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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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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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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).

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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;

— using nitriding. For improved scuffing resistance, if gear accuracy requirements allow, the white layer resulting from nitriding can be left in place.

5.6 Adhesive wear (Adhesion)

5.6.1 General

When new gear units are first operated, the contact between the gear teeth cannot be optimum because of manufacturing inaccuracies. If the tribological conditions are favourable, mild adhesive wear occurs during run-in and subsides with time, resulting in a satisfactory lifetime for the gears. The wear that occurs during run-in is beneficial if it creates smooth tooth surfaces (increasing the specific film thickness) and increases the area of contact by removing minor imperfections through local wear. Run-in performed in accordance with the manufacturer's recommendations is usually beneficial. An effective run-in requires a proper combination of partial load, partial speed and sufficient time. Following run-in, the lubricant is usually drained and the gearbox flushed to remove wear debris, and the filter, if present, changed before refilling the gearbox with the recommended lubricant. An alternate is to use an external filtration system to clean the oil.

The amount of wear that is considered tolerable depends on the application. The wear is considered excessive when the tooth profiles wear to the extent that high dynamic loads are encountered, or the tooth thickness is reduced to the extent that tooth failure by bending fatigue becomes imminent, or the gears generate excessive noise or vibration.

Many gears, because of practical limits on lubricant viscosity, speed and temperature, operate under boundary-lubricated conditions where some wear is inevitable. Reference [21] indicates that highly-loaded, slow speed (less than 0,5 m/s pitch line velocity), boundary-lubricated gears are especially prone to excessive wear. The problem can also affect gears operating at up to 2 m/s pitch line velocity. Tests with slow-speed gears (see Reference [21]) have shown that nitrided gears have good wear resistance whereas carburized and through-hardened gears have similar, but lower wear resistance than nitrided gears. The combination of a carburized and a through hardened gear that are oil lubricated has lower resistance to wear in low speed applications. Reference [21] concluded that lubricant viscosity has a large influence on slow-speed, adhesive wear. It found that high viscosity lubricants reduce the wear rate significantly. It also found that some chemically aggressive additives that contain sulfur-phosphorous antiscuff additives can be detrimental with very slow-speed (less than 0,05 m/s) gears, giving higher wear rates than expected. In some cases with low speeds, adhesion can look like polishing with a resulting mirrorlike finish. However, not all sulfur-phosphorous containing additives are detrimental under these same conditions, the lubricant manufacturer can help recommend the proper lubricant for the application.

Some gear units operate under ideal conditions with smooth tooth surfaces, high pitch line speed and high lubricant film thickness. It has been observed, for example, that turbine gears that operated almost continuously at 150 m/s pitch line speed still had the original machining marks on their teeth even after operating for 20 years. However, most gears operate in the regime of boundary mixed-film lubrication, under elastohydrodynamic lubrication (EHL) conditions. In the EHL mixed film regime, provided that the proper type and viscosity of lubricant is used, the wear rate usually reduces during running-in and adhesive wear virtually ceases once running-in is completed. If the lubricant is properly maintained (kept cool, clean and dry) the gearset usually does not suffer any further adhesive wear damage.

Under certain conditions, adhesion can cause continuous removal of surface films and oxide layers, resulting in severe wear (see Reference [21]).

Adhesive wear can be due to mild interference creating metal to metal contact. More serious interference can cause plastic deformation. See 8.13.

5.6.2 Summary of methods that have been observed to reduce the risk of adhesive wear

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

- reducing surface roughness by:
  - using smoother tooth surfaces;
  - running-in new gearsets by operating initially at partial load;
- optimizing geometry by:
  - using high pitch line speeds if possible. Highly-loaded, slow-speed gears are boundary lubricated and especially prone to excessive wear;
- optimizing metallurgy by:
  - using nitrided gears if they have adequate capacity;
- avoiding combinations of hard and soft materials on oil lubricated slow speed gears;
- optimizing lubricant properties by:
  - draining and flushing the lubricant after the run-in period to remove wear debris, refilling with recommended lubricant, and replacing the filter element if there is one;
  - using lubricants with appropriate additives;
  - using an adequate amount of cool, clean and dry (free of water) lubricant of the highest viscosity permissible for the operating conditions;
  - lowering mesh lubrication temperature by:
    - improving the cooling;
    - using a lubricant that provides a lower coefficient of friction.

5.7 Fretting corrosion

5.7.1 General

Fretting corrosion (often referred to as just fretting) is localized wear of contacting gear flanks that are pressed together and subjected to cyclic, relative motion of extremely small amplitude. Under these conditions, lubricant squeezes from between the surfaces, and the motion of the surfaces is too small to replenish the lubricant. Natural, oxide films that normally protect surfaces are disrupted, permitting metal-to-metal contact, and causing adhesion of surface asperities.

The fretting that occurs on gear teeth is the same as that which can occur on bearing raceways and rollers, in joints that are bolted, keyed, or press-fitted and in splines or couplings. It occurs under specific conditions where the gears are not rotating and are subjected to structure-borne vibrations such as those encountered during transport, or in parked wind turbines (see References [24] and [25]).

The initial period of fretting corrosion can be referred to as false brinelling. For lubricated contacts, under fretting conditions, false brinelling begins an incubation period of mild adhesive wear under boundary lubrication. If the contact becomes starved for lubrication, it can be subjected to severe adhesive wear known as fretting corrosion.

5.7.2 False brinelling

False brinelling is also known as stand still marks. Fretting begins with an incubation period during which the wear mechanism is mild adhesion that is confined to the natural oxide layer that covers steel. When there is a lack of oxygen, the wear debris is iron oxide magnetite (Fe_3O_4), which is black and highly magnetic. Magnetite discolours the lubricant surrounding the contact and forms a black, greasy film. Damage during incubation is false brinelling (see Reference [24]), and it has distinctly different morphology than true brinelling. False brinelling is characterized by dents that do not have raised shoulders. Furthermore, the original machining marks within the dents are worn away by mild adhesive wear. The dents are created by wearing off preexisting and continually reforming oxide films (see Reference [24]). Generally, the damage caused by false brinelling is negligible and the wear rate is low. False brinelling occurs on gear teeth and bearing components when they are not rotating but oscillating through extremely small angles.

True brinelling is a separate damage mode that is unrelated to false brinelling.

5.7.3 Fretting corrosion

Wear debris from false brinelling accumulates in the oil meniscus surrounding the contact. If the amount is sufficient to dam lubricant from reaching the contact area, the lubricating regime changes from boundary lubrication to unlubricated. Once the lubricant within the contact area is depleted by oxidation, the wear rate increases dramatically until the natural oxide layer is broken through. Then strong welds are formed between the asperities of the parent iron components and damage escalates to fretting corrosion. Relative motion breaks strongly-welded asperities and generates extremely small wear particles that oxidize to form the iron-oxide hematite (αFe_2O_3); a non-magnetic powder that has the fineness and reddish-brown colour of cocoa. The wear debris is hard and abrasive, and is in fact the same composition as jeweller's rouge (see References [24] and [25]), and polishing wear (see Reference [22]) (fine scale abrasion) is frequently found around the periphery of a fretting corrosion scar. Hematite discolours the lubricant surrounding the contact and forms rouge-coloured paste. Usually, the wear scar is discoloured with black or reddish films.

Fretting corrosion damages gears by forming ruts along lines of contact. During operation, damaged gears can generate sharp, hammering noise as the wear scars pass through the contact areas. For example, fretting corrosion can occur when gears are in mesh under load and vibrating without significant relative rotation. When the ruts are severe, the gears can be noisy when they rotate.

Pits from fretting corrosion create local stress concentrations that can cause macropitting or initiate fatigue cracks, which if in high tensile stress areas, can propagate to failure. Generally, fretting corrosion reduces fatigue strength significantly.

If rolling element bearing fits are inadequate to stop relative motion between the inner ring and shaft, or between the outer ring and housing, fretting corrosion can develop at these interfaces. In a similar manner, fretting corrosion can also occur between a gear bore and shaft if there is inadequate interference.

False brinelling and fretting corrosion can often be avoided by stopping the vibration, rotating the components to entrain fresh oil, or both. Each time the components entrain fresh oil, the incubation period restarts, and the wear regime shifts to mild adhesive wear. The length of the incubation period depends on the lubricant type and how easily lubricant reaches the contact.

For unlubricated contacts, there is no incubation period, and fretting corrosion can start immediately. The wear rate can be high from the beginning.

5.7.4 Summary of methods that have been observed to reduce the risk of fretting

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

— stopping the vibration, rotating the components to entrain fresh oil, or both;

— for reciprocating systems such as yaw drives or actuators, ensuring the angular motion is sufficient to wipe fresh lubricant into the contact;

— avoiding micro motions between otherwise stationary mated gears;

- ensuring adequate interference fit between shafts and couplings, gears, bearing rings, and other interference-fit components;
- using case hardening or surface hardening to obtain adhesion-resistant surfaces (nitriding is best);
- using physical or chemical vapor deposition (PVD or CVD) hard coatings to obtain adhesion-resistant surfaces;
- using cold work, case hardening or shot peening to induce compressive residual stresses;
- using a lubricant with antiwear additives;
- using oil rather than grease and using a high-pressure jet to flood the contact and flush away wear debris;
- storing the gearbox in a vibration-free environment;
- supporting the gearbox on vibration isolators;
- shipping the gearbox with shafts locked to prevent any motion;
- shipping the gearbox on an air-ride truck.

5.8 Interference wear

When there is only a small amount of gear mesh interference, interference wear can occur. When there is interference, the gears are forced together and there is no chance for the lubricant to keep them separated. See 8.13.

6 Fatigue damage

6.1 Fatigue cracks

Fatigue cracks initiate and propagate under the influence of repeated cyclic or alternating stresses that are below the yield strength (on a macroscopic level) of the material. These cracks can appear at or below the surface on tooth flanks or in tooth root fillets. Non-fatigue-initiated cracks can sometimes propagate slowly like a fatigue-initiated crack.

Fatigue is often characterized as low cycle, high cycle or very high cycle fatigue. The number of cycles at the borders of these areas vary depending on material and heat treatment. For gears, fatigue can be classified as either bending fatigue or contact fatigue.

