Classification of Types of Gear Tooth Wear - Part I.

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Introduction

The phenomena of deterioration of surfaces are generally very complex and depend on numerous conditions which include the operating conditions, the type of load applied, the relative speeds of surfaces in contact, the temperature, lubrication, surface hardness and roughness, and the compatibility and nature of materials.

Wear is a general term covering the local phenomena describing the removal of some material and occurring when two surfaces slide onto one another. This term also applies to the removal of material resulting from the presence of impurities in the lubricant. Other types of gear failures, such as surface fatigue, corrosion, plastic flow, and breakage are not covered by this article.

Wear may be divided into two distinct classifications: Qualitative, which is based on the action modes of different wear phenomena on gear teeth and characterized by surface appearance; and quantitative, which takes into account the intensity of the wear phenomena.

The qualitative wear phenomena we will discuss include abrasive wear with two bodies, streaks and scoring, polishing, hot and cold scuffing, abrasive wear with three bodies, scratches or grooves, and interference wear. In the quantitative analysis we will define normal wear, moderate wear, and excessive wear. A synthesis of these two classifications has been made under a chart found in Part II.

Current Wear (Called Two Body Abrasion)

Current wear is revealed very early in the life of the gear or gear train and is evidenced by the removal of micro-particles of metal on the gear teeth surfaces. This phenomenon is caused by contact and metal-to-metal sliding, which occurs through the oil film. The distinctive machining marks of the cutting procedure or finish (for example, the facets resulting from hobbing, the streaks left by a gear cutter or by a rack cutter, the surface pattern from certain grinding operations) are diminished or erased by wear.

This wear brings about a progressive reduction of gear tooth thickness, along with a more or less marked distortion of the profile in the heavy sliding zones, but without noticeable degradation of the surface roughness.

As indicated in Fig. 1, the wear is almost nil

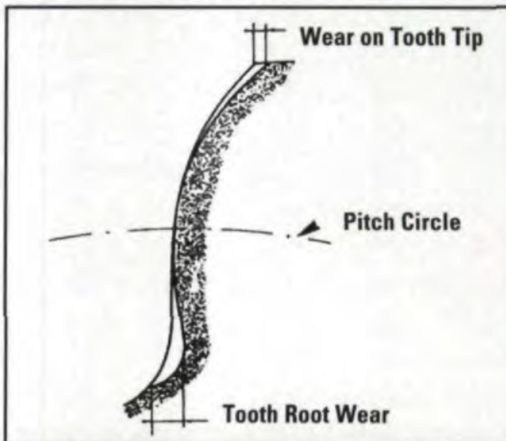

Fig. 1 - Distinctive aspect of distortion of gear tooth profile under wear action

Fig. 2 - Traces of wear recorded on a gear wheel in operation.

in the pitch zone where the sliding speeds are low or nil, and becomes more and more pronounced as we move away from this zone. This zone is maximum at the tip circle and at the active dedendum circle, where the sliding speeds are the highest.

The wear zone is generally gray colored and slightly dull, with sometimes lustrous areas and the presence of scoring. (See Fig. 2). Note the presence of a dull zone below the pitch, where the wear is greater, and of a lustrous area on each side of the pitch and slightly higher. Also note the transverse scoring slightly marked near the tooth tip and the machine streaks still visible near the pitch.

The appearance of this wear, as well as its developing speed, varies greatly according to the pressure level between the contact surfaces, the hardness of the materials, the roughness of surface, and the thickness of lubricant film. For example, in the case of slightly loaded gears operating with an oil of relatively high viscosity at medium speeds, we will have an oil film sufficiently thick to avoid metal-to-metal contact. This will not generate wear except during starting or stopping. The original machining traces will still be intact on the gear teeth after long periods of operation.

In practice it is not always possible to have a continuous lubricant film between the gear teeth according to the load transmitted. Then contact occurs between the top of the asperities made during machining, and there is a tendency to polish or score the surface in contact.

