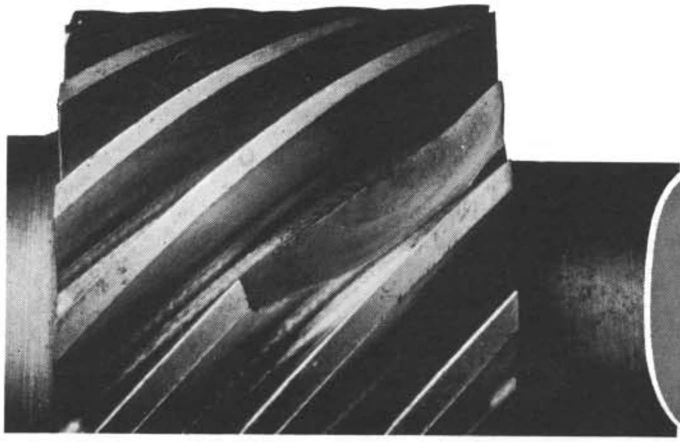
GEAR FAILURES

- *how to recognize them*
- *what causes them*
- *how to avoid them*

Reprinted from MACHINE DESIGN December 7, 1967

This article compliments of: XTEK Inc.
11451 Reading Road
Cincinnati, Ohio 45241
(513) 733-7800



GEAR

• how to recognize them

EUGENE E. SHIPLEY
Manager—Mechanical Transmissions
Mechanical Technology Inc.
Latham, N. Y.

A GEAR has failed when it can no longer efficiently do the job for which it was designed. Cause of failure may range from excessive wear to catastrophic breakage.

Failure in a gear train can in many cases be prevented. When it does occur, the proper redesign will ensure a trouble-free unit. Regardless of when the trouble is rectified—at the design or redesign stage—the most important aid to the designer is the ability to recognize the exact type of incipient failure, how far it has progressed, and the cause and cure of the ailment.

This article rounds up every type—and the major stages—of gear failures. Included are photographs of actual failures, along with probable cause and the most effective remedies.

WEAR: a surface phenomenon in which layers of metal are removed, or "worn away," more or less uniformly from the contacting surfaces of the gear teeth.

Polishing

Polishing is a very slow wearing-in process in which the asperities of the contacting surfaces are gradually worn off until a very fine, smooth surface develops.

Cause: This condition is usually caused by metal-to-metal contact during operation. Generally, "polishing-in" occurs on slow-speed applications where the elasto-hydrodynamic lubrication film is not sufficiently thick and the gears are operating near the boundary-lubrication regime.

Remedy: Often this condition need not be avoided unless the design life of the equipment is much longer than the predicted wear life based on polishing-in. Polishing gives good conformity of the surfaces.

After the gear is well polished-in, the surface can be protected by substituting a lubricant with a higher viscosity, by reducing the transmitted load substantially, or, in some cases, by increasing the operating speed to obtain a better elasto-hydrodynamic oil film.

Polishing: Run-in under operating conditions, this hardened hypoid pinion has developed a highly polished surface. Undoubtedly the extreme-pressure additives in the lubricant had a tendency to promote polishing on the tooth surfaces.

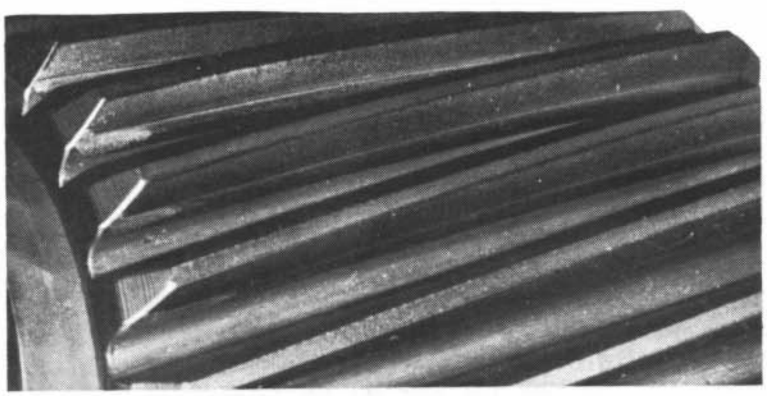
FAILURES

• what causes them • how to avoid them

Moderate Wear

The type of wear classified as moderate takes place over a relatively long period of time. The contact pattern indicates that metal has been removed in the addendum and dedendum area; also, the pitch line begins to show as an unbroken line.

Cause: Moderate wear is most commonly caused by an inadequate lubrication film, with the film thickness being too thin for the load. Dirt in the lubrication system can also cause this type of wear.



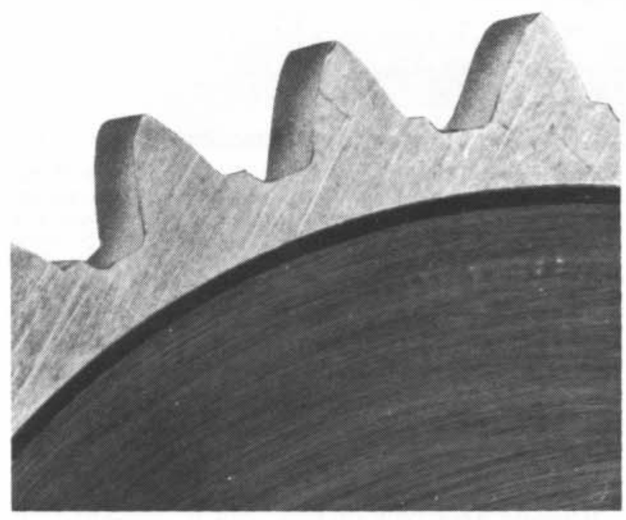
Moderate Wear: The addendum and dedendum sections of these medium-hard gear teeth have worn, causing the operating pitch line to become visible because little if any material has been removed along this line.

Remedy: One solution is to specify a lubricant with a greater film strength, or one with a higher viscosity. Also, the unit can be operated at a greater speed to build up the lubricating film. Finally, a gear material with a higher wear resistance can be specified.

Excessive Wear

This is simply normal wear which has progressed to the point where a considerable amount of material has been removed from the surfaces. The pitch line is very prominent and may show signs of pitting.

Cause: This problem is usually caused by the failure to notice early enough that wear is in progress. When enough material has been worn from the tooth surface, the involute profiles are destroyed and the gears begin to run roughly. The situation is aggravated by the rough running, causing still



Excessive Wear: Material has been uniformly worn away from the tooth surface causing a deep step. The tooth thickness has been decreased and the involute profile destroyed. Some slow-speed gears can operate on such a profile until so much material has been worn away that the tooth fails under beam bending fatigue.

greater wear. Eventually the surface is such that the gears are no longer fit for reliable service.