6.2 Contact fatigue

6.2.1 General

Repeated stresses generated by Hertzian contact in combination with forces caused by sliding and pressure distribution in the lubricating film can cause surface or subsurface fatigue cracks and the detachment of material fragments from the gear tooth surface. The exact mechanism is not fully understood.

6.2.2 Micropitting

6.2.2.1 General

Micropitting is a phenomenon that occurs in Hertzian type of rolling and sliding contact that operates in mixed elastohydrodynamic or boundary regimes. It is more commonly observed on materials with a high surface hardness. Specific film thickness (lambda ratio (λ)) is an important parameter for micropitting that is influenced by many other parameters, see ISO/TS 6336-22. It is a fatigue phenomenon caused by cyclic stresses and plastic flow on the asperity scale (see References [21], [33], [34], [35], [36], and [37]). Micropitting generates numerous surface cracks that grow at a shallow angle to the surface. Micropits form as small pieces of material break off from the surface. The micropits are small relative to the size of the Hertzian contact zone, typically of the order of 10 µm – 20 µm deep. The micropits can coalesce to produce a continuous fractured surface which typically appears as a dull, matte, surface during unmagnified visual inspection.

Micropitting is influenced by:

- operating conditions during run-in and service;
  - load;
  - load distribution;
  - speed, both rolling and sliding;
  - tooth flank temperature;
  - specific film thickness;
- gear properties;
  - gear tolerance class;
  - macrogeometry (basic tooth dimensions);
  - microgeometry (tooth modifications);
  - surface topography (texture, waviness and roughness);
  - instantaneous coefficient of friction;
  - surface hardness;
  - metallurgy at the surface (including any coatings);
- properties of run-in and service lubricants;
  - lubricant viscosity and rheology;
  - lubricant chemistry, both base stock chemistry and additive chemistry;
  - lubricant cleanliness.

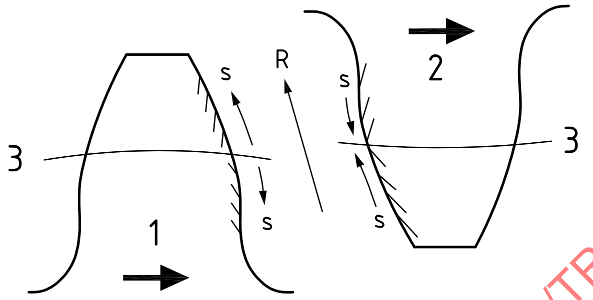
In addition to Hertzian stress due to normal loading, sliding between gear teeth causes traction forces that subject asperities to shear stresses. Some theories suggest that as a result there can be an incubation period during which damage consists primarily of plastic deformation at asperities. Macroscopically, surfaces appear glazed or glossy. Microscopically, the original machining marks can be partially or totally obliterated as the result of plastic deformation. Cyclic Hertzian and shear stresses accumulate plastic deformation on asperities and at shallow depths below asperities. Plastic flow produces tensile residual stresses, and with sufficient cycles, fatigue cracks initiate.

Micropits can rapidly nucleate, grow and coalesce. Periodic inspection of gear tooth surfaces can disclose a steady rate of surface deterioration. Damage can be extreme after a relatively short running time. However, in some cases, the development of micropits stops.

To the unaided eye, micropitted surfaces appear dull grey, etched, frosted, matte or stained with patches of gray. Under magnification, the surface appears to be covered by very fine pits and cracks.

The inclined crater floors reflect light preferentially. Therefore, intense directional lighting is used to disclose micropitting. Different lighting angles can emphasize features. Metallurgical sections cut transversely through micropits show fatigue cracks start at or near the gear surface and grow at a shallow angle (typically 10° to 30°, but sometimes as steep as 45°) to the surface. The cracks typically extend deeper than the visible micropits. A micropit forms when a branch crack connects the main crack with the surface and separates a small piece of material.

Like macropitting, micropitting cracks grow opposite to the direction of sliding at the gear tooth surface, see Figure 1. Because slide directions reverse as the pitch line is crossed, micropitting cracks grow in opposite directions above and below the pitch line. If micropitting grows across the pitch line, it makes the pitch line readily discernible because the opposite inclinations of the floors of micropit craters scatter light in opposite directions above and below the pitch line. See ISO 10825-1, Figure 26.



Key

1 driving gear
2 driven gear
3 pitch line
s sliding direction
R rolling direction

Figure 1 — Crack orientation due to rolling and sliding contact (figure from Reference [33])

External, internal, spur, helical, and bevel gears are susceptible to micropitting. Micropitting can occur with all surface heat treatments including carburized, nitrided, flame hardened and induction hardened. See ISO 10825-1, Figures 23 to 25. With through hardened gears micropitting rarely occurs, and generally only on gears that are above conventional hardness. Experiments (see Reference [21]) have shown that flame-hardened and induction-hardened gears have less resistance to micropitting than carburized gears of the same hardness. This can be due to the lower carbon content of the surface layers of flame-hardened and induction-hardened gears.

Gear teeth dedenda are vulnerable to micropitting, especially along the start of active profile (SAP) and the lowest point of single tooth pair contact (LPSTC). However, micropitting can occur anywhere on the active flanks of gear teeth (see Reference [33]).

There can be micropitting only on the pinion, only on the gear, or on both. Generally, the gear with the roughest surface causes micropitting on the mating gear, especially if it is harder than the mating gear.

Micropitting does not always lead to catastrophic failure. It can occur only in patches and can arrest after the tribological conditions improve after running-in. Mild polishing can remove micropits and smooth tooth surfaces due to wear. In these cases, wear can suppress micropitting. However, arrest is unpredictable, and micropitting can reduce gear tooth accuracy, increases noise, and can escalate to scuffing or full-scale macropitting that can subsequently lead to larger cracks and tooth breakage (see References [21], [34], [35]).

Specific lubricant film thickness (λ) is an important parameter in the evaluation of micropitting. Damage occurs most readily on gear teeth meshing with teeth that have rough surfaces, especially when they are lubricated with low-viscosity lubricants. Surface roughness is a very important influence parameter. Gear pairs finished with special grinding wheels (see Reference [36]) or other processes to mirrorlike finish have reduced possibility of micropitting. See ISO/TS 6336-22 for a proposed rating method.

Gears running at low speed are prone to micropitting because their elastohydrodynamic lubrication (EHL) film thickness is low. Maximizing specific film thickness by using smooth gear tooth surfaces, high-viscosity lubricants, and if possible, high pitch line velocity can help prevent micropitting. ISO/TR 18792 and Reference [18] give recommendations for viscosity as a function of pitch line velocity.

Run-in is critical because it is the incubation period for micropitting. During incubation, contacts between asperities on opposing surfaces occur frequently, causing plastic deformation of asperities; the principle cause of micropitting. In addition, adhesion and abrasion at asperities generate wear debris.

According to some theories, using a series of increasing loads allows progressive reduction of roughness through the action of mild adhesion and limited plastic deformation. This controlled run-in minimizes plastic deformation while limiting adhesion and abrasion to the iron oxide layer covering asperities. Mild adhesion consists of small junctions that generate wear particles smaller than the surface roughness. If adhesion remains mild, asperities are eventually flattened by adhesion and plastic deformation, and subsequent deformation remains elastic for that particular load. Then, when run-in is complete, asperities carry the load solely by elastic deformation.

If adhesion causes strong bonds that break through oxide layers, adhesion escalates to scuffing, large wear particles are generated, and surfaces become rougher rather than smoother.

The run-in properties are likely to depend on lubricant chemistry, temperature, and sliding velocity, so experiments on actual gears are necessary to determine a good run-in lubricant. Experiments (see Reference [37]) have shown that zinc dialkyldithiophosphate (ZnDTP) antiwear additives can be detrimental to run-in.

For some lubricants, water contamination can promote micropitting in gears, and can reduce the anticorrosion, EHL film formation, and friction reducing properties of lubricants. This can be a result of the water adversely interacting with the additives.

6.2.2.2 Summary of methods that have been observed to reduce the risk of micropitting

The following is a summary of methods for mitigating and preventing micropitting. Not every measure is achievable or applicable for a given application.

- specific film thickness can be maximized by:
  - increasing oil film thickness by:
    - using the highest practical oil viscosity;
    - running gears at high speed if possible;
    - reducing gear tooth temperature;
    - choosing lubricant operating viscosity and lubricant chemistry to achieve higher operating film thickness. Both the gearing manufacturer and lubricant supplier are normally consulted before switching lubricants.
  - reducing surface roughness by:
    - avoiding shot-peened flanks unless the flank surface is finished after shot peening;
    - honing or polishing gear teeth, or burnishing by running gears against a hard, smooth master;
    - making the hardest gear as smooth as possible;
    - coating teeth with iron-manganese phosphate, copper, or silver to limit adhesion and scuffing risk;
    - running-in with a special lubricant without ZnDTP antiwear additives;
    - pre-filtering lubricant and using a fine filter during run-in;

  - keeping oil cool during run-in;
  - running-in gears using a series of increasing loads and appropriate speed;
  - draining lubricant and flushing the gearbox after run-in, changing the filter if there is one, and filling with clean service lubricant.
- optimizing gear geometry by:
  - using helical gears with overlap ratio $\varepsilon_\beta \geq 2{,}0$;
  - minimizing Hertzian stress by specifying high accuracy and optimizing centre distance, face width, pressure angle, and helix angle;
  - using profile shift to minimize specific sliding;
  - using proper profile and lead modification;
- optimizing metallurgy by:
  - using a high amount of retained austenite for case carburized gears;
- optimizing lubricant properties by:
  - using oil with sufficient micropitting resistance as determined by tests, such as DIN 3990-16;
  - using oil with low traction coefficient;
  - using oil with high pressure-viscosity coefficient;
  - avoiding oils with aggressive antiscuff additives;
  - keeping oil at appropriate temperature;
  - keeping oil clean, i.e. free from solid contaminants;
  - keeping oil free of water contamination.

6.2.3 Macropitting

6.2.3.1 General

Pitting due to Hertzian fatigue can start after a very high number of load cycles. Therefore, gears are designed for a defined lifetime with a suitable stress safety factor. Rating methods for macropitting are given in ISO 6336-2.

