increased by optimizing the gear geometry such that the gear teeth are as small as possible, consistent with bending strength requirements, to reduce the temperature rise caused by sliding. The amount of sliding is proportional to the distance from the pitch point and is zero when the gear teeth contact at the pitch point, and largest at the ends of the path of action. Profile shift can be used to balance and minimize the temperature rise that occurs in the addendum and dedendum of the gear teeth. The temperature rise can also be reduced by modifying the tooth profiles with tip relief, root relief, or both to ease the load at the start and end of the engagement path where the sliding velocities are the greatest. Also, gear teeth that are accurate, held rigidly in good alignment, and provided with lead modification to minimize the local tooth loading and temperature rise are less prone to scuffing.

The gear materials also influence scuffing resistance. Steels that have been nitrided are generally found to have high resistance to scuffing. Nitriding steels containing aluminium have the highest resistance to scuffing. Some stainless steels can scuff even under near-zero loads. The thin oxide layer on these stainless steels is hard and brittle and it breaks up easily under sliding loads, exposing the bare metal, thus promoting scuffing. Anodized aluminium and titanium also have low scuffing resistance. Hardness alone does not seem to be a reliable indication of scuffing resistance.

The initial run-in of gearing can be critical to ensuring long term service life, which is why many manufacturers provide recommended run-in procedures.

5.5.3 Summary of methods that have been observed to reduce the risk of scuffing

The following methods can be considered for reducing the risk of scuffing:

— reducing pitch line velocity;

— using smooth tooth surfaces produced by careful grinding, honing, polishing or chemically assisted polishing;

— running-in new gearsets following manufacturer's recommendations;

— protecting the gear teeth during the critical run-in period by use of a special lubricant, coating (such as iron-manganese phosphate), or by plating (such as copper or silver);

— using clean oil;

— using lubricants of adequate viscosity for the operating conditions;

— using lubricants that contain adequate antiscuff additives;

— cooling the gear teeth by supplying an adequate amount of cool lubricant evenly cooling the complete flank surface. For circulating-oil systems, using a heat exchanger to cool the lubricant;

— optimizing the gear tooth geometry for scuffing resistance by using small teeth, profile shift and profile modification;

— using accurate gear teeth, rigid gear mountings, profile modification, and lead modification to obtain uniform load distribution during operation;

— avoiding use of stainless steel, aluminium or titanium alloys since they greatly increase the risk of scuffing;