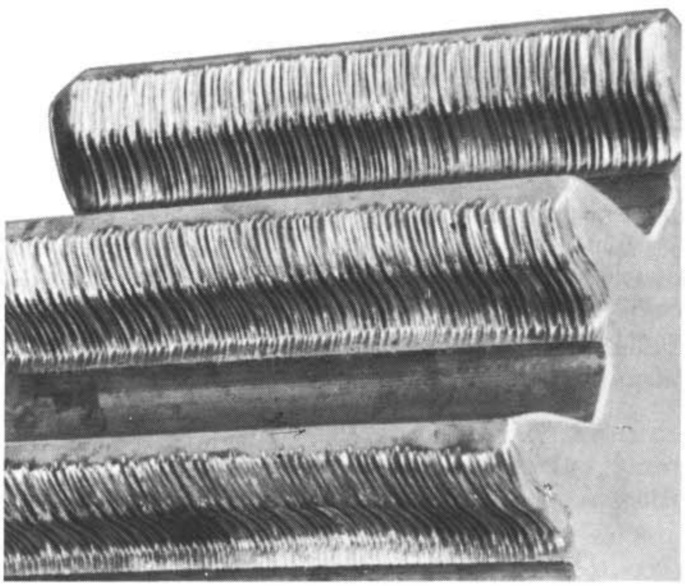
Remedy: This condition could be avoided by using the same methods given for moderate wear—increasing lubricant film strength or viscosity, or increasing pitch-line velocity.

If the gear unit is splash-fed, changing to a positive spray lubrication system with a filter will help keep wear particles out of the gear mesh and ensure that adequate lubricating oil is delivered to the working surfaces.

Abrasive Wear

When abrasive wear has taken place, contacting surfaces show signs of a lapped finish, radial scratch marks or grooves, or some other unmistakable indication that contact has taken place.

Cause: Foreign material in the lubrication system ordinarily causes abrasive wear. The particles may



Abrasive Wear: In this extreme case, a large portion of the tooth of the bronze pinion has worn away due to an accumulation of abrasive particles in the lubricant. Note the deep ridges, and the ends of the gear teeth, which were not subjected to the abrasive action.

be metallic debris from the gear and bearing system, weld spatter, scale, rust, sand, etc. Abrasive wear is often noted soon after startup of a new installation, before the filter has had a chance to clean the system.

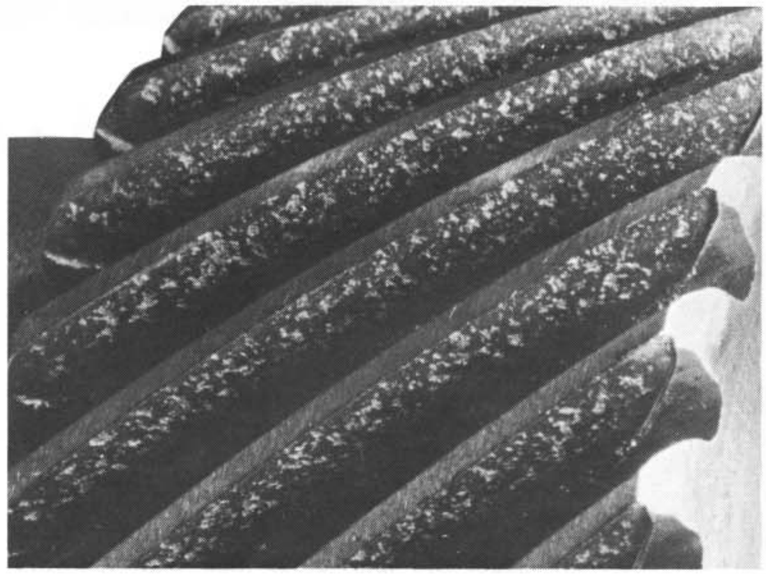
Remedy: This type of wear can be remedied by the use of a filter or, where a filter is already being used, a finer grade of filter. Alternatively, a higher-viscosity lubricant will develop a thicker oil film, which will pass fine particles without scratching. Of course, the best way to guard against early abrasive wear is to see that the gearbox and lubricating system are carefully cleaned before use.

Trouble is often encountered in closed gearboxes without a circulating lubrication system, so that whatever foreign material that accumulates in the box remains there. Therefore, in such cases it is important to change oil often.

Corrosive Wear

This is a deterioration of the surface due to chemical action. It is often caused by active ingredients in the lubricating oil, such as acid, moisture, and extreme-pressure additives.

Cause: The oil breaks down so that corrosive chemicals present in the oil attack contacting surfaces. Often this action affects the grain boundaries, causing fine pitting more or less uniformly over the tooth surfaces. At high temperatures, extreme-



Corrosive Wear: Although considerable wear has taken place, the surface still shows signs of having been attacked chemically. Wear of this nature will continue until the gear surface is beyond usefulness.

pressure additives sometimes form very active corrosive agents. Lubricants can also become contaminated from absorption of foreign material from external sources.

Remedy: Because they are chemically active, lubricants with high anti-scoring, anti-wear additive content must be kept under careful observation to ensure that they are not attacking working surfaces. By checking the lube oil for breakdown and by changing the lube oil at regular intervals, corrosive wear can be avoided.

Often gear lubricants are contaminated with various chemicals from the atmosphere or from foreign material such as salt water or liquid chemicals. In such cases, the gear unit should be sealed from its environment.

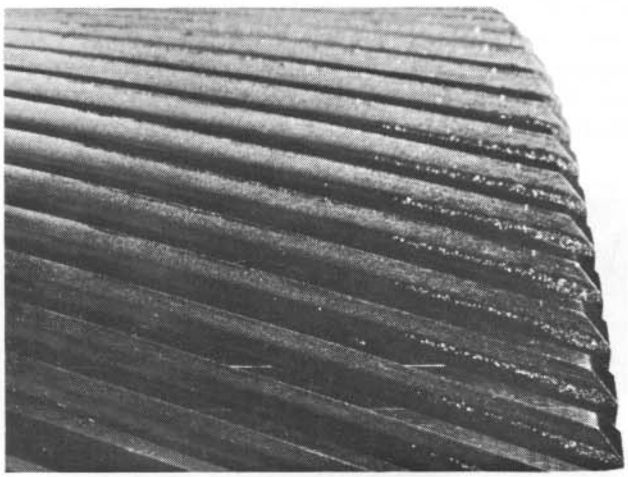
At times, gear-tooth surfaces can be affected chemically during processing in the factory—for example, when copper plate is stripped from the gear after carburizing or when nital-etch is used to detect grinding burns. To avoid trouble of this nature, proper processing procedures must be set up and carefully followed.

PITTING: a surface fatigue failure which occurs when the endurance limit of the material is exceeded, a failure of this nature depends on surface contact stress and number of stress cycles.

Initial Pitting

This condition is characterized by small pits from 1/64 to 1/32-in. in diameter. Initial pitting occurs in localized, over-stressed areas; it tends to redistribute the load by progressively removing high contact spots. Generally, when the load has been redistributed, the pitting stops and the contact surfaces smooth over.

Cause: Initial pitting is usually caused by gear-tooth surfaces not properly conforming with each other or not fitting together properly. This can be a result of minor involute errors or local surface irregularities, but most often it occurs because there is not proper alignment across the full face width of the gear mesh.



Initial Pitting: Pitting began on the outside end of the helix because of a small amount of misalignment, with pits of small diameter. The pitting worked its way from the end to the middle of the tooth. Eventually pitting stopped and the pitted surface began to burnish over, indicating that the load across the tooth had become more evenly distributed. This type of pitting, often called corrective pitting, is most common in medium hard gears.