6.2.3.2 Methods for reducing the risk of macropitting

6.2.3.2.1 General

The macropitting life of a gearset can be prolonged by keeping the Hertzian stress low, material strength high, material relatively free of inclusions, and the lubricant specific film thickness high. The face width and the radius of curvature, which is influenced by geometric variables such as diameter, number of teeth, pressure angle and helix angle, can be optimized to lower the Hertzian stress. Material alloys and heat treatment can be selected to obtain hard tooth surfaces with high strength, such as carburizing or nitriding. Maximum macropitting resistance is obtained with carburized gear teeth because they have hard surfaces, and carburizing induces beneficial compressive residual stresses that lower the apparent shear stresses. Adequate lubricant specific film thickness can be obtained by using smooth tooth surfaces with an adequate supply of the proper temperature, clean and dry (free of water contamination) lubricant that has sufficiently high viscosity and sufficiently high pressure-viscosity coefficient.

Macropitting can initiate at the surface or at a subsurface defect, such as a nonmetallic inclusion. With gear teeth, macropits are most often surface-initiated because the film thickness is usually low, resulting in a relatively high degree of metal-to-metal contact. Interaction between asperities and contact at defects, such as nicks, furrows, or dents creates surface-initiated, rather than subsurface initiated cracks. Point Surface Origin (PSO) macropitting is often caused by geometric stress concentration (GSC) (see Reference [31]).

For high-speed gears with smooth tooth surfaces, elastohydrodynamic lubrication (EHL) film thickness is greater and subsurface initiated macropitting, rather than surface-initiated macropitting, can predominate. In these cases, macropitting usually starts at a subsurface inclusion, which acts as a point of stress concentration. Cleaner steels such as those produced by vacuum remelting, increase macropitting life by reducing the size and number of inclusions. See 6.2.6.2 for a discussion of inclusions.

The chemistry of the base lubricant and the additive package can have an influence on macropitting, especially when the film thickness is low, but the mechanism by which this occurs is not fully understood. See Reference [17] for a description of a test method for lubricant effect on macropitting. Contamination from water in the lubricant promotes macropitting, and solid particles in the lubricant also promote macropitting by indenting tooth surfaces, causing stress concentrations and disrupting the lubricant film.

6.2.3.3 Summary of methods that have been observed to reduce the risk of macropitting

— The methods to reduce macropitting are similar to those to reduce micropitting, see the list in 5.2.2, except optimal coating and lubricant chemistry can differ for macropitting.

— Higher surface hardness generally leads to higher macropitting resistance, up to a limiting value.

NOTE Excessive surface hardness can lead to other problems, such as risk of hardening cracks on induction hardened gears and risk of grinding cracks, see 9.3.

— For surface hardened gearing, ensuring adequate surface hardness and case depth after final processing is helpful.

— There are many material parameters that influence macropitting. For additional information on gear materials and macropitting strength values, see ISO 6336-5.

6.2.3.4 Combined macropitting and wear

When there is high sliding velocity, it can be difficult to separate the usual effects caused by contact pressure fatigue, which stresses both the surface and subsurface of tooth flanks, and the wear effect on their surface caused by sliding which only stresses the surface of the teeth. This is most likely to occur in single stage high gear ratio cross axis worm gear drives, where high sliding velocity occurs due to the combination of the translation of the worm threads, the rotation of the worm wheel, and especially the rotation of the worm.

This specific phenomenon can sometimes be observed on tooth flanks as macropitting on the gear wheel, with wear surrounding macropits in the direction of sliding. Wear can sometimes also be observed by existence of a wear step near the root of the flank (see Reference [51]).

6.2.3.5 Coupling effect between macropitting and wear

With worm gears, the initial contact pattern on a worm wheel usually remains stable for a time after running-in. Since worm wheel material is softer than the worm (bronze against steel), the worm wheel is the first to encounter contact fatigue. After an incubation period, subsurface fatigue cracks initiate and undermine the wheel flank surface. Macropits form when the fatigue cracks grow to the surface of the wheel flanks. The macropitting redistributes the load and a coupling effect between macropitting and wear begins (see Reference [51]). If the wear rate exceeds the macropitting rate, the wear can completely remove the macropitting, and the coupling effect between macropitting and wear begins again. See Figure 2.

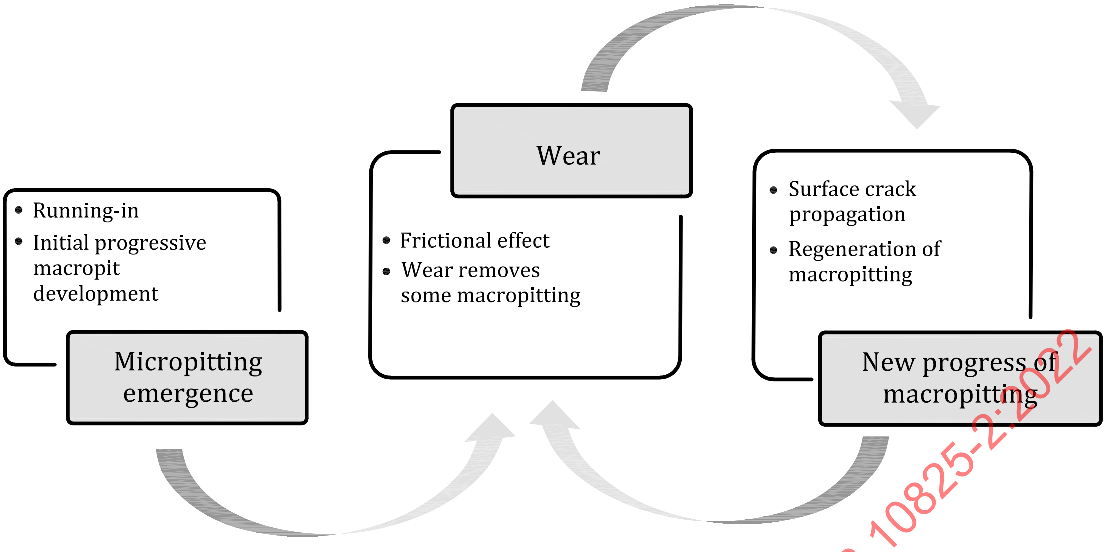


Figure 2 — Coupling effect between macropitting and wear (figure is from Reference [51])

This coupling effect between macropitting and wear is stronger when the lead angle of the worm is higher, i.e. for lower gear ratios.

In some applications, this phenomenon of combined macropitting/wear in a worm gear set is acceptable for a certain amount of tooth thickness reduction before the worm wheel needs to be replaced.

NOTE Figures 3 through 8 show a wear step at the root of the tooth flanks and a reduction of top land thickness caused by wear.

