Gears – and How Their World is Changing

by

Neville W. Sachs, P.E.

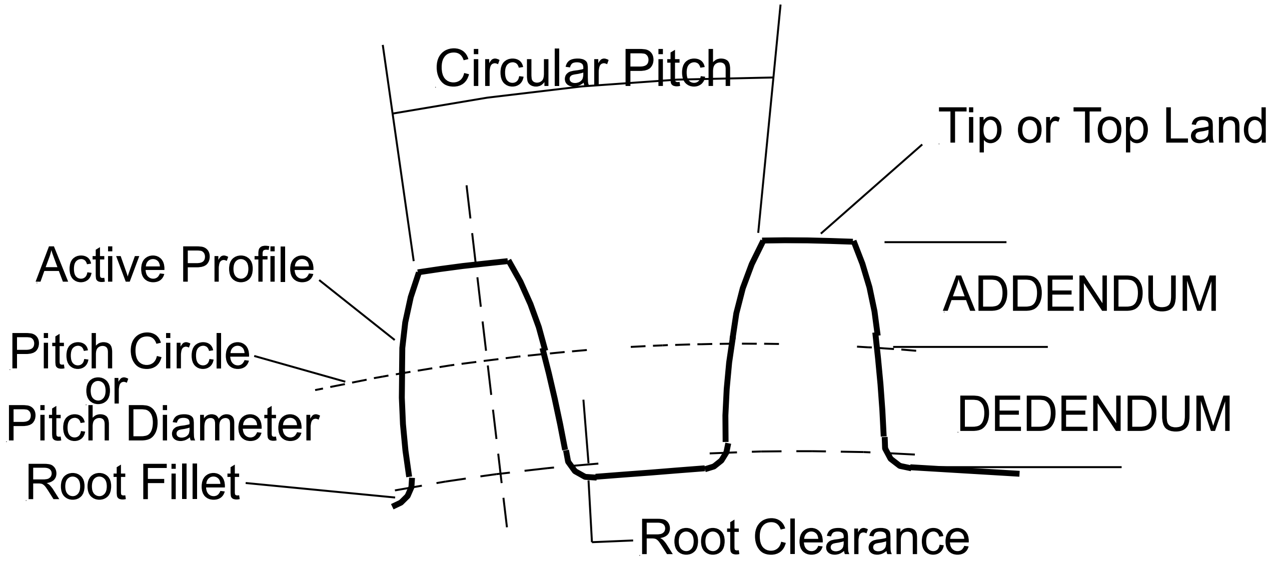
Neville W. Sachs, P.E., PLLC

The Plan

- **Discuss the more important terms**
- **Explain some types of gears and their operation**
- **Describe some basic gear metallurgy and what's changing in gear design**
- **Show how they fail**
- **Ask some questions to see if you're learning anything.**

My thanks to The Falk Corporation (now a division of Rexnord) for some of the pictures and lots of education.

Gear Tooth Terminology



Diametral Pitch (DP) = # of teeth/Pitch Diameter

PINION - the driving unit (usually smaller)

GEAR or BULL GEAR - the driven unit (usually larger)

This is an ***involute tooth*** shape.

Quiz questions

1. What is the basic metallurgy used for most modern industrial and transportation gears?
2. What is the ***diametral pitch***?
3. What is the gear ***module***?
4. There are several common ways of sizing gears. What are the primary differences between the ***AGMA 2001*** and the ***ISO 6336*** methods?
5. With what type of industrial gear metallurgy is pitting ***not*** of immediate great concern?
6. When pressure is put on oils, what happens to their viscosity?
7. In the shop, how should you check for the proper gear alignment of a set of reducer gears that have been in use?

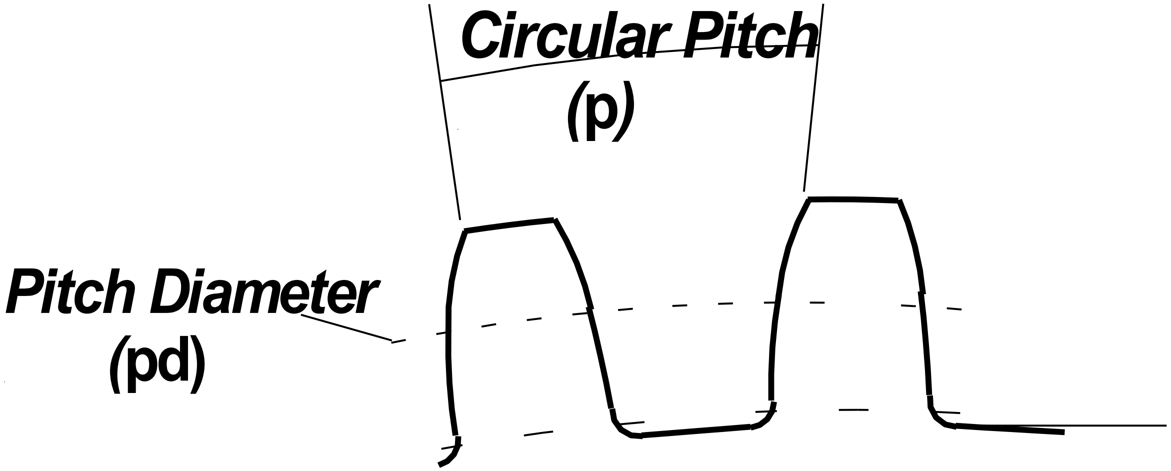
The “gear module”

Module is the metric term used for tooth size.

Larger module = larger tooth

Diametral pitch is the imperial term for tooth size.

Larger diametral pitch = smaller tooth



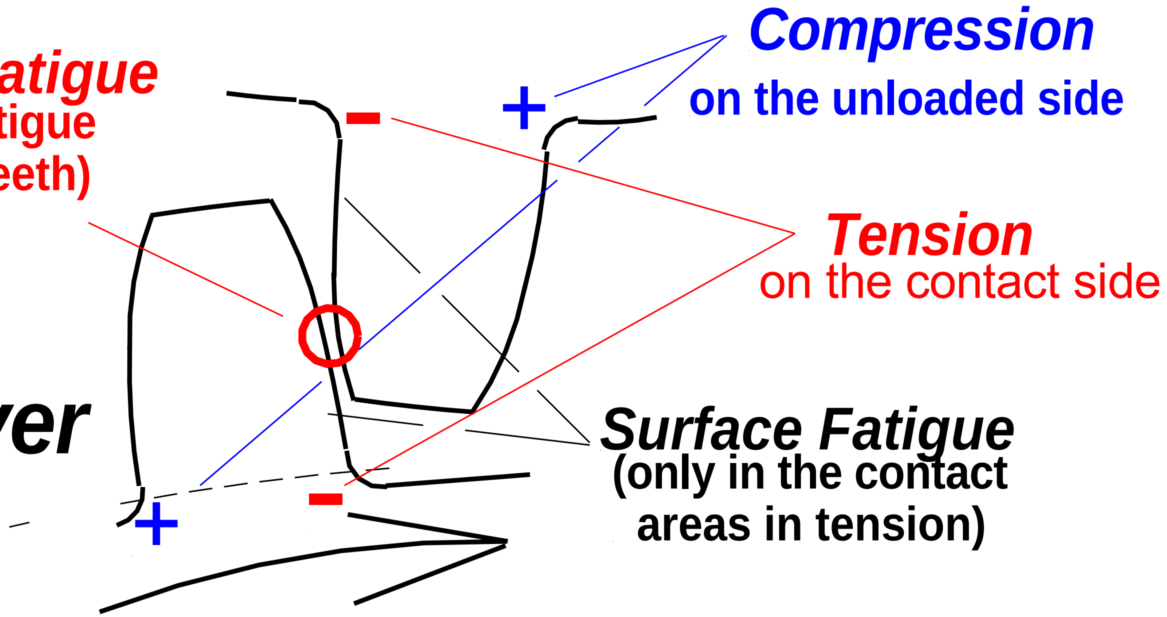
Circular Pitch (p)