In the case of surface-hardened gears, because of the high hardness of flanks in contact, we encounter only slight wear which is often difficult to see.

Scoring - Streaks

This type of wear appears in the form of fine grooves or lines in the sliding direction. These streaks or scores are formed progressively in the zone characterized by a high sliding speed, at the tooth tip and near the root of the gear teeth. (Fig. 3)

They are often developed on pinion teeth and wheel teeth that are in contact at the very beginning of meshing of mating profiles. The bottom of the striae are smooth compared to those found in traces of scuffing.

Causes. The presence of these scores or streaks reveals the existence of relatively high pressures locally affecting the gear teeth flanks. Under high load action, the asperities caused by the roughness of the mating flanks, as well as foreign particles of small dimensions that imprint into the gear teeth flanks, along with the slippage effect, cause cavities which appear as streaks.

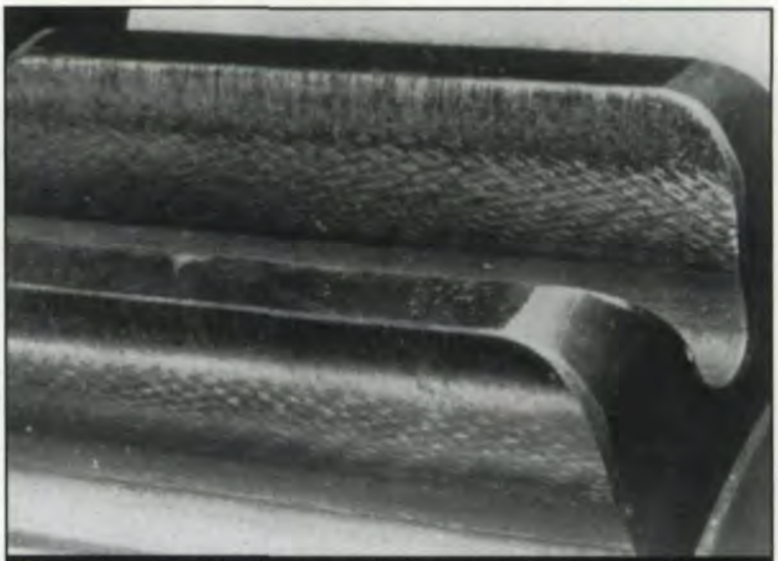

Fig. 3 - Scoring or streaks seen at the beginning of a gear operation.

The formation of scoring can be considered as a preliminary stage preceding scuffing. These streaks generally lead to more severe local wear of gear teeth in the zones where there is a higher pressure. Frequently we note in time a stabilization of these streaks when the wear level of the scored surfaces has been sufficient to generate a better distribution of the load, which as a consequence diminishes the maximum pressure on the gear teeth. In this case only the black color base of streaks or scoring will remain. This stabilization phenomenon can be accelerated by increasing the oil viscosity and by improving filtration. This type of wear is often encountered in worm gears. (Fig. 4)

Adhesive Wear

Adhesive wear appears on two surfaces sliding across one another when the pressure between the asperities in contact is sufficient to cause localized plastic deformations, micro-weldings, or local adhesions. When there is generation or plastic deformation, there is energy absorption which leads to overheating due to friction.

The mildest form of adhesive wear is the formation of "polishing" on the active flanks of the gear teeth. When the load condition and friction become more intense, and when the

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temperature at contact level increases, we may witness the appearance of localized metal adhesions on the teeth, hot scuffing, or cold scuffing (for low speeds and heavy loads).

Polishing. Polishing is a type of very slow progressive wear in which the asperities of the mating flanks are distorted and laminated and then appear on the gear teeth as very smooth and polished surfaces, which take on a mirror aspect. Such wear conditions are caused by metal-to-metal contact during operation. Generally the polishing occurs in applications at low speeds (<20 m/sec) when the lubricant oil film in elastohydrodynamic yield rate is not sufficiently thick and is near the limit of the lubricant performance. Generally, this type of wear does not cause large variations in the shape and in the dimensions of gear teeth. However, when examined under a microscope, the structure just below the contact surface reveals the presence of plastic flows in the material under slippage. Sometimes very localized overheating traces near the surface are also encountered. The polishing encourages establishing gear teeth contact patterns in service and allows obtaining a good conformity of surfaces in contact.