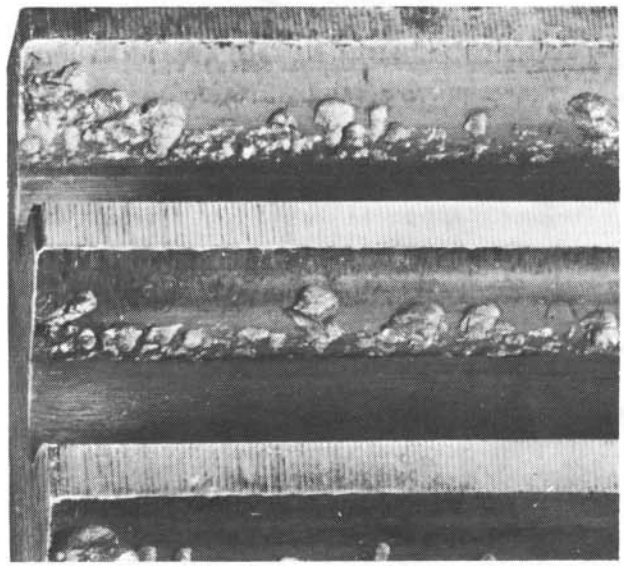
Remedy: This type of pitting can be avoided by providing smooth gear-tooth surfaces and gear-tooth contact patterns that distribute the load evenly across the gear mesh from the very start of operation. To some extent, pitting can be controlled by improving the accuracy of the involute profiles and by introducing profile modification to smooth the meshing action and reduce dynamic loading on the teeth.

Destructive Pitting

In this type of pitting the surface pits are usually considerably larger in diameter than those associated with initial pitting.

The dedendum section of the drive gear is often the first to experience serious pitting damage; however, as operation continues, pitting usually progresses to the point where a considerable portion of all the tooth surfaces have developed pitting craters of various shapes and sizes.

Cause: Destructive pitting usually results from surface overload which cannot be alleviated by corrective (initial) pitting. Once enough stress cycles have been built up, pitting continues until the tooth profile is completely destroyed, causing extremely rough operation and considerable noise. Often a bending fatigue crack will originate from a pit, causing a premature tooth breakage failure.



Destructive Pitting: Heavy pitting has taken place, predominantly in the dedendum region. The pitted craters are larger than those in initial pitting. Some pitting has also taken place in the addendum region.

Remedy: Destructive pitting can be avoided by keeping the load on the surface below the endurance limit for the material. Also, hardness of the material can be increased so that the endurance limit of the material will rise to a point where pitting will not take place. Sometimes pitting can be arrested by increasing the hardness level of only the driving member.

Spalling

Spalling is similar to destructive pitting except that the pits are usually larger in diameter and quite shallow. Often the spalled area does not have a uniform diameter.

Spalling often occurs in medium-hard material, as well as in highly loaded fully hardened material. Spalling of this kind should not be confused with "case crushing" which is associated with case-hardened gear material.

Cause: Spalling is usually caused by excessively high contact stresses. Usually, large pits are formed; because stress levels are high, the edges of the

Spalling: This hardened pinion shows an advanced stage of tooth spalling. Material has progressively fatigued away from the surface until a large irregular patch has been removed.

initial pits break away rapidly and large irregular voids are formed. Often these voids join together.

Remedy: Contact stress on the gear surface can be reduced below the endurance limit of the material. If the gear material is not hardened, hardening will give the material increased surface strength. Often a complete redesign of the gear elements is best since destructive pitting and spalling are evidence that the gears do not have sufficient surface capacity.

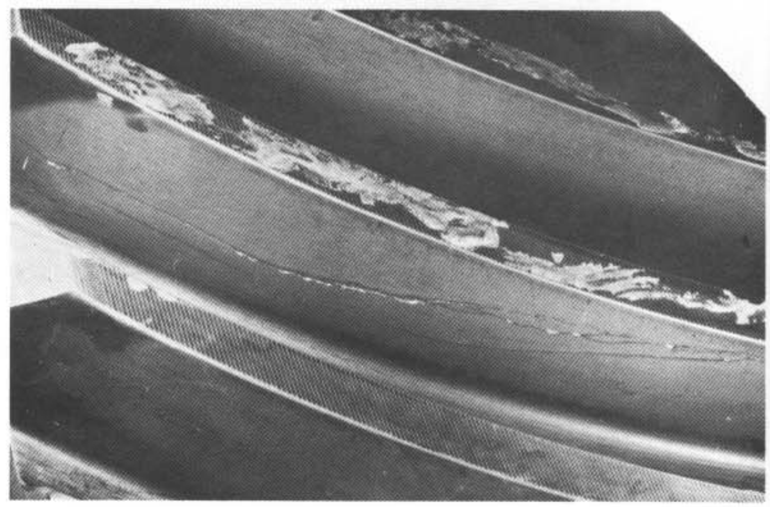
Case Crushing

Although not considered a pitting failure, case crushing may appear similar in that damage has occurred on the contacting surface. It occurs in heavily loaded case-hardened gears, such as those which are case-carburized or nitrided.

Failure often occurs on only one or two teeth of a pinion or gear; the other teeth appear to be undamaged. Often, longitudinal cracks appear on the surface and large, long pieces of the tooth surface break away. The general appearance suggests that the case material has chipped away in large flakes at a parting line just below the case-to-core junction.

Cause: Cracks originate at the subsurface when stresses exceed the strength of the subsurface material. The cracks propagate along the case-to-core boundary and to the surface of the gear tooth. When several cracks reach the tooth surface, large chunks of material are removed. Failures are caused by insufficient case depth or by very high residual stresses in the gear.

Remedy: Failures most often can be overcome by increasing the effective depth of the case material. A change in basic material can be considered—for example, one that produces a hard core material for the same depth of case. Some carburizing materials will produce a 40-Rc core whereas others will only produce 30-32 Rc. This amounts to a considerable difference in strength.



Case Crushing: Several large longitudinal cracks, and several smaller ones, have appeared in the contact surface of this case-carburized bevel gear. The major cracks originated deep in the case-core structure and worked their way to the surface. Long chunks of material are about to break loose from the surface. The cracks should not be confused with normal fatigue cracks, which result from high root stresses and normally form below the contacting face.

SCORING: rapid wear resulting from a failure of the oil film due to overheating of the mesh, permitting metal-to-metal contact; this contact produces alternate welding and tearing which removes metal rapidly from the tooth surfaces.

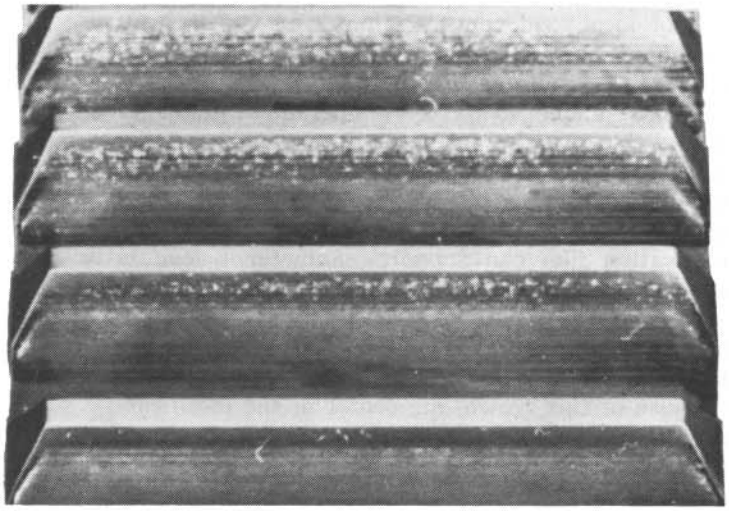
Frosting

Frosting occurs in the early stages of scoring. Usually the dedendum section of the driving gear is the first to show signs of surface distress, although frosting can first show up on the addendum section.