Pitch Diameter (pd)

Module = p/π where p = circular pitch

Diametral pitch = number of teeth/pitch diameter (pd)

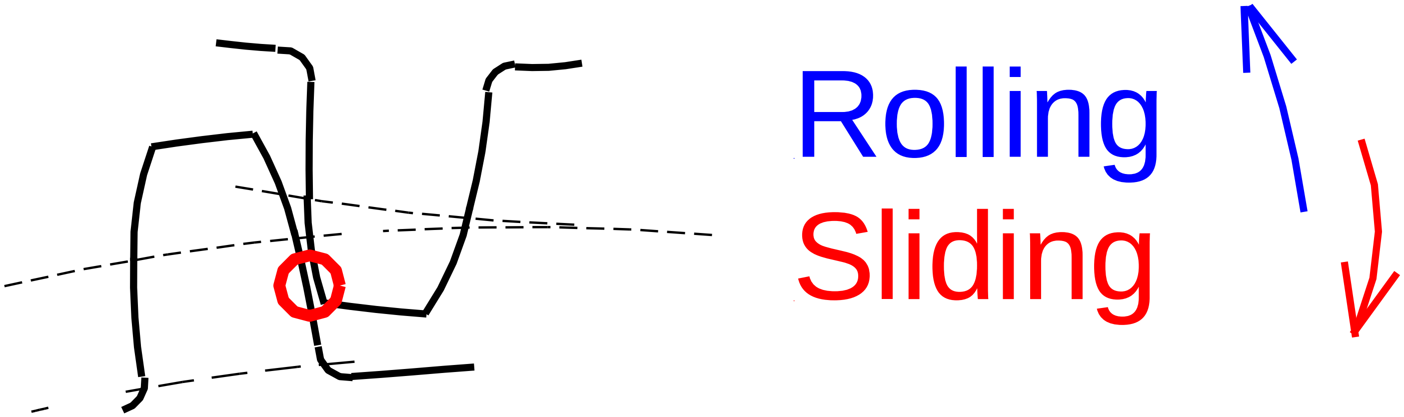
Stress on a Gear Tooth



The tooth is loaded and stressed by:

- Sliding contact causing surface fatigue damage
- Rolling contact Hertzian fatigue damage
- Bending, like a cantilever beam, that always results in deformation and can cause breakage

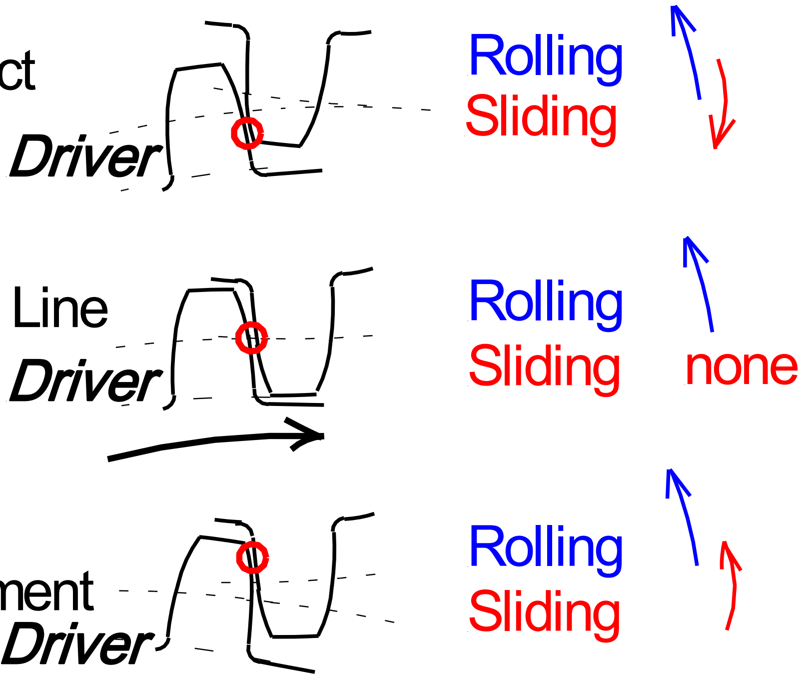
Tooth Contacts



- Tooth contact involves both rolling and sliding
- Understanding the action of this contact is a key to understanding how and why gears wear.
- With *involute teeth,* the teeth tend to slide early in their contact with the relative proportion of rolling increasing until, at the pitch line the contact is pure rolling. As the teeth go out of mesh the sliding proportion continually increases.

Three Stages of Contact

Gear tooth contact showing the varying rolling and sliding directions



Contact Point Action

Initial Contact

Driver

Rolling

Sliding

At the Pitch Line

Driver

Rolling

Sliding none

Just before Disengagement

Driver

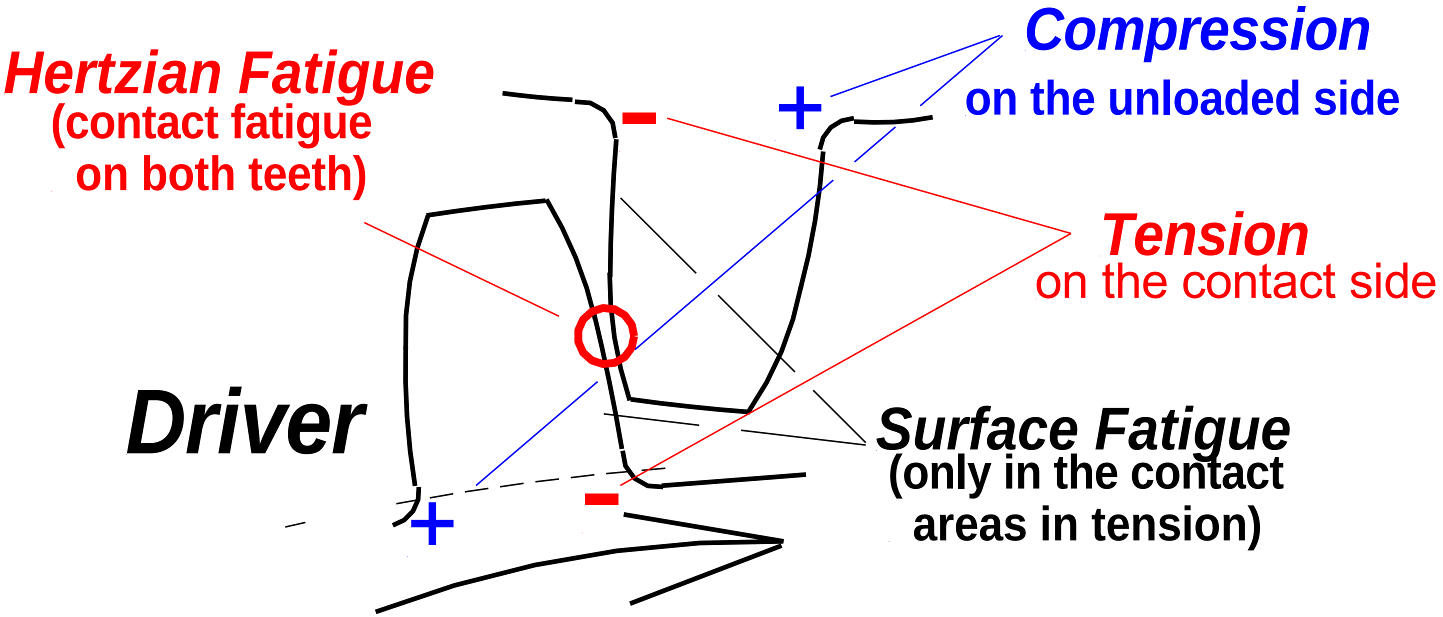
Rolling

Sliding

Gear Design

Looking at the stresses shown on the earlier slides, we see that when a gear is designed simultaneous bending, rolling, and sliding forces have to be considered. In addition, the design has to plan for the appropriate durability rating.