Fig. 4 - Scoring by circular streaks seen on a worm gear.

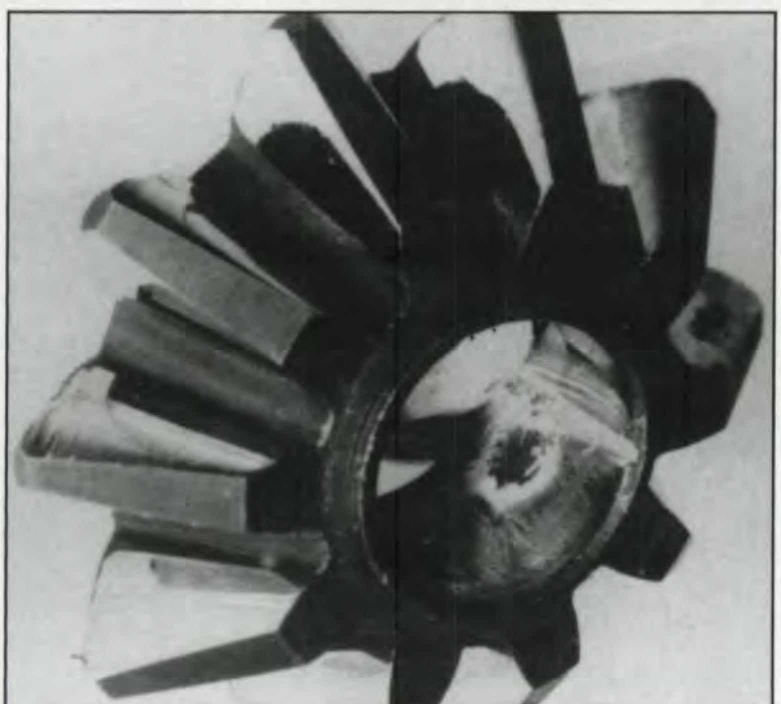

Fig. 5 - Polishing on a gearbox satellite.

This type of wear is not "damage" and can be tolerated in service unless the initial material specifications forbid it. If the load increases, or if the lubrication conditions become insufficient, this type of gear tooth wear can develop because the temperature between surfaces in contact will increase and render them superficially less hard and more sensitive to localized micro-welding formations. The appearance of adhesion or scuffing traces on the gear teeth flanks can then be seen. To prevent such traces, we can, after the appearance of polishing, increase slightly the oil viscosity to obtain in normal working conditions a thicker hydrodynamic film. We can also, when possible, reduce slightly the load to be transmitted, but in all cases we must assure that in service there is no risk of producing severe overloads (no matter how short they may be), which would damage greatly the gear teeth surfaces.

Generally the polishing appears quickly on loaded gears made with good precision and most often on surface-hardened gears. The most noticeable examples are found in automotive gears, such as, satellite and planet gears, gearbox pinions, and spiral bevel gears. (Figs. 5-6)

Adhesions. This phenomenon, which appears on some gear mating flanks, is always very localized and generally is only present on a small area of a few gear teeth. For each metal pull-off or adherence, we can almost always distinguish a zone where a brutal welding has occurred between the profiles in contact and which was immediately sheared. On one of the flanks, a metallic particle has pulled off and is often found fixed by adhesion onto the flank of the other gear. The irregularities on the two surfaces after separation have generated streaks or scratches oriented in the separation direction of the profiles, starting in the zone where the adherence or metal pull-off occurred.