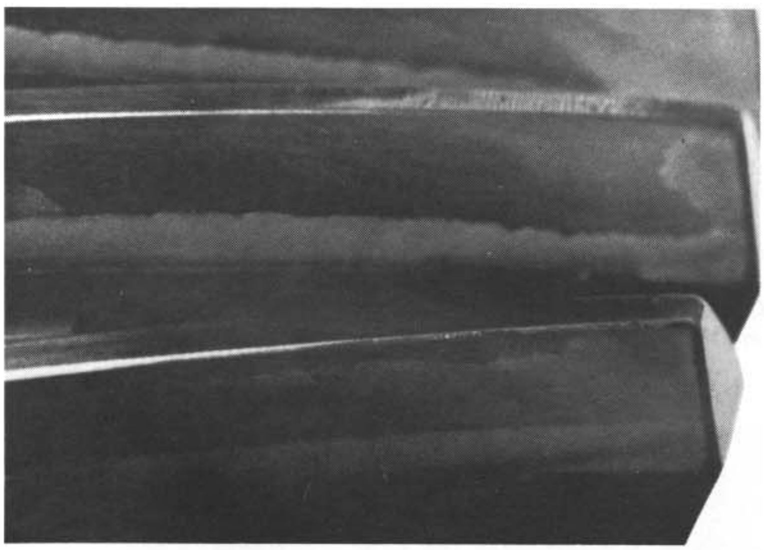
As the name implies, the wear pattern appears frosted. The normal polish of the surface has an etch-like finish. Under magnification, the surface appears to be a field of very fine micro-pits less than 0.0001 in. deep. The frosted pattern will sometimes follow the slightly higher ridges caused from cutter marks or other surface undulations.

Cause: Frosting is caused by heat in the mesh, which results in only marginal lubrication. The heat of the mesh and the bulk temperature of the rotating gears combine to break down the lubrication film.

Remedy: A very careful break-in cycle is often beneficial. A break-in cycle starting with reduced



Frosting: This hardened and ground spur gear shows the early stages of frosting. In this case the addendum portion of the teeth shows the spotty frosting pattern. Damage to this gear is negligible at this stage.



Frosting: This hardened helical gear shows a typical frosting pattern. Note that frosting is predominantly in the dedendum section, although patches do appear in the addendum section. This frosting pattern shows no radial welding and tear marks.

speeds and reduced load will condition the gear-tooth surfaces and improve the conformity of the contacting surfaces so that less local heat will be generated because of better load distribution. Reduced oil temperatures or better control of temperature fluctuations will tend to keep the heat level within safe limits. A mild extreme-pressure oil may be helpful but may not be necessary.

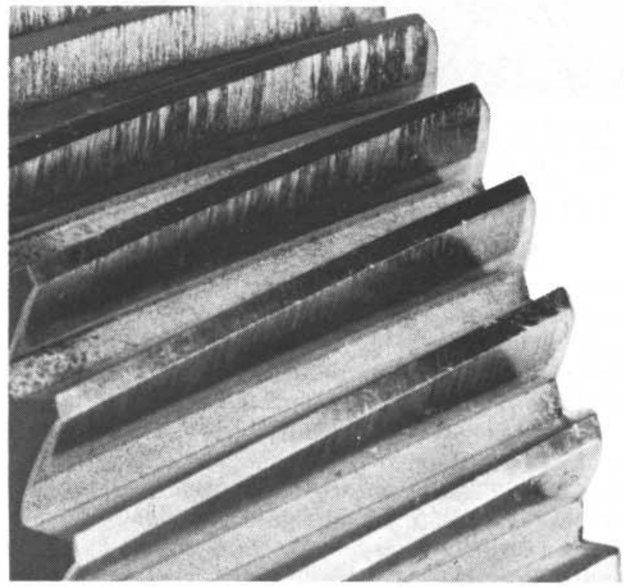
Often, where frosting appears, subsequent operation of the unit will slowly polish away the frosted areas if all operating conditions remain constant.

Moderate Scoring

In this type of failure, a characteristic wear pattern shows up on the addendum or dedendum (or both) of the gear teeth, often in patches. At times, there are indications of radial tear marks; however, this is not always the case. Generally, hard gears appear more frosted. Softer gears show some frosted appearance along with fine radial tear marks.

Cause: Excessive heat in the gear mesh causes this condition, causing lubricant breakdown.

Remedy: The obvious remedy is to reduce the amount of heat in the mesh by cutting down on



Light to Moderate Scoring: At this stage, scoring has a frosty appearance. On close examination, it can be seen that there has been metal-to-metal contact, and alternating welding and tearing.

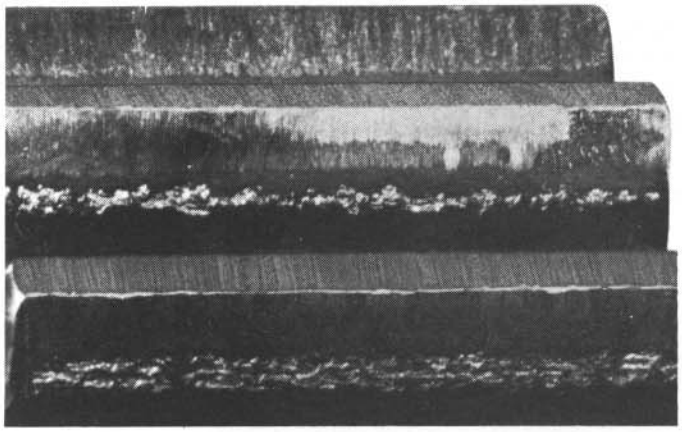
the load being transmitted or the speed of the rotors, or by reducing the inlet oil temperature, which in effect reduces the bulk temperature of the gear rotors. A lubricant with extreme-pressure additives can be substituted. In some cases, a solid lubricant plated on the contact surface helps prevent the scoring from progressing. Also, honing has found increasing use in guarding against scoring.

Destructive Scoring

This type of failure shows definite indications of radial scratch and tear marks in the direction of sliding. Often material has been displaced radially over the tips of the gears. Also, there are indications that considerable material has been removed from above and below the pitch line, and the pitch line itself stands out prominently. The profile is completely destroyed and for all practical purposes the gear is not fit for service.

Cause: This failure is usually caused by inadequate lubrication or by excessive operating temperature, surface load, or surface speed, all of which generate excessive heat. When the lubricant breaks down, the welding and tearing destroys the profile in minutes.