Gear Dedendum Wear



On the dedendum of the driving tooth, as the driven tooth slides downward, the driving tooth surface is subjected to tension, surface fatigue results, and the tooth wears. At the same time, where the driven tooth addendum surface is in compression, fatigue ***can not*** occur.

Design Standards

- The standards have changed about every 15 or so years
- Currently ***AGMA 2001*** and ***ISO 6336*** are in wide use. (AGMA = American Gear Manufacturers Association

  ISO = International Organization for Standardization)
- Both allow for wear, bending and pitting resistance with equation modifiers that are similar, but not identical.
- AGMA is basically experienced-based while the ISO standard is more academically-based.
- AGMA ratings are more conservative.
- ***API*** (American Petroleum Institute) has a series of standards developed from the AGMA standards specifically for refinery and processing facilities.

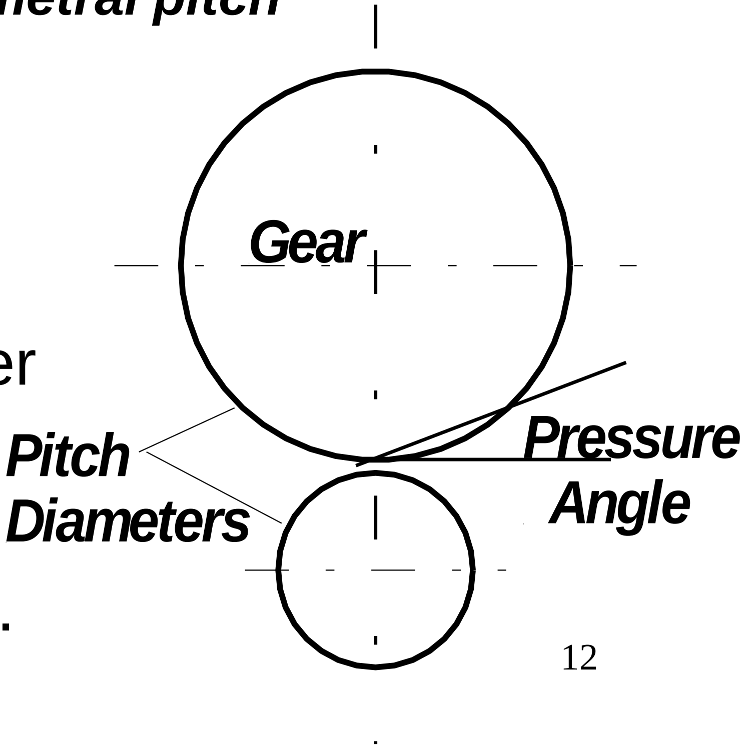
Design Standards

- The original North American design standard was the *Lewis Equation:*

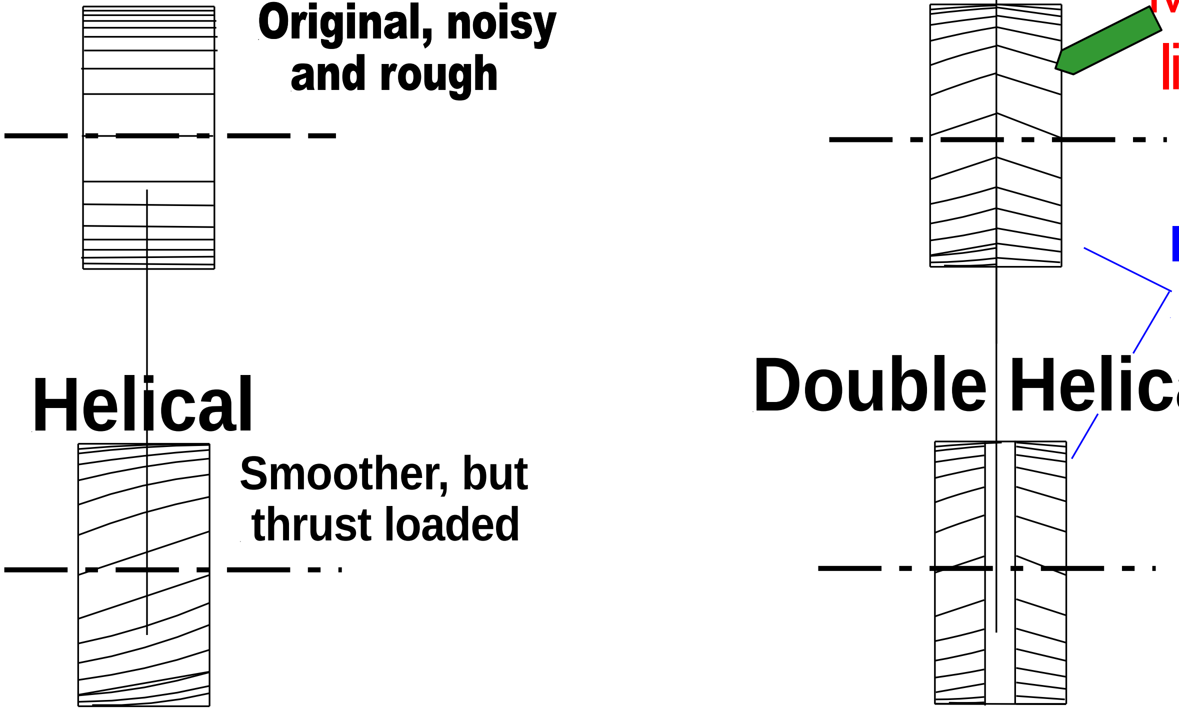
$$W_t = (S \times F \times Y)/D_p$$

W_t = transmitted load in pounds (or N)
S = 1/3 tensile strength
F = Face width
Y = Lewis form factor – based on the pressure angle and # of teeth
D_p = diametral pitch

- Pressure angle is very important. Larger pressure angle results in stubbier, stronger teeth, but almost always more sliding and a little lower efficiency.
- The tendency has been to go to smaller teeth to improve wear rates.



Common Gears



Straight Cut Spur Gear

Original, noisy and rough

Helical

Smoother, but thrust loaded

Herringbone

Most gears that look like this are actually double helical

Both correct for thrust problems

Double Helical

Helical and double helical gears have multiple teeth in mesh at one time, resulting in smoother and quieter operation than spur gears.

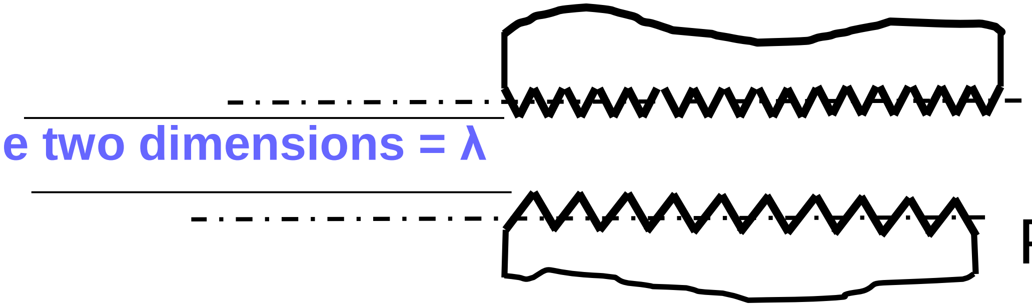
Some Other Common Gears

- **Bevel -** similar to a spur gear but designed for a right angle drive, tends to be rough and noisy.
- **Spiral Bevel -** teeth are at an angle so more than one is in mesh, similar to a helical gear
- **Hypoid -** a variation on spiral bevel with the pinion centerline moved.
- **Worm -** unlike involute gears in that the action only involves sliding

Worm Gears

- Usually used in high reduction applications.
- Worm gear and worm wheel contact action is pure sliding with no rolling.
- Many lubricants used on spur and helical gears are ***not*** suitable for worm gears both because the sliding action results in an extreme example of boundary lubrication and because some common EP additives attack the bronze worm wheels.