In the welding zone, the profile is generally altered in depth, whereas it is more superficial near the scratches, which generally are less and less severe as we go further from the initially damaged zone. This type of damage is encountered on gear teeth flanks in the high slippage zones, where the contact surface is preponderant or localized because of the presence of a slight excess of material caused by a machining defect or a profile with excessive crowning; by a slight alignment defect of gear teeth caused by the machining operation of the gear of by distortion under load; or by a local distortion along the flanks caused by a temperature gradient generated by an irregular flow of heat during meshing. This contact surface localization causes such an increase in load that it no longer can be supported by the lubricant film, which leads to metal-to-metal contact and the formation of micro-welding by friction.

The development of this type of damage is encouraged by a state of "polishing" on the surface of flanks in contact and by the presence of severe undulations or poor teeth surface roughness. The first case is common in surface-hardened teeth, and the second in rough machine-cut teeth of normalized steel.

The formation of localized metal pull-off can also be caused by the passage of a foreign metallic particle between the profiles. In fact, after its lamination between the gear teeth, such a particle will weld itself onto the surface of one of the profiles under slippage, creating a localized excrescence.

This risks generating an overload during meshing which may cause a sudden rupture of the oil film, thus causing the formation of a metal pull-off on the mating profile. When the numbers of gear teeth on the pinion and on the wheel are in an integer ratio, and such an adhesion appears on one tooth, it may cause similar damage on a limited number of other teeth, and the phenomenon has all the chances of stabilizing by itself afterwards. If the numbers of teeth are prime between themselves, we will have a general sweep of all the teeth by those from the pinion and wheel which have been affected by the initial metal pull-off. The deterioration will thus progress to all the teeth flanks, and there is a risk of evolution towards hot scuffing (at high speeds) or cold scuffing (at low speeds). Quite often this evolution can occur within minutes.

We are often tempted to say that the presence of adhesion on a tooth is not too serious because its surface is small. In reality, this type of deterioration, in the case of surface-hardened teeth, can often go along with cracks that develop from the surface down and which will quickly lead to tooth breakage. Such cracks are formed by residual stress of thermal origin and appear at the moment of instant welding by slippage of the two flanks in contact.

Before planning to re-use surface-hardened gears with or without an eventual grinding surface operation, it is essential to perform a dye penetrant or magnetic particle control of the teeth flanks where the adhesion occurred.

In the case of through-hardened gears, this cracking risk is practically non-existent.

If we ascertain, upon opening a reducer or a gear wheel, the presence of adhesions on the teeth, we can come to the following conclusions:

• There has been periodic lubricant film breakage on the teeth where contact pattern area was preponderant.

• The initial precision of the gear or reducer is generally not affected, for we should have noticed this phenomenon under nominal load during start-up of reducer.

The causes of this anomaly may be:

1) Distortion of the gear support or reducer, bringing about an evolution of the contact sur-

Fig. 6 - Polishing on a spiral bevel gear.

face towards the tips of teeth (in cases of adherences near the tooth tip).

2) Progressive loss of lubricant oil viscosity characteristics or temporarily insufficient lubrication (Cf. case of open gears).

3) Unforeseen and brutal overloads.

4) Passage of a foreign body (adherent metallic particle).

When we are faced with such degradation, the remedies are generally simple. After checking that the gear teeth precision and their eventual profile and helix modifications fulfill their function, one must:

1) Assure that the lubricant and lubrication devices are in working order and capable of performing their function.

2) Eliminate the risk of untimely occasional overloads applied to the gear (Torsional vibrations, high torque variation, pumping effect, etc.).

For added safety the lubricant viscosity can be increased (if necessary). Fig. 7 gives an example of metal adhesions encountered on several teeth of a spiral bevel pinion.

Hot Scuffing. This wear phenomenon results from oil film breakage under excessive overheating during meshing, which causes a metal-to-metal contact of teeth flanks. Local welds and shearing are alternately produced between the contact surfaces and contribute to the quick pull-off of metallic particles from the teeth flanks, thus progressively modifying the state of their profile.

The scuffing traces appear in the form of streaks or scratches with rough bottoms and sides, often appearing as bands of variable depth widths oriented in the direction of the height of the tooth, and affect isolated zones or their whole width. The scuffing traces are generally more clearly marked at the tooth tip and root of the teeth in the high sliding zones.