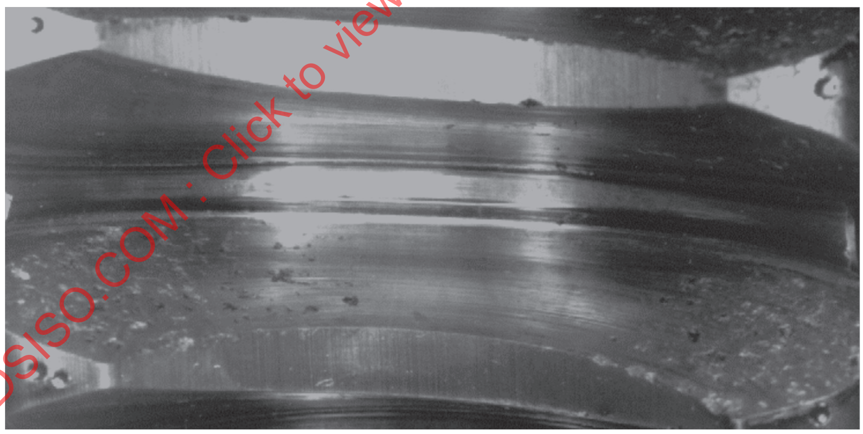


Figure 3 — Macropitting in progress for a low lead angle worm gear set

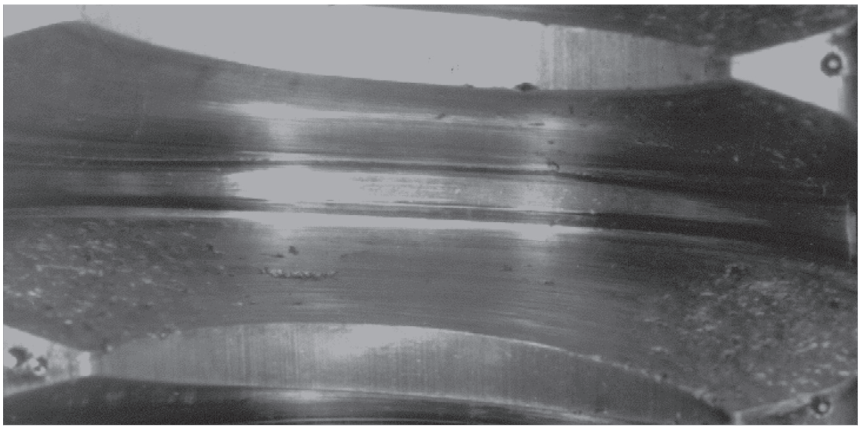


Figure 4 — Same flank as in Figure 3, after macropitting has been removed

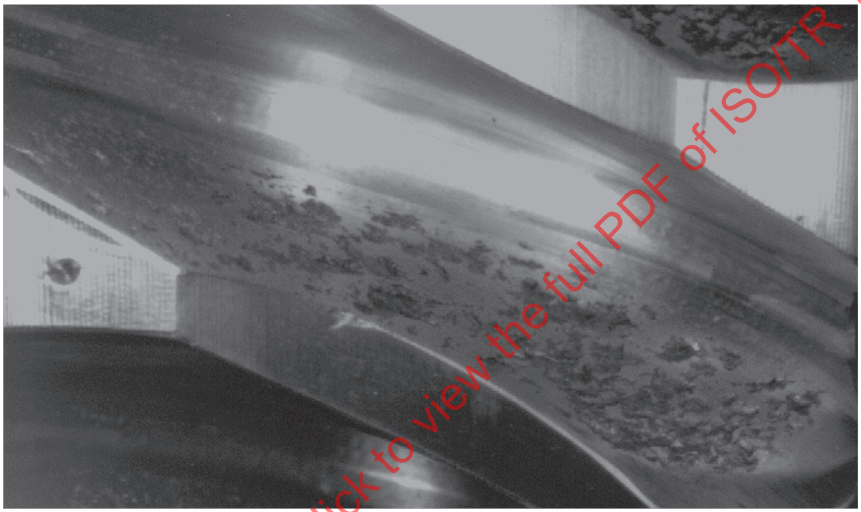


Figure 5 — Macropitting in progress for a high lead angle worm gear set

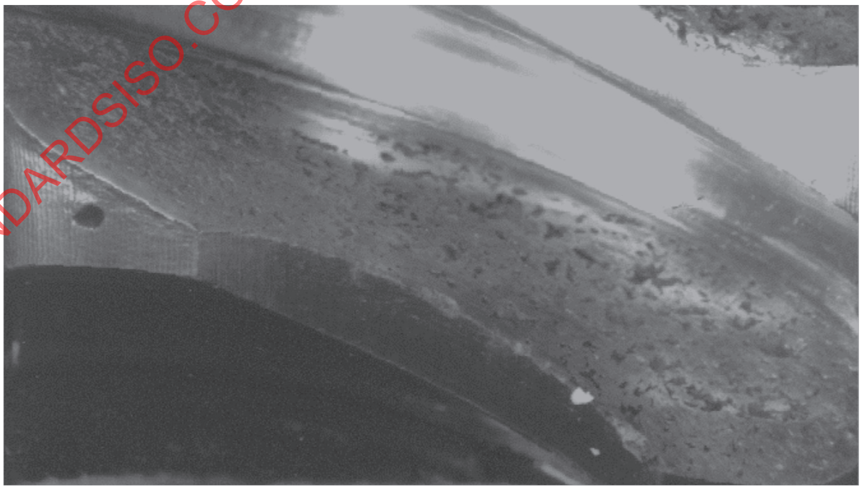


Figure 6 — Same flank as in Figure 5, after macropitting has been removed

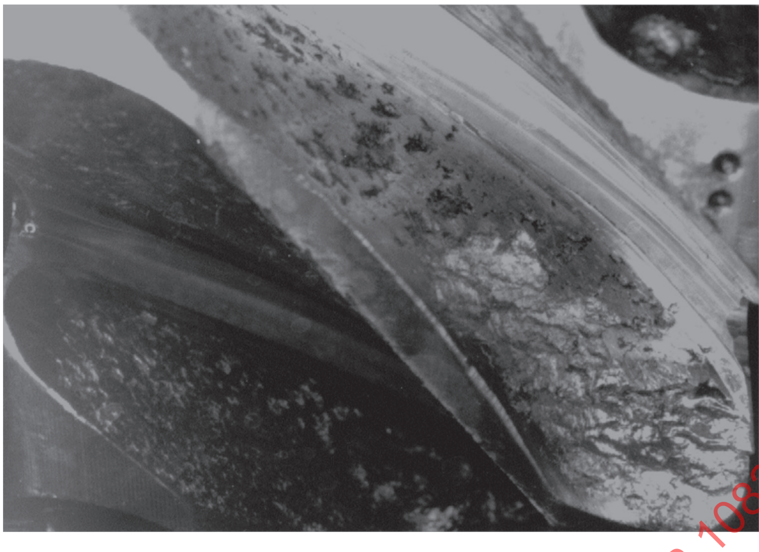


Figure 7 — Macropitting in progress for a very high lead angle worm gear set

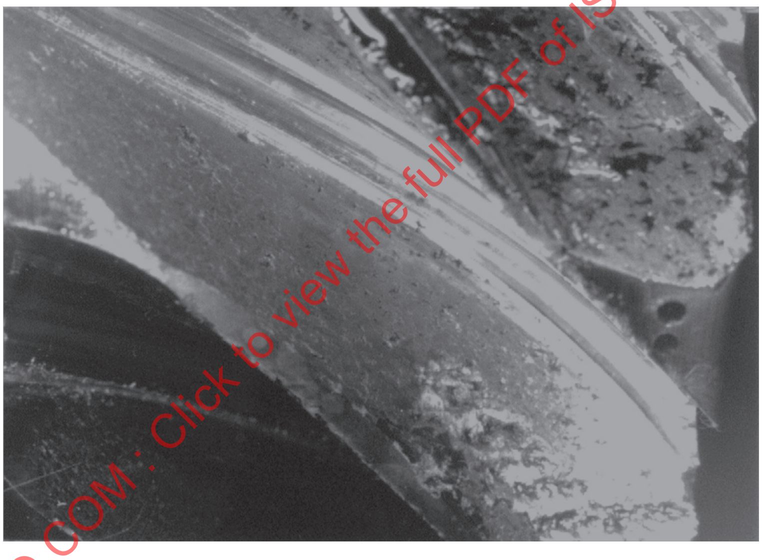


Figure 8 — Same flank as in Figure 7, after macropitting has been removed

6.2.4 Case crushing (subcase fatigue)

6.2.4.1 General

Case crushing, also known as subcase fatigue, can occur when the cyclic shear stresses exceed shear fatigue strength near the case core interface. It is influenced by Hertzian stresses, residual stresses and material fatigue strength. The subsurface distribution of residual stresses and fatigue strength depends on the case hardness, case depth and core hardness (see Reference [39]). The maximum grind stock that is removed effects the finished case depth, so it needs to be accounted for when specifying the case depth. To prevent case crushing, steels with adequate hardenability are used to obtain optimum case and core properties. The use of clean steel can be beneficial since inclusions can initiate fatigue cracks if they occur near the case/core interface in areas of tensile residual stress. See 6.2.6.2 for a discussion of inclusions.

Overheating gear teeth during operation or manufacturing, such as surface temper from grinding, can lower case hardness, alter residual stresses, and reduce resistance to subcase fatigue. See 9.3 for discussion of surface temper from grinding.

References [39] to [44] give methods for analysing the risk of subcase fatigue.

6.2.4.2 Summary of methods that have been observed to reduce the risk of case crushing (subcase fatigue)

The following methods can be considered for reducing the risk of case crushing (subcase fatigue):

— reducing Hertzian stresses by reducing loads or optimizing gear geometry;

— using clean steel with adequate hardenability to obtain acceptable case and core properties;

— obtaining acceptable values of case hardness, residual stresses, hardness gradient, case depth and core hardness to maximize resistance to subcase fatigue;

— avoiding overheating gear teeth during manufacturing and operation;

— using analytical methods to ensure that subsurface stresses do not exceed subsurface fatigue strengths.

6.2.5 White layer flaking

6.2.5.1 General

White layer flaking occurs when the compound layer (white layer) on nitrided gears locally chips off partially or completely leaving shallow scars that have a white appearance. Local flaking of the complete compound layer can be detrimental. If only the porous zone on the surface of the compound layer is worn off, in some cases this has no detrimental effect on the gear load capacity.

The white layer is sometimes removed by grit blasting, grinding, honing, lapping or chemically assisted polishing. However, for some applications the compound layer is left on the gears. The risk of flaking is influenced by the thickness and chemical composition of the compound layers. Different processes, such as single-stage gas nitriding versus two-stage gas nitriding or ion nitriding, can also influence the composition of the layer. The edge of the shallow scar resulting from white layer flaking can generally be felt when a fingernail is run across it.

6.2.5.2 Summary of methods that have been observed to reduce the risk of white layer flaking

The following methods can be considered for reducing the risk of white layer flaking:

— removing the white layer with grit blasting, grinding, honing, lapping, or polishing, while being aware of a possible reduction of flank load capacity;

— avoiding an excessively thick compound layer;

— closely controlling of the chemical composition and thickness of the compound layer.

6.2.6 Tooth flank fracture (TFF) (subsurface initiated bending fatigue)

6.2.6.1 General

TFF is influenced by factors such as gear geometry, load distribution and the local subsurface stress condition. A rating method for TFF is proposed in ISO/TS 6336-4.

Assumed influence parameters of the material and microstructure include case hardening depth (CHD) and hardness profile, residual stresses, cleanliness and homogeneity of the microstructure, especially in regions at and below the transition zone.

— TFF is often, but not always, associated with nonmetallic inclusions. In particular, macroscopic nonmetallic inclusions, which can be detected with NDT methods, can increase the risk of TFF. Also, stringers of nonmetallic inclusions that are shattered during the forging and are more difficult to detect by NDT can increase the risk for TFF. See 6.2.6.2 for a discussion of inclusions.

— Dendrites and porous structures have also occasionally been found close to the crack origin, as well as cracks related to quenching, and cracks of unknown cause showing white etching constituents of ultra-fine, recrystallized ferrites with no or very finely distributed carbides.

— Stress raisers related to coarse singular grains, or large grain size gradients, can also cause increased TFF risk.

— Hardness variation due to banded structures of segregated alloys further increase the risk for TFF, or the susceptibility of the microstructure against TFF initiated by nonmetallic inclusions.

— Finally, failure analyses suggest that steep transition of the hardness from case to core can, especially in combination with nonmetallic inclusions, cause an increased risk for TFF-related failures.

6.2.6.2 Inclusions

All steel contains inclusions. Steel cleanliness is a measure of the inclusions present. See ISO 6336-5 for steel cleanliness requirements and material inspection methods.

The harmful effects of nonmetallic inclusions depend on the chemistry, size, location, and quantity of the inclusions, tensile strength of the steel and residual stresses immediately adjacent to the inclusions and the stresses imposed on the final part. Hard, nondeformable inclusions such as calcium aluminates, single-phase alumina, spinels, titanium nitride and some silicates are especially damaging, whereas manganese sulfide inclusions are regarded as being the least potent stress concentrators. See References [38] and [50] for additional general information on inclusions. Inclusions are commonly identified on a fractured surface or on a sectioned sample either by optical microscopy or more precisely by use of SEM EDX methods.