How does a Lubricant Prevent Wear?



Part One Surface

Ratio of the two dimensions = λ

Part Two Surface

- ***This sketch shows a greatly magnified view of two parts separated by a lubricant film. The separation is important because the greater the distance, the less the parts contact each other and less wear occurs. The Greek symbol lambda, λ, is usually used to denote the relative film thickness.***
- ***λ is a result of the viscosity, relative speed, and the shape (relative roughness) of the parts.***

Rolling Element Contact and Lubrication

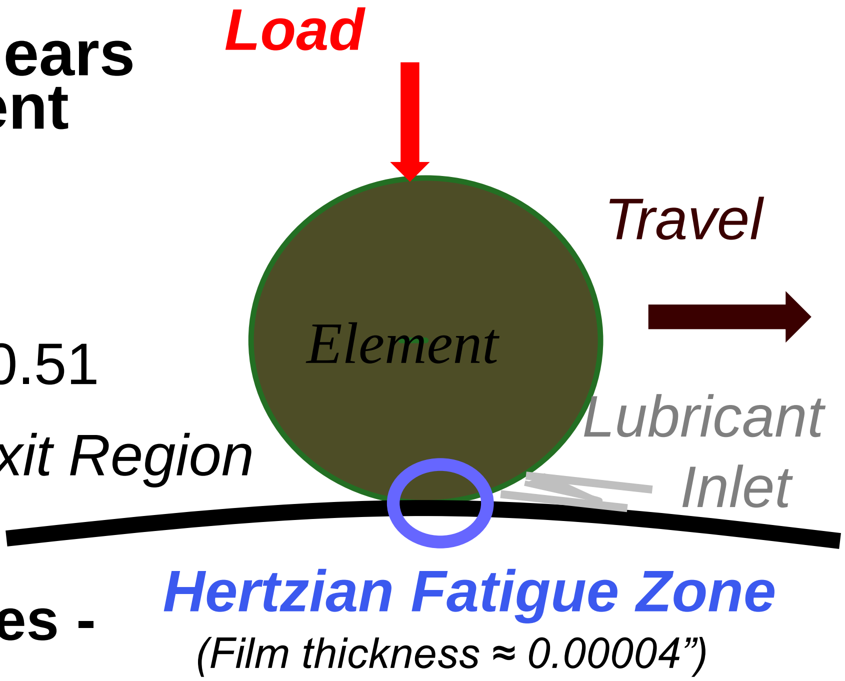
Rolling element bearings and gears in general industrial equipment

Pressures - As high as 2 GPa in the contact areas

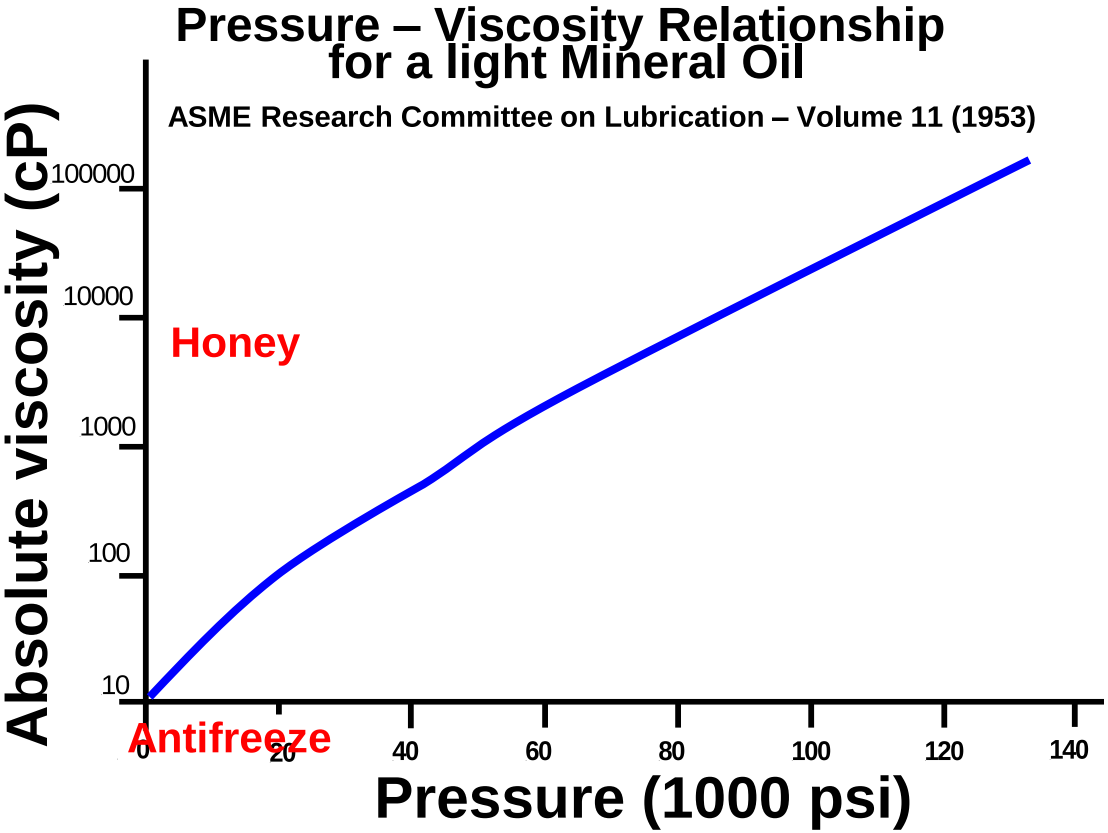
Clearance - In the range of 0.25 to 0.51 µm

Most Important Lubricant Properties - Viscosity, Cleanliness

Action - Inlet zone viscosity transformation supports clearance



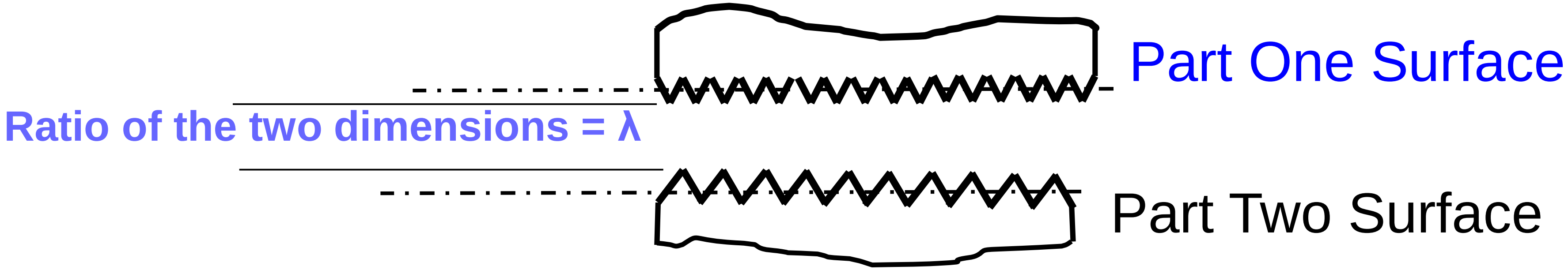
How Pressure Affects Viscosity



Pressure – Viscosity Relationship for a light Mineral Oil

ASME Research Committee on Lubrication – Volume 11 (1953)

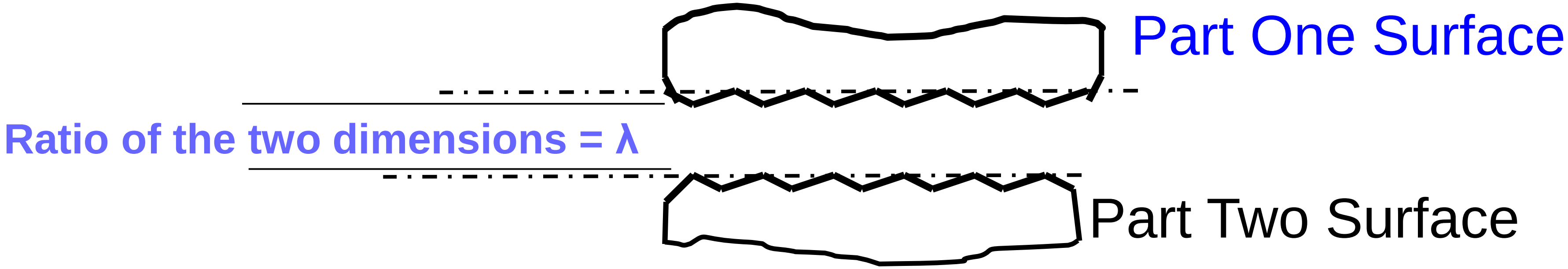
How does a Lubricant Prevent Wear?