Remedy: The lubricant must be able to stand up under the load, speed, and temperature con-



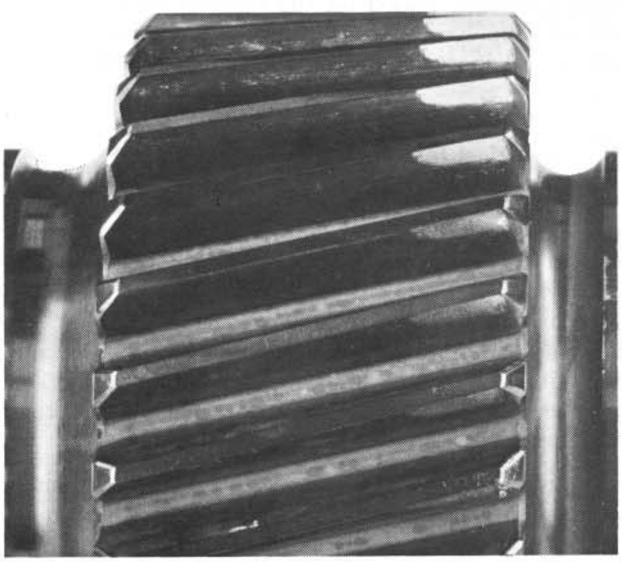
Destructive Scoring: Heavy scoring has taken place above and below the pitch line, leaving the material at the pitch line. As a result, the pitch line pits away as it attempts to redistribute the load. Usually the gear cannot correct itself and ultimately fails.

ditions of the mesh. Extreme-pressure additives are useful. Also, special high-viscosity compounded gear oil will often prevent scoring of this nature. Synthetic fluids with anti-scoring additives will prevent scoring at higher temperature.

In general, a careful analysis of the amount of heat being generated by the mesh is necessary, so that a fluid can be chosen that matches these conditions. If this is not possible, the gear set must be redesigned to reduce surface stresses, mesh losses, pitch-line velocity, and inlet-oil temperature.

Localized Scoring

This scoring, similar to moderate scoring, takes place in localized areas along the contacting pattern of the gear teeth. Scoring is usually concentrated in these areas and does not spread across the full face width of the contacting gears.



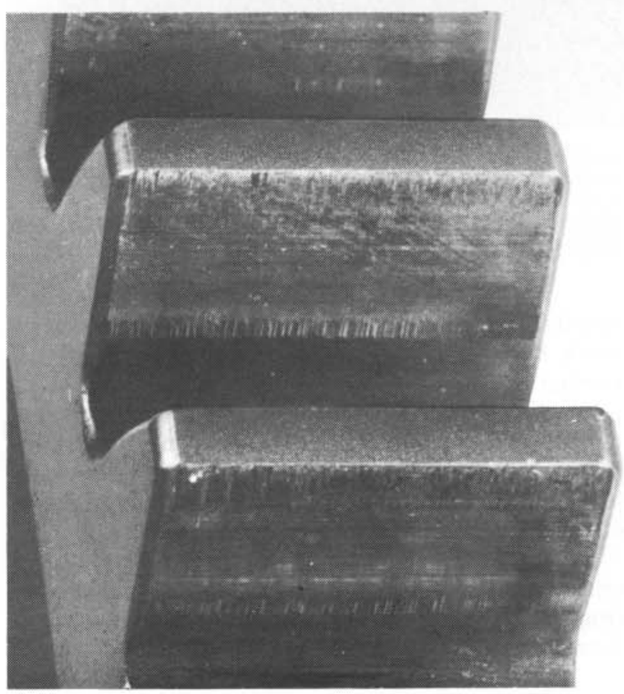
Localized Scoring: This high-speed, high-load helical gear shows localized scoring on the ends of the teeth. This failure was caused by a design oversight: when the gear casing reached operating temperature, differential expansion caused a shift in alignment across the face of the gear. The resulting load distribution caused scoring.

Cause: Scoring of this nature is usually the result of local load concentrations caused either by design or by unintentional factors such as a misalignment resulting from poor manufacture, deflections under load, or temperature gradients across the face due to non-uniform cooling of the mesh. If the load concentration is near the ends of the teeth, the cause is misalignment, with more load being carried on this portion of the teeth than the lubrication film can support. Sometimes load is concentrated in the center of the gear teeth.

A crown is sometimes used at the center of the tooth to prevent the load from shifting if the design is prone to misalignment under operation. Because of this crown, the center of the tooth carries more load; often the higher load breaks down the lubrication film, permitting metal-to-metal contact and subsequent scoring. Sometimes an "effective crown" can be caused by unequal cooling of the mesh, which in effect causes the diameter of the gear in the center to grow with respect to the diameter of the two ends. Wide-face gears are particularly prone to this difficulty.

Remedy: Scoring failures of this nature can be avoided by eliminating localized loading. If misalignment is present, the gear casing may be deflecting non-uniformly, gear-shaft deflection may be excessive, bores of the casing may be out of parallel, or the gears themselves may be cut with a helix-angle error.

To eliminate localized scoring due to temperature gradients, particular attention must be paid to obtaining uniform heat removal across the mesh. Changes may be necessary in the amount of cooling oil and how it is applied to the mesh. If scor-



Tip and Root Interference: This gear shows clear evidence that the tip of its mating gear is fouling the root section. Localized scoring has taken place, causing rapid metal removal in the root section. Generally, interference of this nature can cause considerable damage.

ing is the result of too much crown, this crown can be reduced to a safer level.

Tip and Root Interference

In this type of scoring, the deep-dedendum portion of the gear shows definite signs of metal removal and may often show destructive radial scratch marks. Other portions of the contacting face look undamaged. Sometimes the tip of the gear or pinion shows unmistakable signs of metal removal, with the damaged tips having an abraded look and tear marks in the direction of rotation.

Causes: This condition is not entirely dependent on the normal causes of scoring failure. The tip of the pinion may require tip modification, the root section of the gear may have a profile error, or the gear pair may be running on tight centers. The heavy loading at the tip or root of the mating pair or the interference caused by a tight mesh prematurely breaks down the lubricant film, causing rapid metal removal at the tips and roots and general abrasion of the teeth.

Remedy: Tip and root interference can be avoided by designing a generous profile modification into the true involute form. Often, tight centers can be avoided by specifying more backlash for the assembled gear pair.

I

FRACTURE: failure caused by breakage of a whole tooth or a substantial portion of a tooth; this can result from overload or, more commonly, by cyclic stressing of the gear tooth beyond the endurance limit of the material.

Fatigue Breakage

Gear-tooth failure from bending fatigue generally results from a crack originating in the root section of the gear tooth. The whole tooth, or a part of the tooth, breaks away. Most often there is evidence of a fatigue "eye" or focal point of the break. The break shows signs of fretting and conventional smooth beach marks in the break area. Generally there is a small area that shows a rough, jagged appearance, indicating this was the last portion of the tooth to break away.