6.2.6.3 Summary of methods that have been observed to reduce the risk of TFF on case carburized gears

When ISO/TS 6336-4 or other method indicates there is a risk of TFF, the following measures can be considered to reduce the risk of TFF:

— specifying mandatory UT inspection in roughed condition according to ISO 6336-5, possibly with a better material quality class, to reduce the risk of undetected nonmetallic inclusions;

— specifying additional UT inspection after hardening and grinding to detect quenching cracks;

— specifying more stringent requirements on microscopic cleanliness, especially of the DS-type;

— alleviating residual stress gradients by specifying a low slope of the hardness gradient;

— increasing forging reduction ratio to reduce the risk for dendrites and alloy segregations.

NOTE Increased area reduction ratio can further shatter nonmetallic inclusions, so is often supplemented with increased cleanliness of steelmaking and UT inspection practices with improved detection capability for small defects.

6.2.7 Tooth interior fatigue fracture, TIFF

References [46] and [47] describe tooth interior fatigue fracture (TIFF). TIFF failures that initiated from inclusions have been reported (see Reference [46]), but TIFF failures typically occur at moderate stress levels where inclusions are less damaging. See 6.2.6.2 for a discussion of inclusions.

TIFF failures can occur after long running times, but also can have a lifetime of only 10^5 to 10^6 cycles (see Reference [46]).

Reference [46] concludes:

— TIFF has been observed in case hardened idlers.

— The surface of a TIFF has a characteristic shape with a distinct plateau in the centre at approximately tooth mid-height.

— The mechanical driving forces of the crack are residual tensile stresses in the interior of the tooth and alternating stresses due to the idler usage of the gear.

— An analysis technique based on finite element computations for the study of TIFF is presented.

— The analysis shows that alternating stress due to the idler usage of a gear wheel and tensile stresses due to case hardening lead to potential fatigue initiation in a large region in the interior of the tooth.

— The risk of fatigue initiation in the interior of the tooth is increased by idler usage of the gear wheel as compared to single stage usage.

Reference [47] concludes:

— TIFF is a possibility at loads lower than the load where tooth root bending fatigue is achieved and at loads higher than the load where contact fatigue occurs.

— By using the gear wheel as an idler instead of as a single stage gear, the risk of TIFF is increased by 20 %.

— The more slender the tooth (greater whole depth) and the higher the load, the greater the risk of TIFF.

— The influence of the carburizing depth on TIFF is small, but the risk of TIFF is lower for a high carburizing depth than for a low carburizing depth.

NOTE TFF and TIFF are unrelated.

6.3 Bending fatigue

6.3.1 Tooth root fatigue fracture

6.3.1.1 General

Fatigue cracks can culminate in a fracture when the fatigue cracks grow to a size where the remaining tooth section can no longer support the load. In this sense the remaining material is overloaded; however, the fracture is a secondary failure mode that is caused by the primary mode of fatigue cracking.

6.3.1.2 Low cycle fatigue

Low cycle fatigue occurs when macroscopic plastic strain occurs in every cycle and the number of cycles to failure is less than 10 000 according to many sources. It is an uncommon failure mode for many gear applications unless the gear teeth are overloaded because they are under-designed, severely misaligned, or the load is unexpectedly high.

Surface conditions of a gear tooth subjected to low cycle fatigue are less important than under high cycle fatigue loading because cyclic plastic deformation tends to relax both stress concentrations and residual stresses. Cracks can initiate within gear teeth, as well as on the surface, and a smaller fraction of the life is spent initiating rather than propagating cracks.

Low cycle fatigue life can be extended by maximizing ductility and toughness (see discussion in 7.1.1 regarding factors that promote toughness). Reference [44] lists the following methods that can be used to increase toughness of carburized gears:

— using steels that contain nickel as a major (more than 1 %) alloying element;

— quenching to produce 15 % to 30 % retained austenite in the case microstructure;

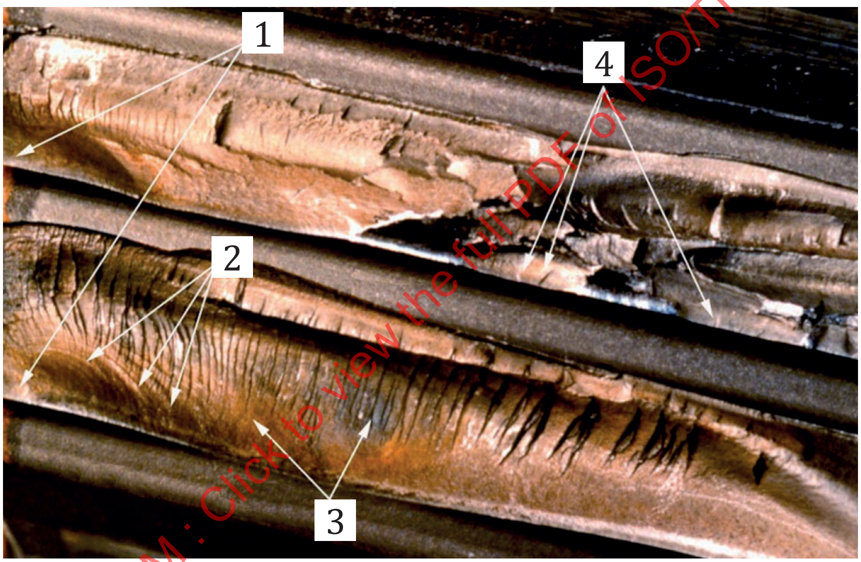
— tempering as-quenched case hardness from 58 to 62 HRC down to 51 to 55 HRC, provided that this does not reduce the strength to an unacceptable level. Avoid tempering temperatures of 250 °C to 400 °C because this temperature range can cause embrittlement of the core.

Changing the material or heat treatment to improve low cycle fatigue life can result in a decrease in high cycle fatigue life. However, designing gears so stresses are reduced generally not only helps avoid low cycle fatigue but can also reduce the chance of some of the other types of damage.

6.3.1.3 High cycle fatigue

High cycle fatigue is defined as fatigue where the cyclic stress is below the yield strength of the material and the number of cycles to failure is high. Most gear tooth bending failures are due to high cycle fatigue rather than low cycle fatigue. See ISO 6336-3 for a rating method to avoid both high and low cycle fatigue.

NOTE Fretting corrosion on the fracture surface indicates high cycle fatigue.



Key

1 origins

2 beach marks

3 fretting corrosion

4 ratchet mark

Figure 9 — Two adjacent teeth on a helical pinion that failed by bending fatigue

With high cycle fatigue, a large fraction of the crack life is spent initiating rather than propagating cracks. See Figure 9.

High cycle fatigue life can be extended by maximizing the ultimate tensile strength of the material and ensuring that the microstructure of the surface of the gear teeth is optimum.

6.3.1.4 Morphology of fatigue fracture surfaces

Ratchet marks – High tensile stresses or high stress concentration can initiate several fatigue cracks on different planes. A ratchet mark forms where the cracks join to form a common plane. Ratchet marks help locate the crack origins. If there are no ratchet marks, it indicates there was a single crack origin. One or more ratchet marks indicate there were multiple crack origins. The higher the stress, or more acute the stress concentration is, the more likely multiple ratchet marks occur.

Beach marks – If a fatigue crack grows intermittently, marks form along lines of arrest where the crack stopped because the load decreased. If the range of cyclic load remains constant, the beach marks are less visible. Fine, closely-spaced beach marks indicate slow growth. Beach marks surround and help locate the crack origin and show the direction of crack growth.

Case/core origins – Case hardened gears have tensile residual stress below the case/core boundary. Subsurface fatigue cracks can initiate at material flaws such as nonmetallic inclusions if the flaws are near the case/core boundary in an area of high tensile residual stress. See 6.2.6.2 for a discussion of inclusions.

At an inclusion – Nonmetallic inclusions are often the root cause of bending fatigue cracks that initiate at a subsurface location. In some instances, the severe stress-raising effects of an inclusion can even initiate cracks on the compression side of the gear tooth.

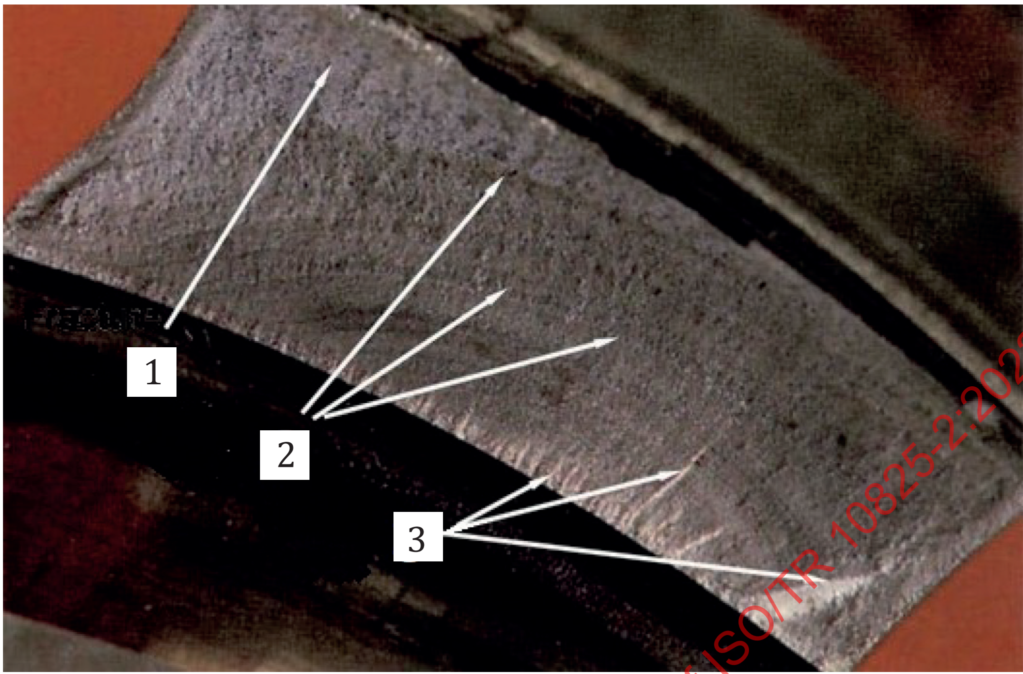
Smeared polished areas of fracture surface – If a fatigue crack opens and closes repeatedly under alternating tension and compression, the surfaces of the crack can appear polished. These areas are often found around subsurface fatigue origins caused by nonmetallic inclusions or other material flaws.