Part One Surface

Ratio of the two dimensions = λ

Part Two Surface



Part One Surface

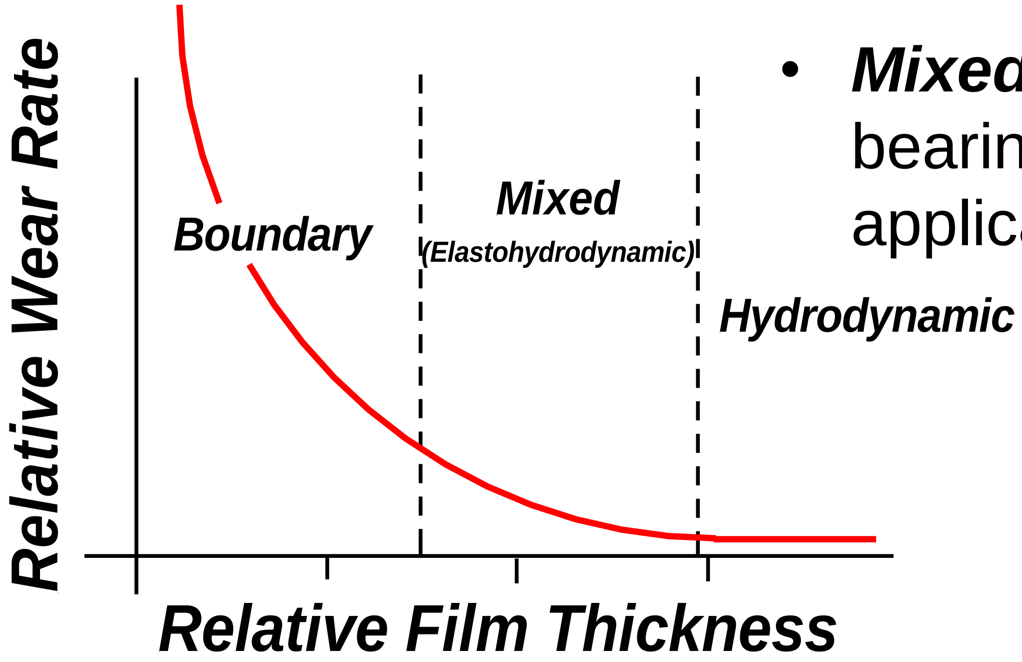
Ratio of the two dimensions = λ

Part Two Surface

In recent years improving the surface finish ***(superfinishing)*** has enabled gear tooth contact stresses to almost double without having pitting.

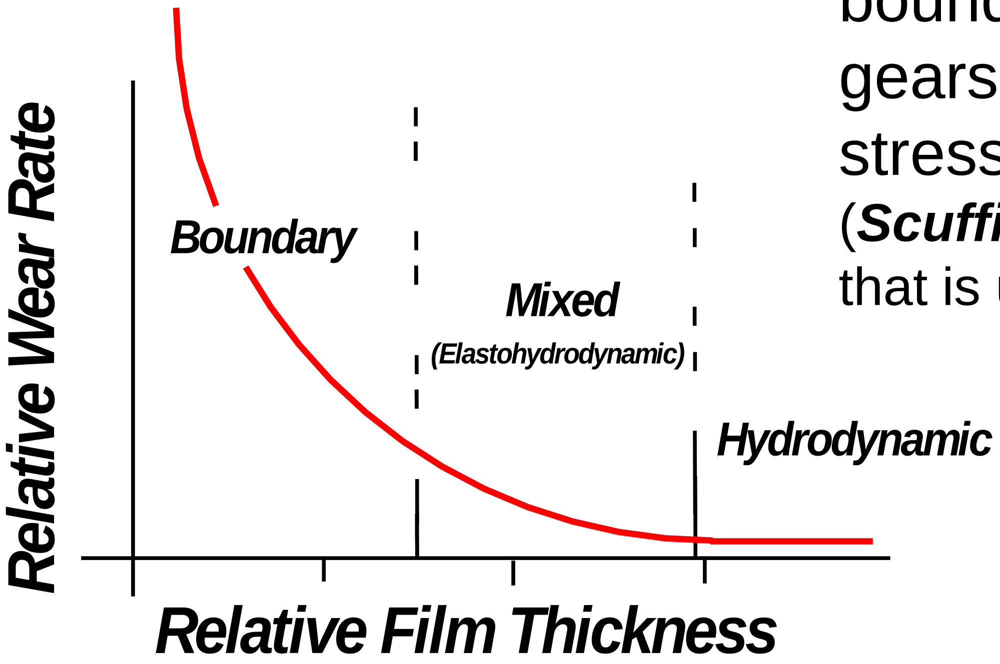
Lubricant Films and Wear

- ***Hydrodynamic Lubrication -*** full separation of the two mating parts - low wear - usually on medium to high speed gears
- ***Boundary Lubrication -*** with thin to non-existent films and metal-to-metal contact, additives are critical. (low speed and very heavily loaded gears)
- ***Mixed (elastohydrodynamic) –*** bearings and many plant gearing applications fall in this category



Changing Lubricant Films and Wear

- Newer synthetic lubricants (PAO, POE, PAG, PIB) with higher pressure-viscosity coefficients are effecting better lubrication with improved films, less heat generation, and higher efficiency.
- Newer additives are improving the boundary lubrication of low speed gears resulting in higher contact stresses without scuffing failure. (***Scuffing*** is adhesive wear. Another term that is used is galling.)



Stress causes Elastic Deformation

During Operation the Teeth Deform

- The gear rim and hub also deform to some extent
- Changing loads will change this deformation and the contact patterns

Quiz questions

1. What is the basic metallurgy used for most modern industrial and transportation gears?
2. What is the ***diametral pitch***?
3. What is the gear ***module***?
4. There are several common ways of sizing gears. What are the primary differences between the ***AGMA 2001*** and the ***ISO 6336*** methods?
5. With what type of industrial gear metallurgy is pitting ***not*** of immediate great concern?
6. When pressure is put on oils, what happens to their viscosity?
7. In the shop, how should you check for the proper gear alignment of a set of reducer gears that have been in use?