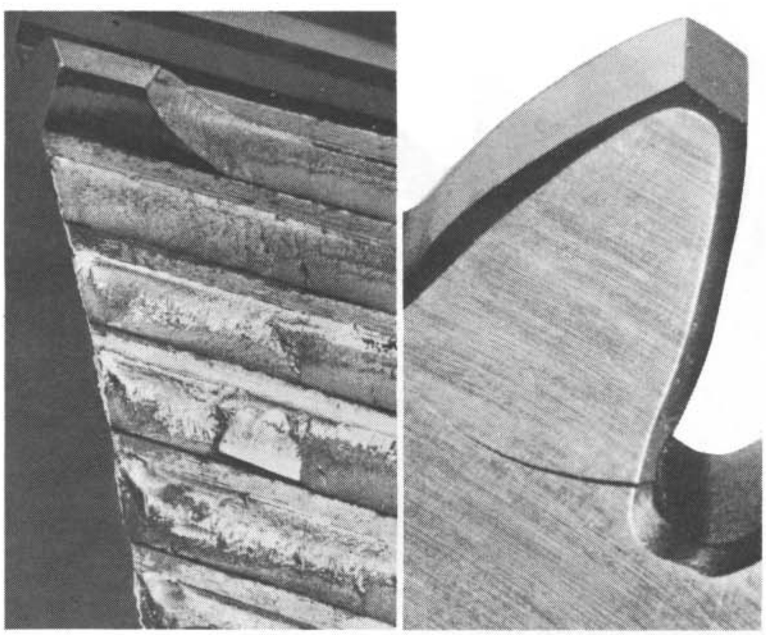
Cause: The causes of bending fatigue failures are many. Most failures result from excessive tooth loads, which result in root stresses higher than the endurance limit of the material. When gears are loaded in this manner and subjected to enough repeated stress cycles, the gear tooth will fail.

Sometimes stress risers help to aggravate this condition and subject the gear to higher root stress levels than would normally be predicted. Such risers include notches in the root fillet, hob tears, inclusions, small heat-treat cracks, grinding burns, and residual stresses.

Remedy: The best way to avoid fatigue breakage is to design the gear-tooth elements so that the transmitted load will result in stresses well within the endurance limit of the material. Alternatively, a higher-strength material may be specified.

Root fillets can be polished and shot-peened. Often, adjustments to the root fillet areas are helpful. A full fillet-radius tooth has more capacity than a tooth having two sharp fillet radii.

Care should be taken that the material has been properly heat-treated to obtain the best structure and to minimize any harmful residual stresses.



Beam Bending Fatigue: (right) This aircraft power spur gear shows a fatigue crack caused by stresses at the root fillet.

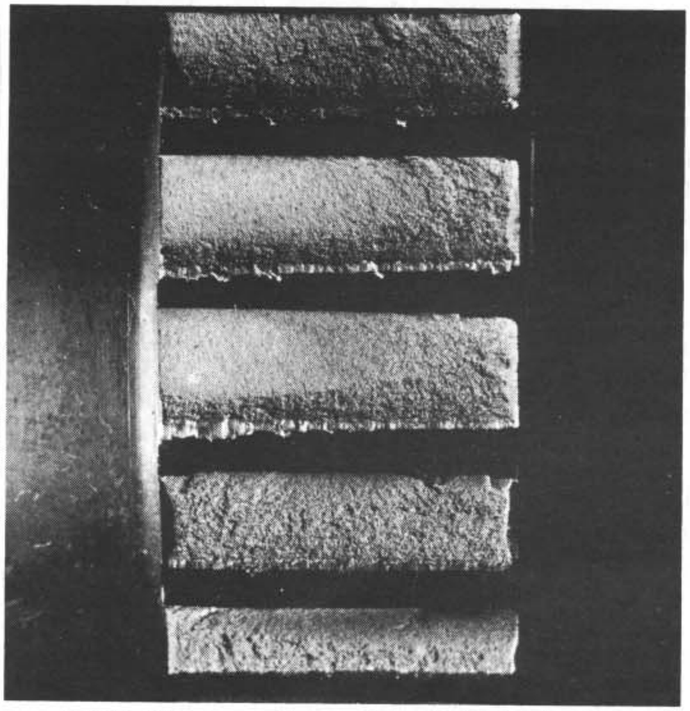
Beam Bending Fatigue: (left) Each failed tooth started at a crack that had been in progress for some time. All the failed teeth show evidence of fretting corrosion and typical beach marks common to this kind of failure. Undoubtedly one tooth broke away first, causing an impact that then quickly broke the remainder of the teeth.

Overload Breakage

An overload fracture results in a stringy, fibrous break showing evidence of having been pulled or torn apart. In harder materials the break has a finer stringy appearance but still shows evidence of being pulled apart abruptly.

Cause: Tooth breakage is caused by an overload which exceeds the tensile strength of the gear material; this results in a short-cycle break generally starting on the tensile side of the root fillet. Overload may result from a bearing seizure, failure of driven equipment, foreign material passing through the mesh, or a sudden misalignment from a failed or wiped gear bearing.

Remedy: It is difficult to design against failures of this type, since often the failure is a direct result of some unpredictable occurrence. It may

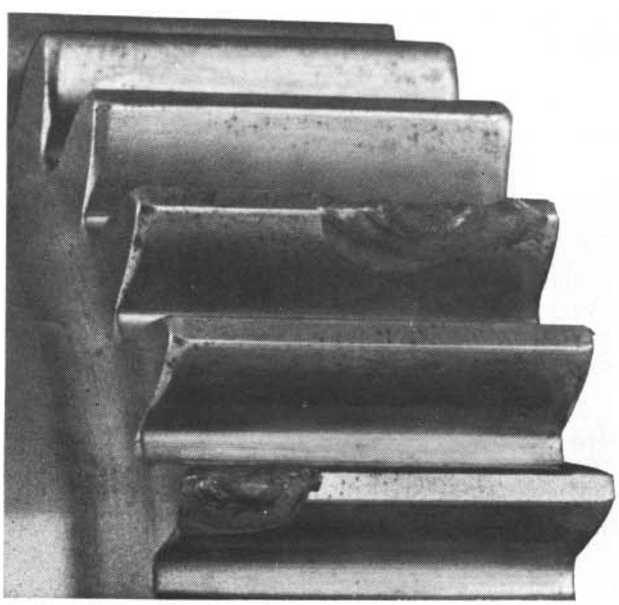


Overload Breakage: The break in this hardened and ground spur gear has a brittle fibrous appearance and the complete absence of any of the common beach marks associated with fatigue failure. In this case, one tooth failed from shock and the force was transmitted to successive teeth. As a result, several teeth were stripped from the rotating pinion.

be possible to incorporate overload-protection devices, such as torque-limiting couplings with shear sections.

Random Fracture

Gear-tooth breakage is usually associated with the root-fillet section of the gear tooth; however, breakage failure can occur in other portions of the gear tooth. Sometimes, the top of a gear tooth will break away or large chips will fatigue away from the end of a tooth.