Fretting corrosion – Fretting corrosion often occurs on a fracture surface when the faces of the fatigue crack rub together during slow, high cycle fatigue growth. Fretting corrosion is often found on the oldest, smoothest, and largest fatigue zone.

Size of the fatigue zones on adjacent teeth – The first tooth to fail usually has the largest, smoothest fatigue zone because the tooth unloads as the crack grows and the tooth loses stiffness, decreasing the bending stress and the crack growth rate. Due to the loss in load sharing, adjacent teeth take on more load and crack sooner, have faster crack growth rate and a rougher fracture surface. Adjacent teeth can have secondary distress such as macropitting.

Ratio of fatigue/fracture surface area – A large fatigue zone and a small fracture zone indicate the bending stress was low, whereas a small fatigue zone and a large fracture zone indicate the bending stress was high. The size of the final fracture zone is an indication of the magnitude of the stress at final fracture.

ISO 10825-1, Figure 9 shows two adjacent teeth that failed by bending fatigue. The lower tooth failed first. It has a single crack origin, the largest, smoothest fracture surface and extensive fretting corrosion. The adjacent tooth failed next, and it has a smaller, rougher fracture surface. Ratchet marks formed on the adjacent tooth because the bending stress was higher and more fatigue cracks initiated. See Figures 10 and 11 for additional examples.



Key

1 fracture zone
2 beach marks
3 rachet marks

Figure 10 — Bending fatigue of spiral bevel tooth

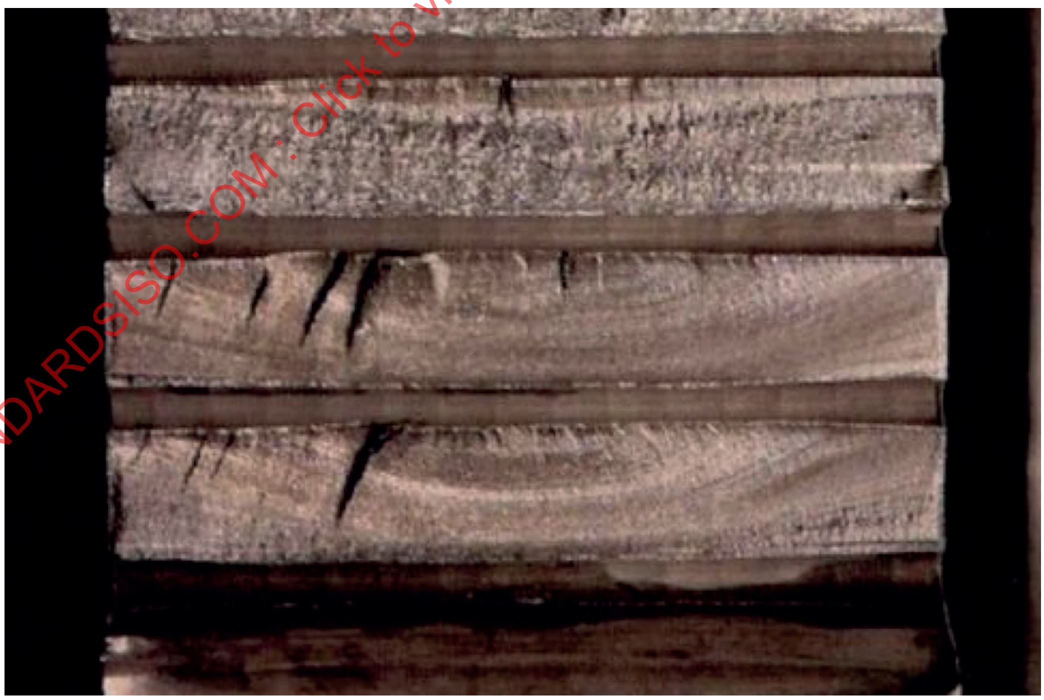


Figure 11 — Bending fatigue of several spur gear teeth

6.3.1.5 Progression of fatigue

Bending fatigue is a progressive failure consisting of three distinct stages:

— Stage 1, crack initiation (plastic deformation at stress concentrations leading to microscopic cracks).

— Stage 2, crack propagation (cracks grow perpendicular to maximum tensile stress).

— Stage 3, fracture (when a crack grows large enough, it causes sudden fracture).

Most of the fatigue life is occupied by stages 1 and 2 until the cracks grow to critical size where sudden fracture occurs in stage 3. The fracture can be ductile, brittle or mixed mode depending upon the toughness of the material and the magnitude of the applied stress.

During stage 1, the peak bending stress is less than the yield strength of the material and no gross yielding of the gear teeth occurs.

The stage 2 propagation phase begins when the crack turns and grows across grain boundaries (transgranular) in a direction approximately perpendicular to the maximum tensile stress.

Under the scanning electron microscope, contours, called fatigue striations, can be seen on a fatigue cracked surface. They can be associated with the advance of the crack during each stress cycle. The orientation of the striations is at 90° to the crack advance.

If the crack propagates intermittently, it can leave a pattern of macroscopically visible “beach marks”. These marks correspond to positions of the crack front where the crack stopped because stress decreased. The origin of the fatigue crack is usually on the concave side of curved beach marks and is often surrounded by several concentric beach marks. Beach marks are not always visible, especially if the fatigue crack grows continuously under steady state operating conditions. The presence of beach marks is a strong indication that the crack was due to fatigue, but not absolute proof, because other failure modes can leave beach marks (for example, stress corrosion under changing environment).

If there are multiple crack origins, each producing separate crack propagation zones, ratchet marks can be formed. They are caused when adjacent cracks, propagating on different crystallographic planes, join together to form a step. Ratchet marks are often present on fatigue cracked surfaces of gear teeth because the stress concentration in the root fillet frequently initiates multiple fatigue cracks.

6.3.1.6 Methods to reduce the risk of tooth root bending fatigue fracture

Gear teeth bend slightly each time they pass through mesh. Teeth on idler gears are subject to alternating tensile and compressive stress, which is more detrimental that unidirectional stress. Bending fatigue cracks typically initiate in the root fillet on the tensile side of the gear tooth but can also start below the surface of the root fillet. Fatigue life can be extended both by decreasing stress and by improved material properties.

High cycle fatigue life can be extended by maximizing, up to a point, the ultimate tensile strength of the material and ensuring that the microstructure of the surface of the gear teeth is optimum. Surface hardness correlates with tensile strength, which is why surface hardening improves fatigue life. There are many other material properties and characteristics that influence bending fatigue life, see ISO 6336-5 for further information.

Case or surface hardening, in particular by carburizing, can be beneficial because this hardening process can induce compressive residual stresses that counteract the tensile bending stresses. Also, controlled shot peening or mechanical cleaning by shot blasting can be used to increase compressive residual stresses, although subsequent root fillet finishing operations can reduce these stresses in that area. For carburized gears there are optimum values of case hardness, case depth and core hardness that give the best balance of residual stresses and fatigue strength to maximize gear tooth resistance to bending fatigue. For nitrided and induction hardened gears, there are also optimum values of case hardness, case depth and core hardness. While cracks usually initiate at the surface of the gear tooth root fillets, with increased surface compressive stresses the likelihood of subsurface initiated cracks can increase.

There are several geometric variables, such as module, diameter, face width, number of teeth, pressure angle, helix angle and profile shift that can be optimized to lower the bending stress and increase the bending fatigue life. The gear tooth geometry can be designed to reduce the tensile bending stress in the root fillets. When gears are finished by shaving or grinding, avoiding creation of notches in critical areas of the root fillets reduces the chance of crack formation.

Stress concentrations can be avoided by, as much as possible, eliminating all cracks, especially near the surface of the root fillets, and eliminating defects on or near the surfaces of the root fillets. Designing and manufacturing gear teeth to obtain large radius root fillets can minimize stress concentrations in critical areas of the root fillets.

6.3.1.7 Summary of methods that have been observed to reduce the risk of high cycle bending fatigue

The following methods can be considered for reducing the risk of high cycle bending fatigue:

- optimizing geometry by:
  - using full fillet roots, the root shape has a strong influence on bending stress;
  - using larger module;
  - using a combination of centre distance, face width, number of teeth, pressure angle, helix angle and profile shift to optimize and lower the bending stress;
  - ensuring that the surfaces in critical areas of the root fillets are free from significant notches and tool marks;
  - ensuring good load distribution;
  - reducing bending stresses by reducing loads;
- optimizing metallurgy by:
  - ensuring that, as a minimum, the material quality requirements of ISO 6336-5 are met;
  - using case hardening or shot peening, or both, with proper process control to increase compressive residual stresses. For carburized gears, material and heat treatment parameters can be selected to maximize residual compressive stress in the case;
  - for case hardened gears, specifying values of case hardness, case depth and core hardness to maximize resistance to bending fatigue;
  - using steel with sufficient hardenability to obtain a microstructure of primarily tempered martensite in the gear tooth root fillets;
  - avoiding embrittlement;
  - for carburized gears, making sure that the microstructure of the case is essentially free of bainite, pearlite, network carbides and especially microcracks within martensite platelets or needles;
  - using fine-grain steel;
  - ensuring that the surfaces of the root fillets are free from significant cracks, nonmetallic inclusions, decarburizing, corrosion, intergranular oxidation, or other potential stress risers.

6.3.2 Rim web and hub cracks

6.3.2.1 General

If the gear rim is thin, it can be subjected to significant alternating rim bending stresses that are additive to the gear tooth bending stresses. These stresses can result in fatigue cracks in the rim. Rim cracks are similar to tooth bending fatigue cracks, except that rim cracks usually propagate radially through the gear rim, whereas bending fatigue cracks propagate across the base of the teeth. Rim cracks can grow into the web of the gear.

Web cracks can be caused by cyclic stresses due to vibrating loads near a natural frequency of the gear blank. A fatigue crack can originate in the web of the gear and can grow into the rim of the gear.

Rim and web cracks generally originate at stress concentrations. These concentrations can arise from one or more of the following: sharp corners or notches in the root fillets, keyways, splines, holes, shrink fits, web-to-rim or hub-to-web fillets or metallurgical defects such as inclusions.