Gear Inspection Steps

Gears are designed for strength and for durability

1. ***With a bright light (and possibly a magnifying glass) look at both the active and inactive sides of the teeth, very carefully noting the contact patterns***
2. ***Rotate the gears to see if the contact patterns and surface conditions are consistent***
3. ***Determine the tooth metallurgy***
4. ***Decide if the wear or damage is acceptable***

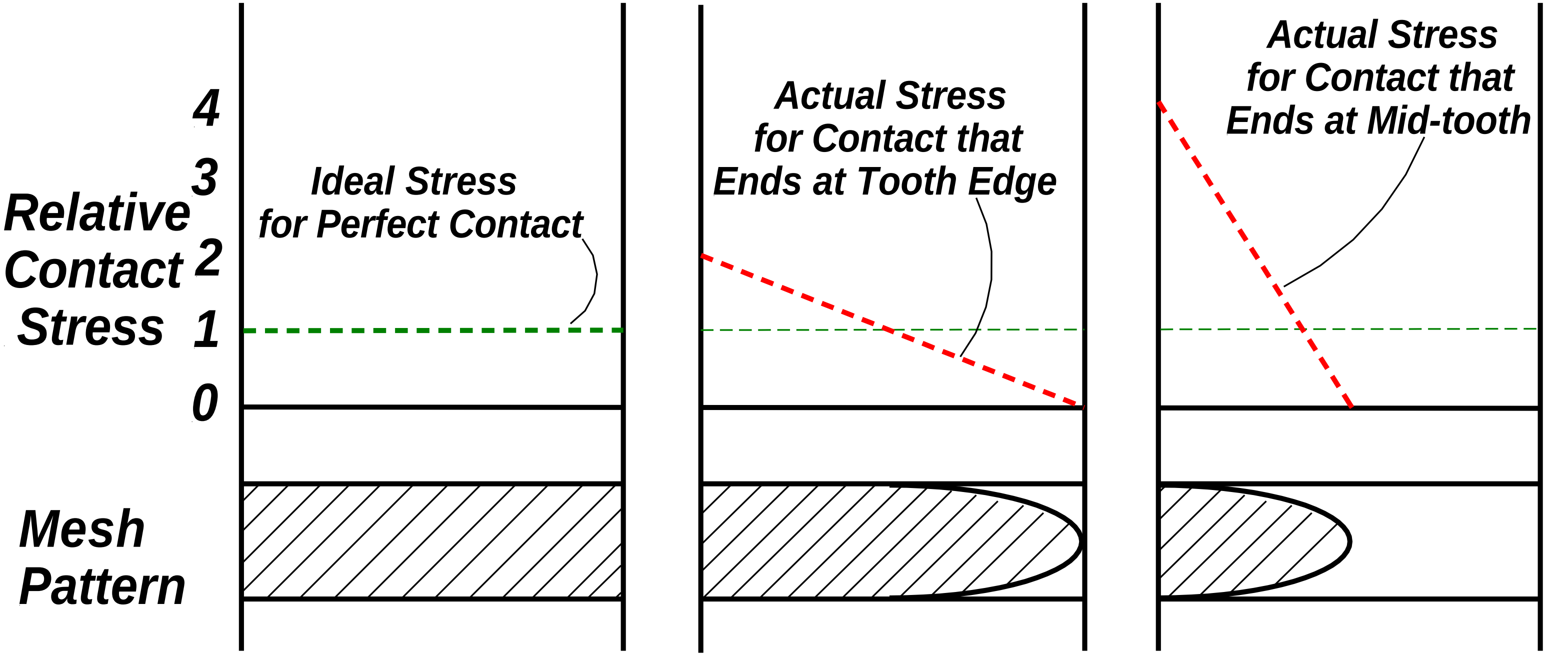
Q. Why are the contact patterns important?

A. They show us the actual loads (forces) on the gear teeth.

1. ***Both root and contact stresses will vary substantially with the accuracy of the meshing pattern.***
2. ***Contact on the inactive flank (unloaded tooth side) from driving forces will cause a huge increase in stresses.***
   - ***With very good lighting, start by looking carefully at the active flank contact all the way around the gear. (Does it vary?)***
   - ***Then look at the back (inactive side) of the teeth.***

Look at the Active Profile

Load Intensity vs. visible Contact Pattern for three applications

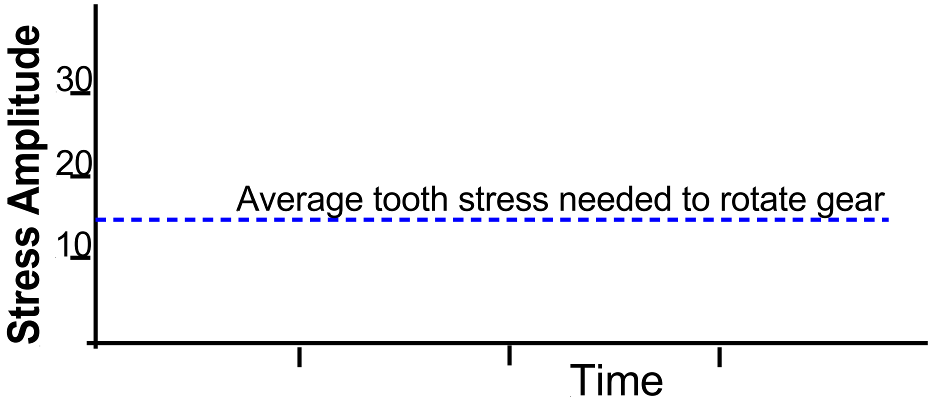


Don’t forget to rotate the gear to see how the pattern varies.

A problem with contact patterns

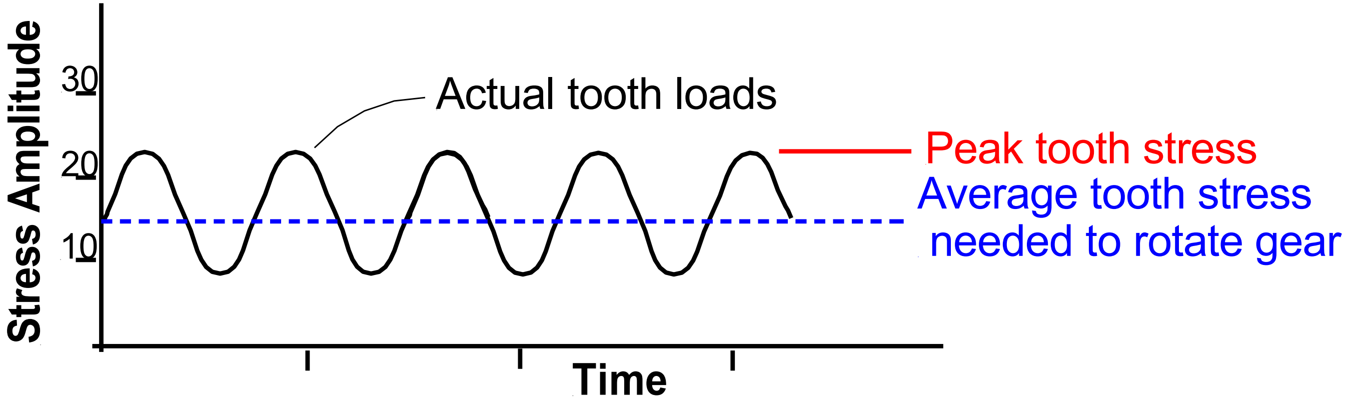
- As reducer marketing becomes more competitive, gear housings have become lighter.
- What can happen to gear alignment as that lighter housing sees the same magnitude stress as an older heavier housing?