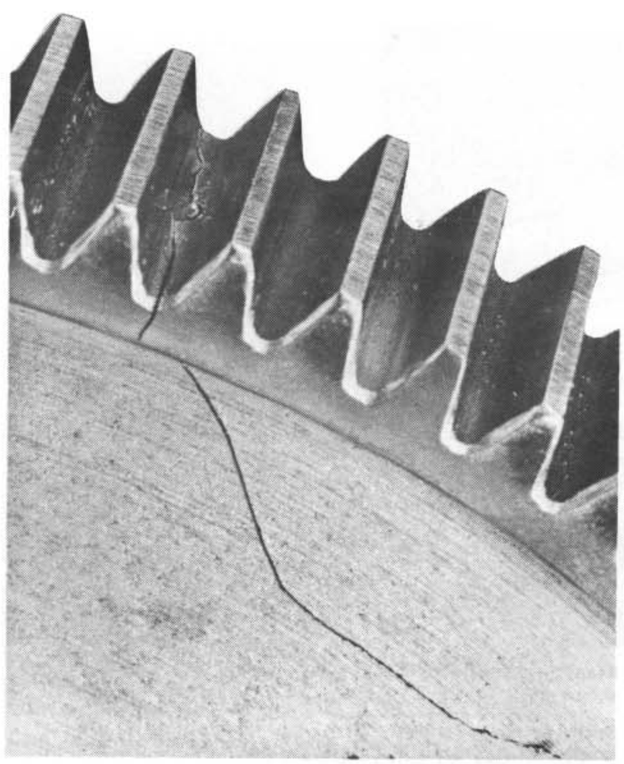
Random Fatigue Breaks: These breaks are not typical beam bending failures. They originate high on the tooth flank and are somewhat uniformly dispersed across the face of the gear. Failures of this nature originate from stress risers other than at the root fillet. In this installation, fatigue failure resulted from grinding cracks on the tooth flanks.

Cause: Failures of this kind are often caused by deficiencies in the gear tooth which result in a high stress concentration at a particular area. Often, flaws or minute grinding cracks will propogate under repeated stress cycling and a fracture will eventually develop. Foreign material passing through the gear mesh will also produce short-cycle failure of a small portion of a tooth. High residual stresses due to improper heat treatment can cause local fractures that do not originate in the tooth section.

Remedy: It is difficult to prevent failures of this type except by good design and manufacturing practices. If trouble is encountered, the gear surfaces should be checked for possible previous damage that may have contributed to local stress risers. The history of heat treatment and manufacturing techniques should be reviewed to ensure that proper processing was carried out during all steps of the manufacturing cycle. Cleanliness of the gear material should also be examined.

Rim and Web Failure

The rim of a gear usually fails between two adjacent teeth. Cracks propogate through the rim and into the web. Sometimes, cracks appear in the web near the rim and web junction without disturbing the rim itself.



Rim and Web Failure: This hardened and ground spur gear fractured through the root section. The crack propagated from the root section into the web of the gear. Such failures are not uncommon on highly loaded thin rims and webs.

Cause: Often, the failures are caused by flexure stresses in the gear teeth. If the crack starts from a high stress point, it may propagate through the rim instead of across the tooth at the root section. Web cracks may be caused by stress risers from holes in the web, or by web vibrations.

Remedy: If the gear fails through the rim, the rim thickness may be increased. The rim thickness below the root diameter should be a minimum of 1.5 times the whole depth of the root. Stress risers in the root section—such as hob tears, grinding-wheel nicks, and grinding cracks—must be eliminated. If the web fails, increasing the web thickness may be helpful. All stress risers in the web area—such as deep tool marks, lightening holes in the web, and sharp fillets in the web-to-rim junction—should be eliminated.

Often, rim and web failures are caused by vibrations. In cases of this nature, the natural frequencies of the gear must be changed either by redesign of the gear or by damping.

PLASTIC FLOW: cold working of the tooth surfaces, caused by high contact stresses and the rolling and sliding action of the mesh; it is a surface deformation resulting from the yielding of the surface and subsurface material, and is usually associated with the softer gear materials—although it often occurs in heavily loaded case-hardened and through-hardened gears.

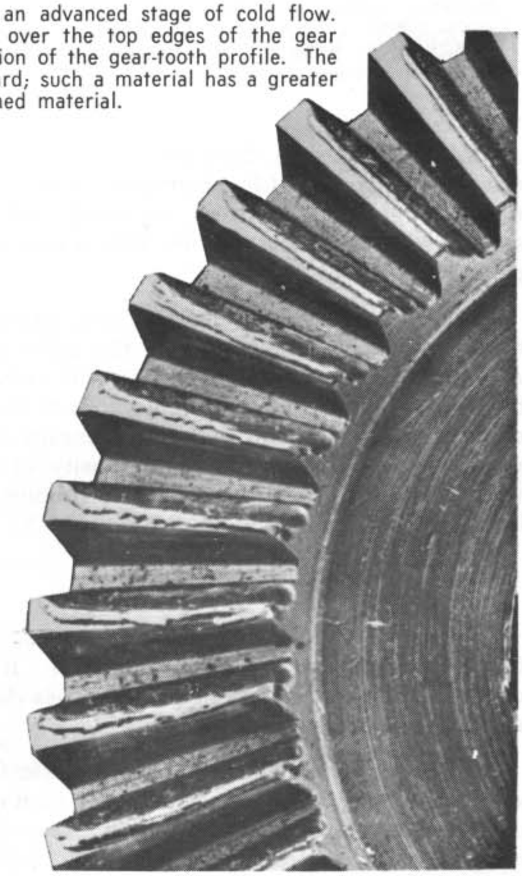
Cold Flow

In this type of failure, the surface and subsurface material shows evidence of metal flow. Often surface material has been worked over the tips of the gear teeth, giving a finned appearance. Sometimes the tooth tips are heavily rounded-over and a depression appears on the contacting tooth surface.

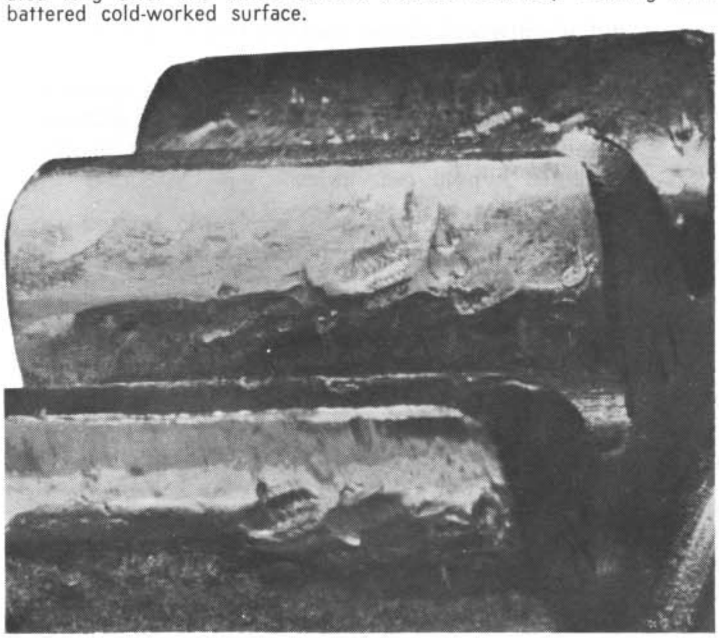
Cause: Under heavy load the rolling and peening action of the mesh cold-works the surface and subsurface material. The sliding action tends to push or pull the material in the direction of sliding, if the contact stresses are high enough. The dents and battered appearance of the surface are the result of dynamic loading due to errors produced during the manufacturing process, or caused by continuous operation while the profile is in the process of deteriorating from a combination of cold-working and wear.