Fig. 7 - Metal adhesion on two teeth of a spiral bevel pinion. Note the metal pull-off located on the contact surface and in the maximum slipping zone with transverse scratches in the direction of the sliding motion.

In the case of hot scuffing, it is the combined action of high pressure between surfaces, high sliding speeds, and excessive contact temperature, resulting from pressure and sliding speed values, which causes oil film rupture between the teeth flanks. During start-up or running-in of certain gears, some local scuffing of lesser importance, which is characterized by shallow traces and very fine roughness, may appear in certain points of the teeth in the zone where the contact pressure is maximum. In general, after a certain time of operation at reduced load, these localized traces of scuffing diminish by wear. Once this happens, the gear may be operated under its nominal load. In this case, a slight increase in the lubricant viscosity will allow a better safety in service. On ground gears, we can see the presence of localized scuffing at the tip and root of the teeth, which is the result of insufficient tip relief or too great a deviation in the profile. We can also encounter identical phenomena near tooth ends due to insufficient longitudinal corrections or too great helix deviation. As long as scuffing traces caused by these phenomena remain slight or shallow, they may be tolerated in service, for they will end up wearing off and reducing in time. (Fig. 8)

If they become coarse, the scuffing can evolve either toward periodic adhesions or toward more severe scuffing, which may become destructive. In general, the appearance of destructive scuffing is revealed in service by brutal oil temperature rise at the meshing exit. If the load and the operating conditions are maintained, the scratches will generalize on the whole surface of the flanks and will become deeper. There is also the risk of local metal pull-off, transfer of metallic particles, and progressive deformations of the profile surfaces.

When this deformation becomes serious enough, the noise level of the gear will increase. The same is true for the temperature of the wheel and pinion bodies.

If the operation is maintained under such conditions, signs of overheating will quickly appear on the teeth surface (brownish, bluish, or violet tempering colors).

In the case of surface-hardened gears, cracks will often occur under thermal stress of teeth, which lead quickly to their breaking.

In the case through-hardened gears, we can ascertain some extreme cases of very serious rise in temperature of gears able to cause a hot flow of the teeth, bringing their destruction.

General scuffing is a brutal phenomenon which can develop very quickly on the teeth (in the matter of a few minutes to a few hours) and bring about *irremediable gear failure*. It occurs because of thermal stress, which leads quickly to tooth breakage. (Figs. 9-10)

When the failure occurs a long time after start-up of the gearing, it is caused by an accidental faulty lubrication or an overload resulting from continuous use of the machine in a manner for which it was not designed. However, if failure occurs a short time after start-up, one should check whether the amount of heat generated by the gear is compatible with the choice of the gear geometry and the choice of lubricant.

Cold Scuffing. This wear phenomenon is the result of lubricant (oil or grease) film breakage under excessive pressure action during meshing, causing a metal-to-metal contact of teeth flanks. The generation mechanism of degradation is identical to that of hot scuffing (welding and metal pull-off). In this case, it concerns only the joint action of high pressure between surfaces or extremely low sliding velocity (linear speed not over approximately 4m/s), which causes the breakage of the lubricant film between the contact profiles.

In general this type of scuffing begins with one or more adhesions on a few teeth flanks and spreads gradually nearer and nearer until the whole circumference of the gear is involved. The spreading speed of damage is a function of the type of lubricant used, the finishing process, and the hardness of the gear materials.

If we consider a gear of normalized steel or through-hardened, rough-cut finished, and grease lubricated, the destruction process of the teeth can be very quick once the lubrication becomes insufficient for the load transmitted (from a few minutes to a few hours).

We then see the formation of successive deep metal pull-offs and adherences on the flanks, which are partially rolled during meshing, thus causing an emission of metallic particles which remain blended in the grease. These particles generally initiate an abrasive wear which in a way re-establishes a uniform contact surface on the teeth, but in many cases is not sufficient to stop the scuffing.