Other causes of rim or web cracks include:

— tip to root interference, operation in tight mesh;

— use of lower strength web materials in fabricated blanks;

— incorrect welding procedures, particularly inadequate stress relieving;

— gear blanks with significant changes in section thickness that lead to changes in stiffness and a redistribution of stress that overloads the adjacent thin (weaker) section;

— poor load distribution across the face width;

— impact loading.

Rim or web cracks can cause catastrophic failure in high speed gears if centrifugal forces cause the fatigue cracks to propagate to a brittle fracture mode, opening the rim.

Magnetic particle or dye penetrant inspection can be used to ensure that the gear tooth fillets, gear rim and gear web are free of material flaws.

6.3.2.2 Summary of methods that have been observed to reduce the risk of rim or web cracks

The following methods can be considered for reducing the risk of rim or web cracks:

— using adequate rim thickness;

— designing the gear blank such that its natural frequencies do not coincide with excitation frequencies;

— paying attention to details that cause stress concentrations such as keyways, splines, holes and web-to-rim fillets;

— using magnetic particle or dye penetrant inspection to ensure that the gear tooth fillets, gear rim and gear web are free of material flaws;

— controlling manufacturing to avoid notches in the root fillets;

— avoiding uneven load distribution across the gear face width;

— controlling operating centre distance, tooth clearance, and avoiding tip-to-root interference.

7 Non-fatigue fracture

7.1 General

Gear tooth fractures without prior fatigue cracking are infrequent but can result from shock loads. The shock loads can be generated by the driving or driven equipment. They can also occur when foreign objects enter the gear mesh or when the gear teeth are suddenly misaligned and jam together or operate in tight mesh after a bearing or shaft fails.

7.1.1 Brittle fracture

Three primary factors control the susceptibility of gear teeth to brittle fracture:

— material toughness;

— material flaws;

— tensile stress level resulting from load and residual stresses.

Brittle fracture occurs when combinations of tensile stress and flaw size create a critical stress intensity for a particular material toughness. Part shape, machining marks and material flaws can lead to stress concentration, which usually plays a role in brittle fracture. The material toughness determines the critical rate of loading and stress intensity that leads to brittle fracture.

The compliance of shafts and couplings in a drive system helps to cushion shock loads and reduce the loading rate during impact. Gear drives with close-coupled shafts and rigid couplings have less compliance. When drive systems with low compliance are used in applications where overloads are expected, the use of gears large enough to absorb the overloads can help achieve reasonable stress levels. Also, gears can be isolated from shock loads by using torque-limiting couplings. However, using torque-limiting couplings in critical applications such as hoists can lead to problems such as a load being dropped.

The toughness of a gear material depends on many factors, especially temperature, loading rate and constraint (state of plane stress or plane strain) at the location of material flaws. Many steels have a transition temperature where the fracture mode changes from ductile-to-brittle as temperature decreases. For low temperature service (including temperature at start-up), the transition temperature is of primary importance. Since the transition temperature is influenced by the loading rate and constraint, operating close to the transition temperature can be problematic. When selecting materials, it is often possible to find a material that has a transition temperature well below the gear tooth service temperature. The ductile-to-brittle transition can be determined with the Charpy V-notch impact test. Some high strength, alloyed, quenched and tempered steels do not exhibit a transition temperature behaviour.

The toughness of a material depends on its elemental composition, heat treatment and mechanical processing. Typically, alloy steels with a very high core hardness have limited fracture toughness. Many alloying elements that increase the hardenability of steel also decrease its toughness. Exceptions are nickel and molybdenum that increase hardenability while improving toughness. Tests on the impact fracture toughness of carburized steel have found the following, see Reference [45]:

— High-hardenability steels have greater impact fracture toughness than low-hardenability steels.

— High nickel content does not guarantee good impact fracture toughness, but nickel and molybdenum in the right combination results in high impact fracture resistance.

— High chromium and high manganese contents tend to give low impact fracture toughness.

The microstructure of steel depends on initial microstructure, hardenability and heat treatment. Tempered martensite gives the highest toughness. Microstructures consisting of ferrite, pearlite or bainite have lower fracture toughness. Steel with sufficient hardenability, so that its heat-treated microstructure consists primarily of tempered martensite, can lead to maximum toughness. Steel can be selected so the desired hardness is achieved without tempering in the range that promotes embrittlement.

Most material properties are improved when grain size is uniform and fine. This is especially true for toughness; fine-grained steel has increased toughness and a lower transition temperature. Steel-making practice, alloying elements, mechanical treatment and heat treatment influence grain size. Steels containing nickel and molybdenum resist grain coarsening during austenitizing better than plain carbon steels. Elements such as aluminium, vanadium or niobium can help produce fine grain size.

In summary, toughness can be optimized by proper alloy design. This is a very complex subject that requires a high degree of expertise.

Material flaws or other discontinuities create stress concentrations that elevate the stress locally ahead of the discontinuity. The discontinuity can be a notch, crack, surface tear, surface or subsurface inclusion or porosity. Fracture can initiate at these locations. Adjacent material, at lower stress, constrains and limits plastic deformation. The discontinuity size can be small, but if it initiates a fatigue crack, that crack can grow until a critical size is reached, at which point the crack can extend in a brittle fracture. The critical discontinuity size is not constant, but depends on the geometry of the part, shape and orientation of the discontinuity, applied stress, and the fracture toughness of the material at the service temperature and loading rate. See 6.2.6.2 for a discussion of inclusions.

The root fillets of gear teeth are especially vulnerable to fracture because this is the location where tooth bending stresses are highest. Clean materials increase fracture resistance.

The gear tooth geometry can be selected to reduce the tensile bending stress in the root fillets. The gear teeth can be cut with full-fillet tools to obtain a larger root fillet radius to decrease stress concentration effects. If the gears are to be finished by shaving or grinding, protuberance tools can be used to reduce the risk of notching the root fillets. Case hardening can be beneficial because these hardening processes can induce compressive residual stresses that reduce the net tensile bending stresses. Also, controlled shot peening can be used to increase compressive residual stresses.

7.1.2 Summary of methods that have been observed to reduce the risk of brittle fracture

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

— optimizing design by:

  — reducing tensile bending stresses by improving gear tooth geometry;

  — reducing loading rates by using compliant shafts and couplings;

  — protecting gears from impact loads by using load limiting couplings;

  — for case hardened gears, using appropriate case depth;

— optimizing metallurgy by:

  — using materials with high cleanliness;

  — selecting material:

    — using materials and heat treatments that give high toughness, such as steel with sufficient hardenability to obtain a microstructure of primarily tempered martensite;

    — using steel in which the desired hardness is achieved without tempering in the temperature range that causes embrittlement;

  — using steels with high nickel content:

    — for carburized gears, nickel and molybdenum in the right combination gives maximum toughness;

  - avoiding use of steels with high chromium and manganese content;
  - keeping the phosphorous and sulfur content as low as possible;
- avoiding use of steels at service temperatures below their transition temperature;
- avoiding very high core hardness;
- using fine grained steel;
- minimizing material flaws, especially in the root fillets of gear teeth. Using magnetic particle or dye penetrant inspection to detect flaws;
- using case hardening to increase compressive residual stresses.

7.1.3 Ductile fracture

Gear tooth failures that occur solely by ductile fracture are relatively infrequent because most fractures occur at a preexisting flaw which tends to promote brittle behaviour. If the following factors are present, a fracture is more likely to be ductile rather than brittle:

- high material toughness;
- high gear tooth temperature;
- slow loading rate;
- no significant material flaws;
- low tensile stress level resulting from the combination of load and residual stresses;
- high shear stress.

Under these conditions gear teeth yield when the stresses exceed the yield strength of the material, and subsequently shear off with significant plastic deformation before ductile fracture.

7.1.4 Mixed mode fracture

A local area of a fracture surface that exhibits both ductile and brittle characteristics is termed mixed mode. This is not to be confused with a fracture surface having features that suggest successive crack propagation by different mechanisms, for example a fatigue crack causing a ductile fracture.

7.2 Tooth root rupture

Tooth root rupture can be a brittle, ductile or mixed mode fracture. This term is not used for tooth root fatigue fracture (6.3.1) or fracture after plastic deformation (8.7).

7.3 Tooth end rupture

Tooth end rupture is similar to tooth root rupture; however, it generally occurs when the teeth are loaded more heavily at one end. There are many causes for this, including improper flank modifications or misalignment.

Misalignment can result in end loading of the teeth, increasing the stresses in that section of the teeth and thereby increasing the risk of damage or failure. There are many possible causes of misalignment, including:

- inaccurate lead, profile, spacing, or runout of pinion or wheel;
- inappropriate lead or profile modifications;
- assembly or mounting errors;

— bearing failures or supports not parallel;

— distortion of the gearbox housing or foundation due to applied stresses or thermal effects;

— distortion of the gear teeth due to transmitted loads, centrifugal stresses or thermal effects;

— excessive radial space in the bearings, particularly those which do not have rolling elements;

— excessive internal clearance in rolling-element bearings;

— excessive tapered roller bearing endplay.

Misalignment is always detrimental; proper alignment during operation is very important.

7.4 Tooth shear fracture

Tooth shear is almost always caused by a single severe overload.

8 Plastic Deformation

8.1 General

Plastic deformation is permanent deformation that remains after removal of the applied load. It occurs when the stress exceeds the yield strength of the material. It can occur at the surface or subsurface of the active flanks of the gear teeth due to high contact stress, or at the root fillets of the gear teeth or the rim due to high bending stress (see 8.7). High contact stress can result from large loads or gear tooth impact (see 8.9) caused by vibration.

8.2 Indentation

The active flanks of gear teeth can be damaged by indentations caused by foreign material that becomes trapped between mating teeth. Depending on the number, size and severity of the indentations, the damage can initiate other types of damage or failure. If plastic deformation associated with the indentations causes raised areas on the tooth active flank surface, it creates stress concentrations that can lead to subsequent contact fatigue. For gear teeth subjected to contact stresses greater than roughly 1,8 times the tensile yield strength of the material, local, subsurface yielding can occur. The subsurface plastic deformation causes grooves (see 8.3) on the surfaces of the active flanks of the teeth corresponding to the lines of contact between the mating gear teeth.