Understanding Gear Design Loads



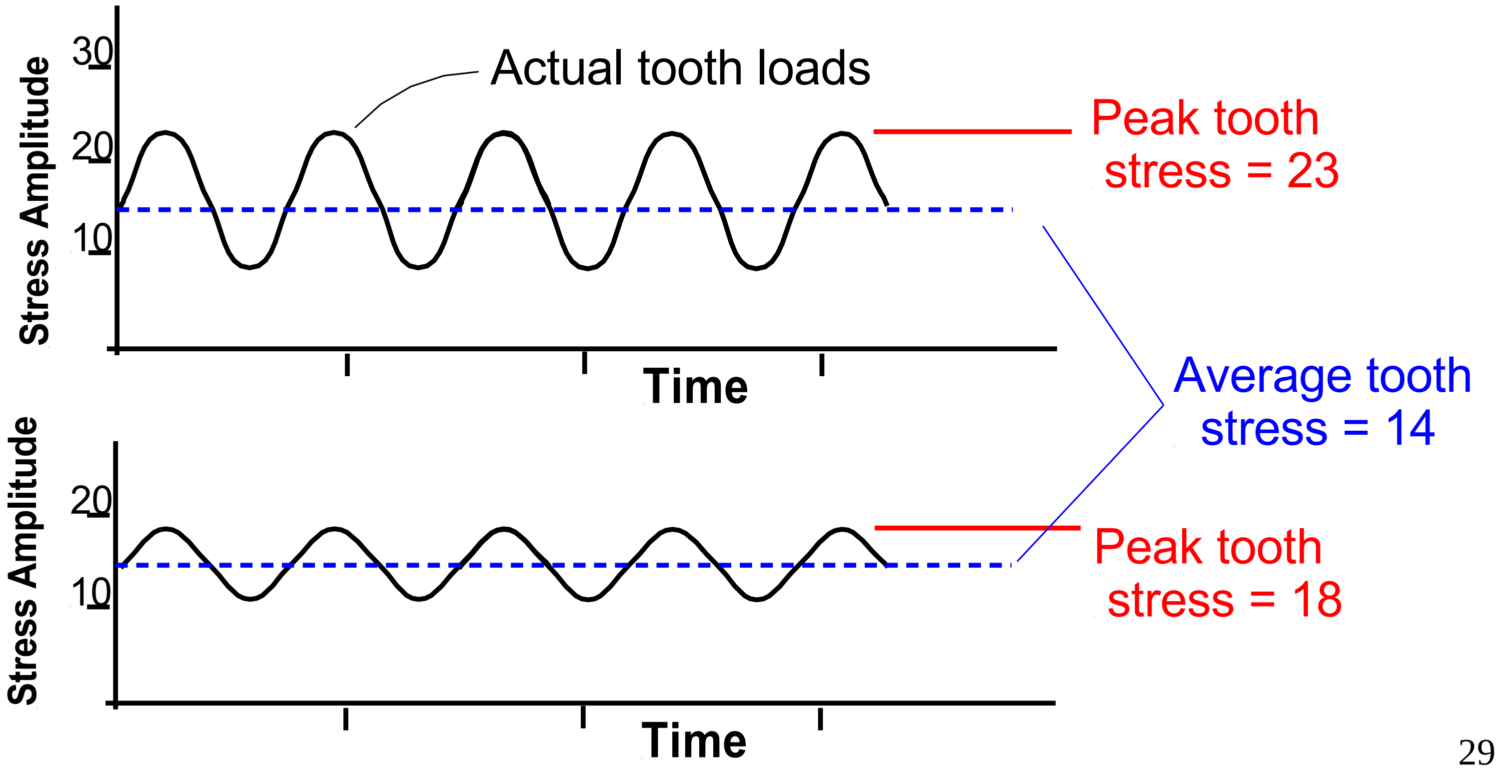
Ideally the load should be absolutely constant

But there are always variations and peak stress is critical



Load Variations

Look at the difference in peak loads with these identical gears! Same average load, but the upper one is much more highly stressed and will only last half as long.



Peak tooth stress = 23

Average tooth stress = 14

Peak tooth stress = 18

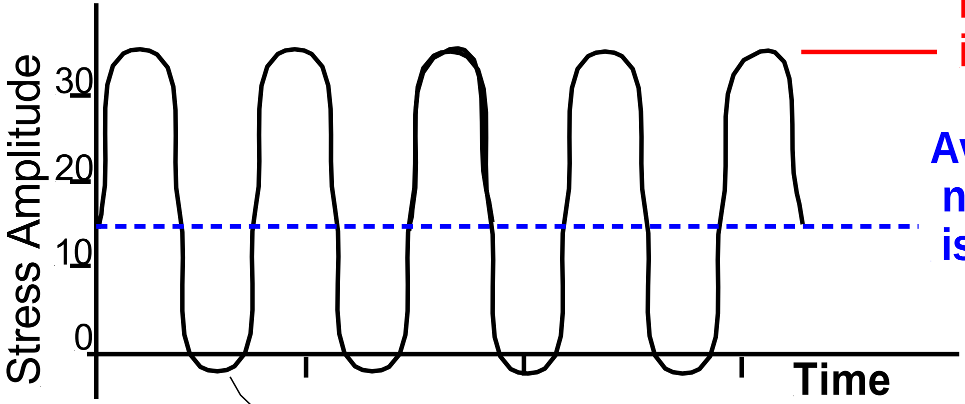
Look at the Wear on Both Sides of these Teeth

Mounted on the driveshaft of an oilfield gas engine

Green Arrows

More on Varying Stress

Graphing the load seen on that gear …



Peak tooth stress is now 34.

Average tooth stress needed to rotate gear is still 14

Negative tooth loads shown by opposite side contact

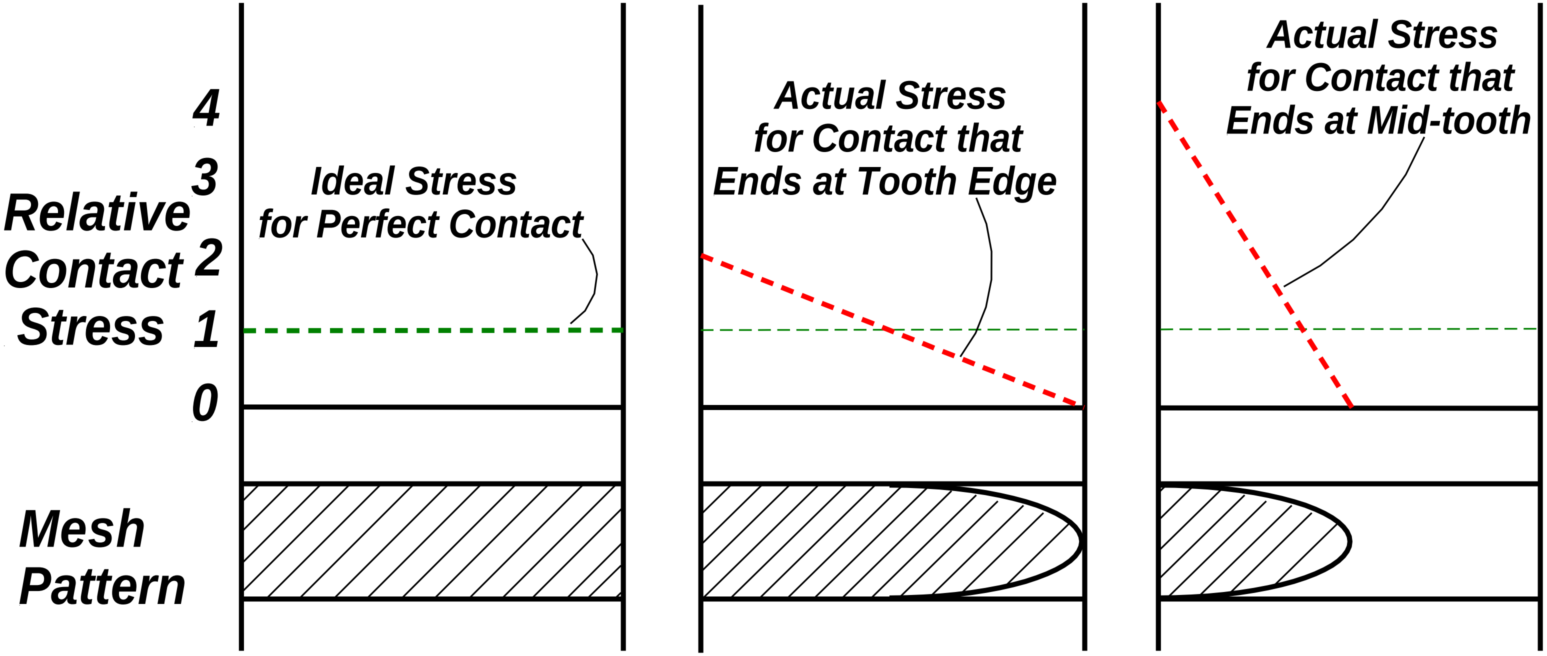
With reversing loads the peak stress is ***much*** higher and the relative life of this gear is less than 15% of the earlier example!

Same average load, incredible difference in life.