Remedy: Failures of this type can be eliminated by reducing the contact stress and by increasing the hardness of the contacting surface and subsurface material. Increasing the accuracy of tooth-to-tooth spacing and reducing profile deviations will give better tooth action and reduce dynamic loads.

Cold Flow: This bevel gear shows an advanced stage of cold flow. Much material has been rolled out over the top edges of the gear teeth, resulting in complete destruction of the gear-tooth profile. The material of this gear was medium-hard; such a material has a greater tendency to flow than a case-hardened material.



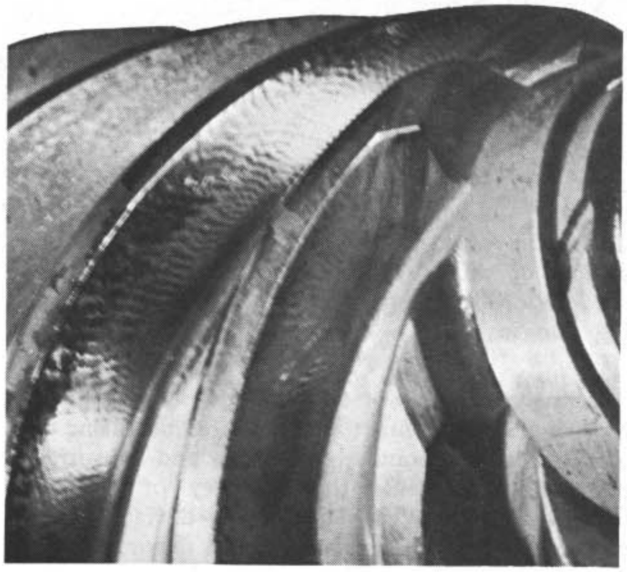
Cold Flow: This medium-hard spur gear shows signs of bad surface deformation due to rolling and peening action. This gear was operated long after the initial surface distress occurred, resulting in a battered cold-worked surface.



Rippling

This is a periodic wave-like formation at right angles to the direction of sliding or motion. It has a fish-scale appearance and is usually observed on hardened gear surfaces, although it can occur on softer tooth surfaces under certain conditions. Rippling is not always considered a surface failure, unless it has progressed to an advanced stage.

Cause: High contact stresses under cyclic operation tend to roll and knead the surface causing the immediate subsurface material to flow. Slow-speed operation is usually associated with this type of failure, because it does not build up adequate elasto-hydrodynamic film thickness. This combination of high contact stress, repeated cycles, and an inadequate lubricating film will produce a rippled surface.



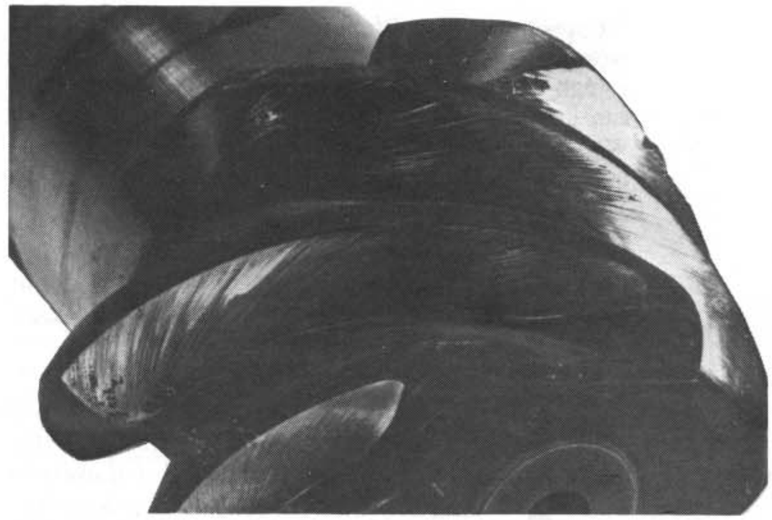
Rippling: A typical case of rippling appears on this hardened hypoid pinion. Note the waviness or fish-scale pattern. Rippling often shows up on highly loaded hypoid gears but can be produced on highly loaded spur gears as well.

Remedy: If the gear material is soft, rippling can be prevented by case-hardening the tooth surface. Also, reduction in contact stress will reduce the tendency of the surface to ripple. Since the lubricating film is marginal, extreme-pressure additive in the oil and an increase in viscosity of the oil will be beneficial. An increase in rubbing speed is sometimes helpful.

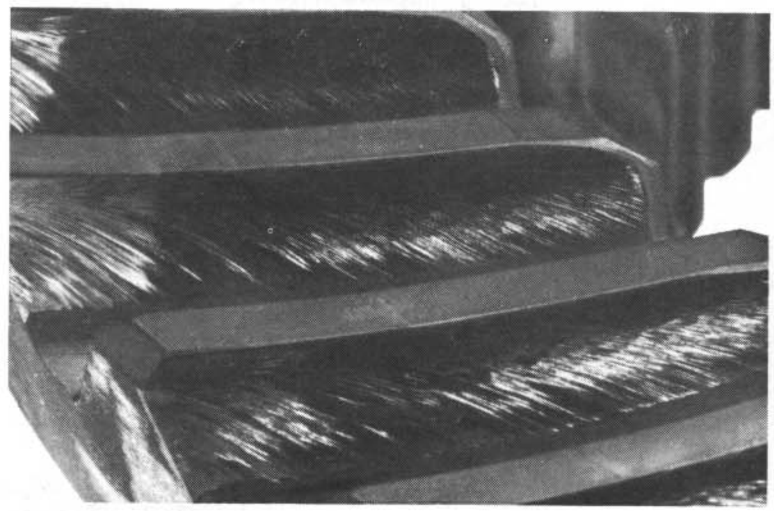
Ridging

This is the formation of deep ridges by plastic flow of surface and subsurface material. It shows definite peaks and valleys or ridges across the tooth surface in the direction of sliding.

Cause: Ridging is caused by the plastic flow of surface and subsurface material due to high contact compressive stresses and high relative sliding velocities. It is often present on heavily loaded worm and wormwheel drives and on hypoid pinions and gear drives.



Ridging: On this hardened pinion, note that some wear has taken place and that some surface pitting is present although the predominant mode of failure is ridging.



Ridging: This is an excellent example of how ridges form on the surface of a hardened gear. Although the surfaces are very hard, the ridges show a definite peak-to-valley effect in the direction of sliding.

Often, ridging exists on low-hardness materials but may also be present in high-hardness materials if the contact stresses are high, such as in case-hardened hypoid rear axles.

Remedy: Ridging can be prevented by reducing the contact stress, increasing the hardness of the material, and using a more viscous lubricating oil with extreme-pressure additives. It is also helpful in drives that do not have circulating lubricating systems to change the oil often and to ensure that no foreign particles remain in the lubricant.

ACKNOWLEDGMENT

Much of the data contained in this article was assembled while the author was employed at the General Electric Co. in Lynn, Mass. The author also wishes to thank the following companies who contributed data and photographs: Lubrizol Corp.; Socony Mobil Oil Co.; Gleason Works; The Buehler Corp.; Continental Oil Co.; Celanese Corp.; Rocketdyne Div. of North American Rockwell.