This degradation mechanism will result in overheating of the surface in contact, which generally will remain at an acceptable level because the sliding velocities are low, and in the appearance of vibrations and meshing noises in the installation. When we stop the gear, we find teeth profiles which are often deeply altered in their geometry and which we can consider as being practically destroyed. In this case, it is essential to repair the teeth

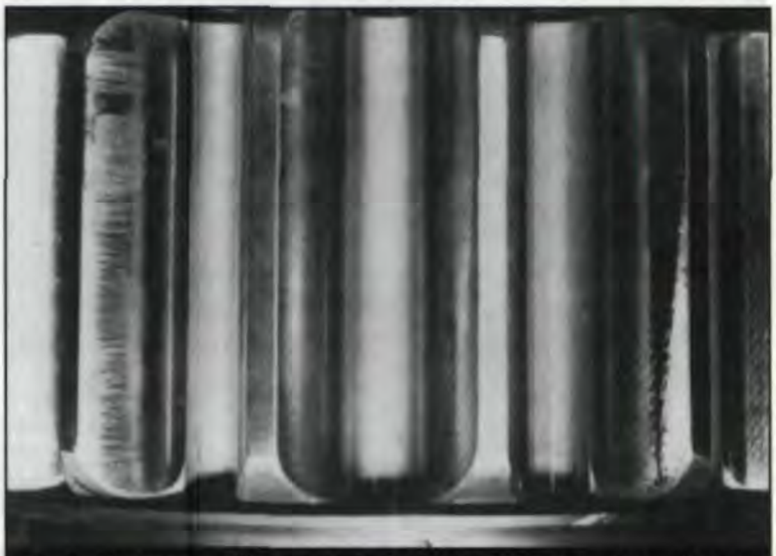

Fig. 8 - Moderate scuffing on the flanks of a case-hardened gear. Note the streaks spread over in bands and more or less intense on the profile. This scuffing is not destructive, for it does not notably alter the profile. This gearing can operate again after a run-in period and with better lubrication and load in service conditions.

Fig. 9 - Destructive scuffing on the teeth of a spiral bevel wheel. Note the presence of deep streaks and important deformations of the profile in the contact zones. This gear wheel can be considered as destroyed.

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before planning to re-start the gear.

Whenever possible, it is preferable to proceed to a machining of the teeth at least so as to remove the particles embedded on the teeth flanks.

In the cases where we see the presence of too many metal pull-offs, we should make a more complete machining on the wheel flanks, which will require the design of a new pinion if we want to preserve an identical backlash to the one initially planned.

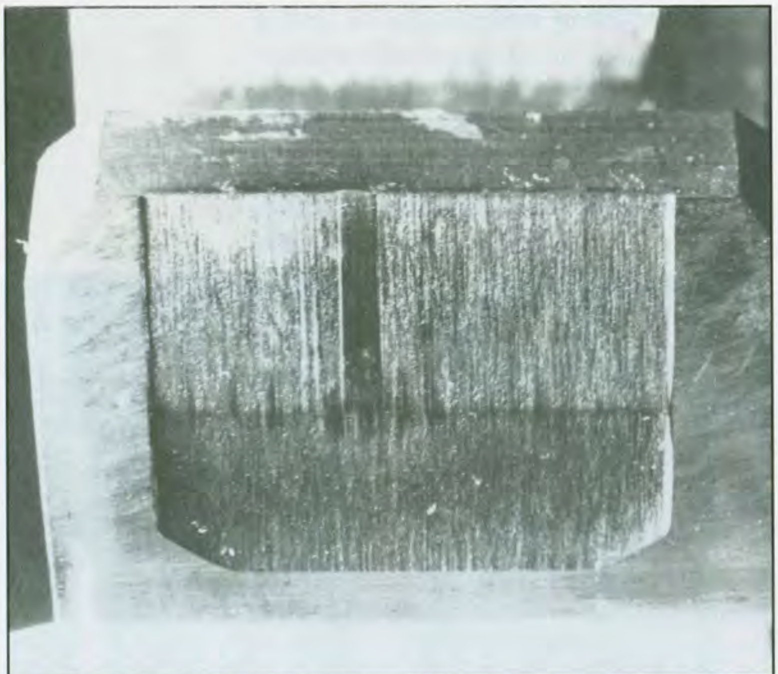

Fig. 10 - General and destructive scuffing on a gear wheel. Note an important wear of the profile with the presence of radial rough irregular streaks. Also note a metal pull-off toward the tip of the tooth.