8.3 Brinelling

True brinelling can occur on gear tooth flanks, typically when they are not rotating and are subjected to a sudden high impact load. With brinelling, usually the original grinding marks are visible microscopically in the bottoms of the dents. There is no relation between brinelling and false brinelling (5.7.2).

8.4 Cold flow

Cold flow is plastic deformation that occurs on the flank in the direction of sliding at a temperature lower than the recrystallization temperature. For steel, the recrystallization temperature usually ranges from around 450 °C to 900 °C, depending on severity of plastic deformation, grain size prior to plastic deformation, temperature at which plastic deformation occurs, time for which the plastically deformed metal is heated to attain recrystallization, and presence of dissolved or undissolved elements (see Reference [48]). It can occur with insufficient lubrication.

8.5 Hot flow

Hot flow is plastic deformation that occurs at a temperature higher than the recrystallization temperature. Keeping the gears lubricated and keeping the teeth within an acceptable temperature range for the gear material helps avoid hot flow.

8.6 Root fillet yielding

Gear teeth can be permanently bent if the bending stress in the root fillets exceeds the yield strength of the material. Usually the bending deflection at initial yielding is small and there is a margin of safety before gross yielding causes significant gear tooth spacing error. If the teeth have sufficient ductility, initial yielding at the root fillets redistributes the stress and lowers the stress concentration. Hence, root fillet yielding sometimes only results in rougher running and a higher noise level. However, if the yielding causes significant spacing errors between loaded teeth that are permanently bent and unloaded teeth that are not, subsequent rotation of the gears usually results in destructive interference between the pinion and wheel teeth.

8.7 Fracture after plastic deformation

This is a secondary failure mode that can occur by various mechanisms, see Part 1.

8.8 Rolling

Plastic deformation can occur on the active flanks of gear teeth caused by high contact stresses in combination with both the rolling and sliding action of the gear mesh. Displacement of surface material can form a groove along the pitch line and burrs on the tips and in the roots of the driving gear teeth. The surface material of the driven gear can be displaced toward the pitch line forming a ridge.

8.9 Tooth hammer

Tooth hammer results in plastic deformation, which increases transmission error and can also increase noise and can subsequently lead to other failure modes. See ISO 10825-1.

8.10 Rippling

Rippling usually occurs under high contact stress and boundary-lubricated conditions. Lubricant influences the load and sliding velocity at which rippling occurs. In some cases, sulfur-phosphorous and borate additives can prevent rippling. See Reference [30].

8.11 Ridging

There is a hypothesis, although it has not been proven, that ridging is initiated by scuffing and is subsequently polished over. This eventually masks the scuffing damage and results in smooth ridges consisting of smooth peaks and valleys. This hypothesis is supported by the fact that rear axle lubricants have aggressive sulfur-phosphorous additives that promote polishing wear (see 5.2). The wear debris from scuffing provides the abrasives for polishing.

8.12 Burr

The burr in ISO 10825-1, Figure 85 was generated by plastic deformation due to the contact pressure and the sliding action along the surface of the active flanks.

8.13 Interference deformation

8.13.1 Tip to root fillet interference

Interference in the root fillet is engagement below the form diameter which can result from insufficient centre distance, inadequate protuberance on the tool or excessive addendum of the mating gear. It is the result of manufacturing, assembly or design errors. Subsequent cyclic contact on areas with damage due to tip to root fillet interference can lead to plastic deformation or local breakage. Operating with tip to root fillet interference can result in tooth damage or failure, or catastrophic blank failure (typically through the rim).

8.13.2 Tip-to-dedendum interference

As gear teeth approach one another near the start of engagement, the corners of teeth on the driven gear are very close to the Start of Active Profile (SAP) on dedendum flanks of the driving teeth. High loads can deflect the teeth already in mesh and close the gap between incoming teeth, resulting in tip-to-dedendum interference. Subsequent cyclic contact on areas with damage from tip-to-dedendum interference can lead to contact fatigue, plastic deformation or local breakage (see Reference [31]). To avoid tip-to-dedendum interference, sufficient tip and root relief can be provided to account for pitch errors and the deflection of the teeth under load.

8.13.3 Tight mesh

Typically, when the mesh is running tight (i.e. in double flank contact), scuffing appears on the load flank as well as the coast flank on the mating gear. In severe cases both flanks of both gears can be affected.

9 Manufacturing problems

9.1 Forging cracks

Forging cracks are mainly due to a fold in the rough material that was introduced into the matrix during the forging process. Consequential deep cracks within the material can be attributed to the presence of nonmetallic inclusions at the time of forging.

9.2 Hardening cracks

9.2.1 General

Hardening cracks are caused by excessively high localized internal stresses generated during heat treatment. They usually occur during or after quenching and their orientation is not normally linked to those resulting from in-service gear loading. Sometimes cracks initiate during quenching and only become visible later or during subsequent machining.

The cracks can be caused by nonuniform heating or cooling, or by volume changes due to metallurgical phase transformation. Stress risers make the part more susceptible to cracking.

Crack formation can be related to some of the same factors that cause intergranular fracture in overheated steels.

Cracks resulting from stress induced by heat treatment usually appear immediately but can appear after a period of time or in operation.

9.2.2 Thermal stresses

Thermal stresses are caused by temperature differences between the interior and exterior of the gear and increase with the rate of temperature change. Cracking can occur either during heating or cooling.

The cooling rate during quenching is influenced by the geometry of the gear, the agitation of the quench, quench medium and temperature of the quenchant. The temperature gradient is higher and the risk of cracking greater with thicker sections, asymmetric gear blanks and variable thickness rims and webs. The following preexisting conditions and events can lead to cracking of parts:

— insufficient top or bottom discard practice in ingot casting;

— severe core segregation;

— coarse grain formation (especially in the core of the material);

— solid parts with large cross sections made from high alloyed quenched and tempered steel.

9.2.3 Stress concentration due to heat treatment

Features such as sharp corners, the number, location and size of holes, keyways, splines and abrupt changes in section thickness within a part, cause stress concentrations, which increase the risk of cracking.

Surface and subsurface defects such as nonmetallic inclusions, forging defects such as hydrogen flakes, internal cracks, seams, laps and tears at the forging flash line increase the risk of cracking. See 6.2.6.2 for a discussion of inclusions.

9.2.4 Quench severity

Quenching conditions and severity are usually designed considering size and geometry of the gear, required metallurgical properties and hardenability of the steel. Keeping the quenching only as severe as required lowers the risk of hardening cracks.

Quench severity with an uncontrolled vigorously agitated process can increase the risk of cracking compared to quiescent, slow-oil or polymer quenchants.

Hardening cracks can occur after quenching if the gear is allowed to stand without proper tempering since hydrogen can diffuse to an inclusion where it can initiate a crack.

9.2.5 Phase transformation

Transformation of austenite into martensite is always accompanied by expansion and can result in cracking. See Reference [44].

9.2.6 Material defects

Surface defect or weakness in the material can promote cracking, for example, deep surface seams or nonmetallic stringers (a series of small inclusions in a line) in both hot-rolled and cold-finished bars. Other problems are inclusions and part stamp impressions. See 6.2.6.2 for a discussion of inclusions. Forging defects in small forgings, such as seams, laps, flash line or shearing cracks as well as in heavy forgings such as hydrogen flakes and internal ruptures, aggravate cracking. Similarly, some casting defects, such as porosity, can promote cracking.

9.2.7 Heat treating practice

Through hardening alloy steels can be normalized prior to hardening or any other high-temperature treatment, such as forging or welding, to produce grain-refined microstructure and relieve stresses. Carburizing alloy steels can be normalized or normalized quenched and tempered prior to carburizing. Improper heat-treating practices, such as nonuniform heating or cooling, contribute to cracking. Hardening can cause cracking if the steel is not properly processed.

9.2.8 Tempering practice

As-quenched martensite is brittle and high tensile residual stresses are produced by the volumetric expansion associated with the transformation of austenite to martensite. Minimizing the time between quenching and tempering reduces the risk of quench cracking. Although the parts are often tempered as soon as possible to avoid quench cracking, care is taken to ensure that sufficient time is permitted for large parts to transform to the desired structure through to the centre. Two tempering practices can lead to cracking problems:

— If the parts are tempered too soon, before transformation to the desired structure has taken place, later transformation of the core can induce sufficient stress due to the volumetric expansion to crack the surface.

— Superficial or "snap tempering" of the surface does not always reduce the internal stresses sufficiently to prevent cracking. This problem is particularly severe if rapid heating methods such as induction, flame, or molten salt baths are used, which can induce additional thermal stresses between the surface and the core.

9.2.9 Detection of hardening cracks

Hardening cracks are not permitted as specified in ISO 6336-5, which also provides information on detection of cracks.

9.2.10 Summary of methods that have been observed to reduce the risk of hardening cracks

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

- optimizing geometry by:
  - designing the gear blanks to be as symmetric as possible and keeping section thickness uniform;
  - minimizing stress risers such as abrupt change in cross section, holes, keyways, sharp corners and steel stamp marks. Using chamfers or radii on all edges, especially at the ends of the teeth and at the edges of the gear tooth top lands;
- optimizing metallurgy by:
  - selecting steel type carefully;
  - minimizing surface and subsurface material flaws such as nonmetallic inclusions, forging flaws such as hydrogen flakes, internal cracks, seams, laps, and tears at the flash line;
  - designing the quenching method, including the agitation, type of quenchant and temperature of the quenchant, for the specific gear and hardenability of the steel;
  - tempering the gear immediately after transformation to martensite has finished.

9.3 Grinding cracks

9.3.1 General

Grinding cracks can be caused by excessive gear flank surface temperature resulting from the grinding technique if the grinding cut is too deep, grinding feed is too high, incorrect grinding speed, grinding wheel grit or hardness is incorrect, or flow of coolant is insufficient. Excessive gear flank surface temperature can also result in grinding burn, see 9.5.

Magnetic particle or dye penetrant inspection can be used to detect grinding cracks.

Steels with hardenability provided by carbide-forming elements such as chromium are prone to grinding cracks. This is especially true for carburized gears with a case that has high carbon content, particularly if there are carbide networks. See ISO 6336-5. Extremely high surface hardness increases