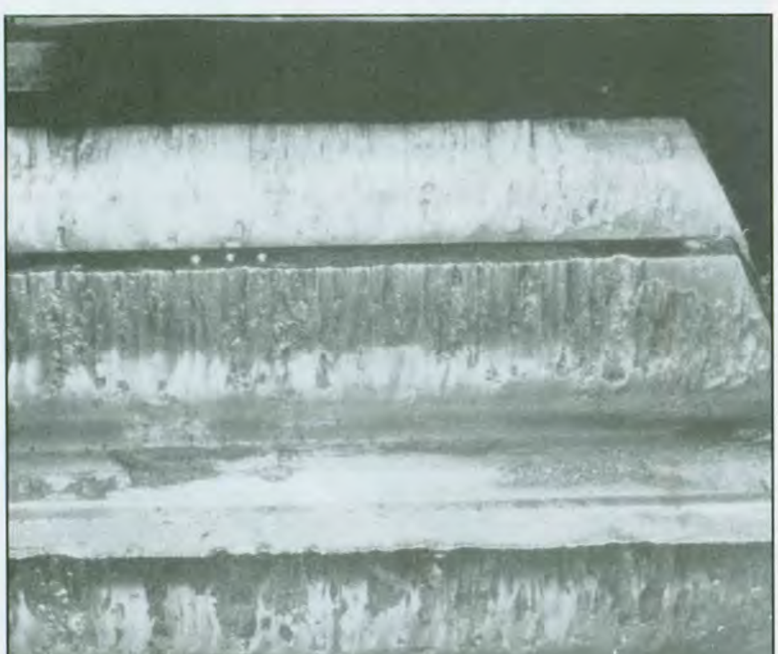

Fig. 11 - Cold scuffing on the teeth of a winch wheel.

When this scuffing happens on large, open gears used for driving ovens, crushers, or winches, the repair has to be done most of the time *in situ,* for it is often impossible to remove such gears. (Fig.11)

We can, as a first operation, remove by manual grinding all welded metallic particles that are too thick in relation to the initial profile of the teeth. Then we must run-in the teeth before thinking of restarting of the gear to obtain a good contact pattern on the flanks.

For this operation, we can use an abrasive compound of grain size structure adapted to the size of the teeth or special synthetic graphite grease. The running-in should not be too harsh, otherwise we risk deforming the profile of the teeth by abrasive wear.

If we have a surface-hardened and ground gear often used at the low speed stage of a reducer, the metal pull-off on the flanks is often accompanied by plastic micro-distortion of flanks due to embedding and micro-welding of large particles, which may damage the hardened surface layer because it has to support very heavy local pressure for which it has not been designed.

The surface overheating generated by the micro-weldings may be high and can also sometimes generate surface cracks, which may evolve rapidly in service through the hardened surface layer and lead to the rupture of one or more teeth.

For such gears in general, the appearance of cold scuffing is brutal and often results in their breaking during use.

The possible causes of cold scuffing are insufficient lubrication or a severe overload of the gearing over a sufficiently long period. (These two causes can occur simultaneously).

This type of damage is generally destructive for the teeth and develops most often on grease-lubricated teeth. The surface roughness of the teeth is of great importance, and when it is great, it encourages the formation of micro-welding and the development of deep scuffing. ■

Part II of this article will cover wear with three bodies, interference wear, and varying intensities of gear tooth wear.

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