Some Sources of Load Variations

- Coupling Misalignment
- Gear Misalignment
- Input Torque Changes
- Pinion and Gear Eccentricity
- Machining Errors
- Torsional Vibration and Resonances

Tooth Alignment is Critical



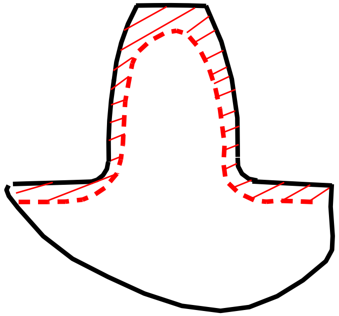
With Hertzian fatigue stresses, the fatigue life is a function of 1/load$^{3.33+}$. As the tooth misalignment becomes worse, the life decreases rapidly.

Some Gear Materials

- Wood
- Bronze
- Cast Iron
- A Variety of Steels - Hardened and Unhardened
- Plastics
- …

Steel Gears - with VERY Different Metallurgies

CASE or SURFACE HARDENED TOOTH

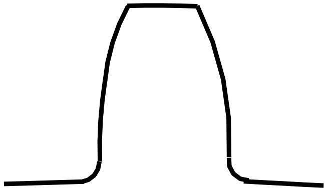


Hard Case - usually between HRc 42 and HRc 60

Soft Core

Commonly – case at HRC 55-60 and core at HRC 30-40

THROUGH-HARDENED TOOTH



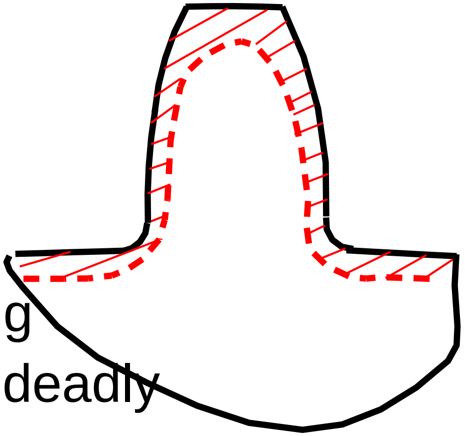
Same hardness throughout (May or may not be hardened)

Almost always below HRC 40

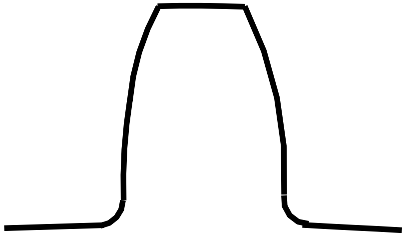
Case Hardening - may be from furnace, flame, induction, …
The case may be carburized, nitrided, carbonitrided, ...

Why the difference?

- **Case (Surface) Hardened Gears**
  - More power in a smaller package
  - Used on almost all mobile equipment
  - Demand closer tolerances in manufacturing
  - Surface damage and impact loads can be deadly



- **Through Hardened Gears**
  - Used on large gear sets and reducers where great precision is difficult
  - More tolerant of shock and impact loading
  - Can tolerate substantial wear before failure



Same hardness throughout

How do you tell the difference?

Hardness test or …

North American Reducer Gear Metallurgy – changes over the years

- Essentially every fixed reducer made before 1960 had through hardened gears. (Cars and trucks have had case hardened gears since the 1930's.)
- Starting in the early 1960's small reducers, less than 40 hp, because of the changes in the rebuilt European gear industry, have used case hardened gears and an occasional large reducer also had case hardened pinions.
- By the early 1980's, many 200 hp reducers had surface hardened gears.
- Today, essentially everything 1000 hp and smaller has case hardened gears.

What Affects Gear Life?

- Load
- Load Distribution (Alignment)
- Materials
- Temperature
- Lubricant Film Thickness
- Gear Tooth Geometry, Finish, and Hardness

Pitting and pitting resistance

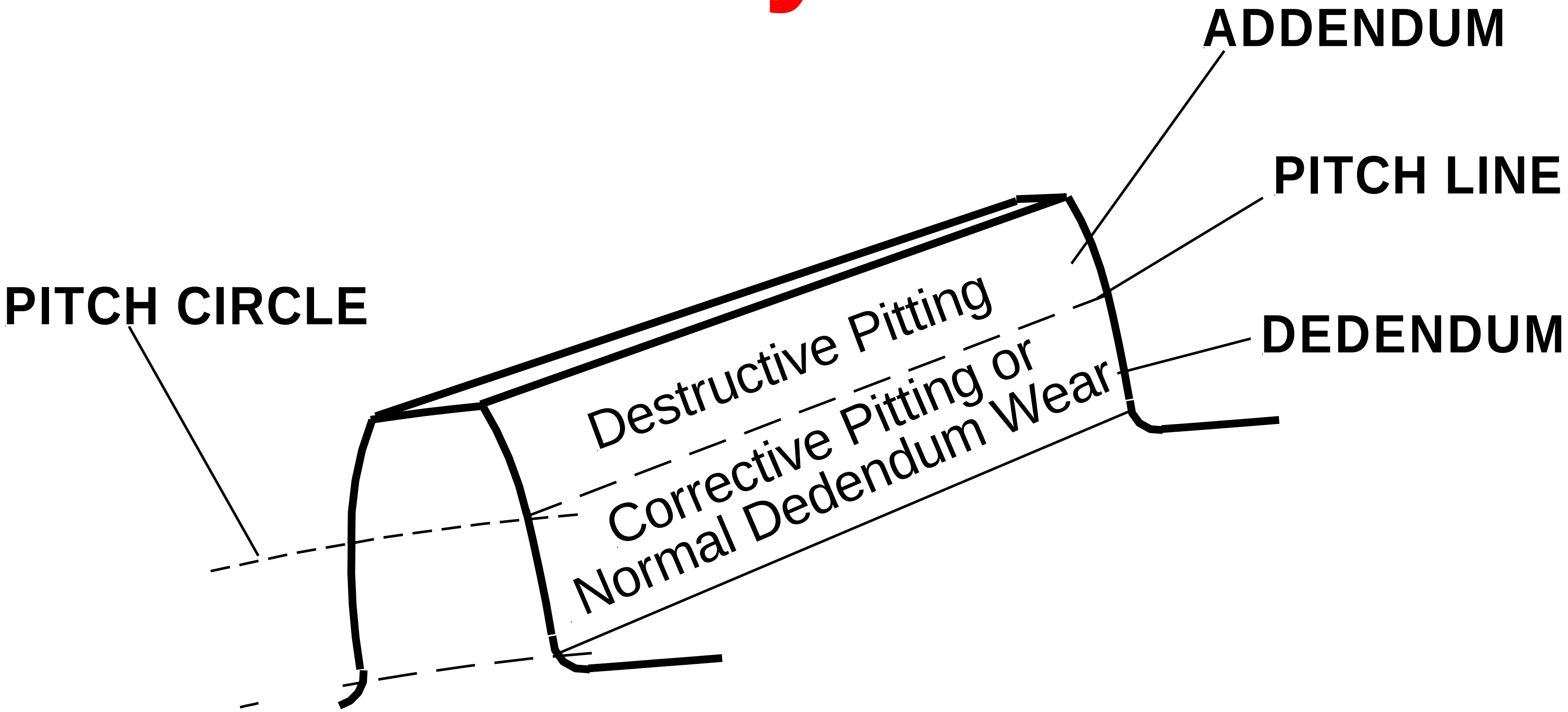
- The result of Hertzian fatigue loads.
- Acceptable ***only on*** through hardened gears.
  - Three basic types - corrective, destructive, and normal dedendum wear
- Harder gear materials are more resistant to pitting.
- Pitting is frequently a ***disaster warning*** on surface (case) hardened gears – because the core is much weaker than the case.

Three Types of Pitting

- ***Corrective*** - "break-in" that eventually reduces wear rates. (The corrective pitting rate decreases with time.)
- ***Normal dedendum wear*** - the result of millions of fatigue cycles.
- ***Destructive*** - severe fatigue loading that continually worsens and rapidly destroys the teeth.

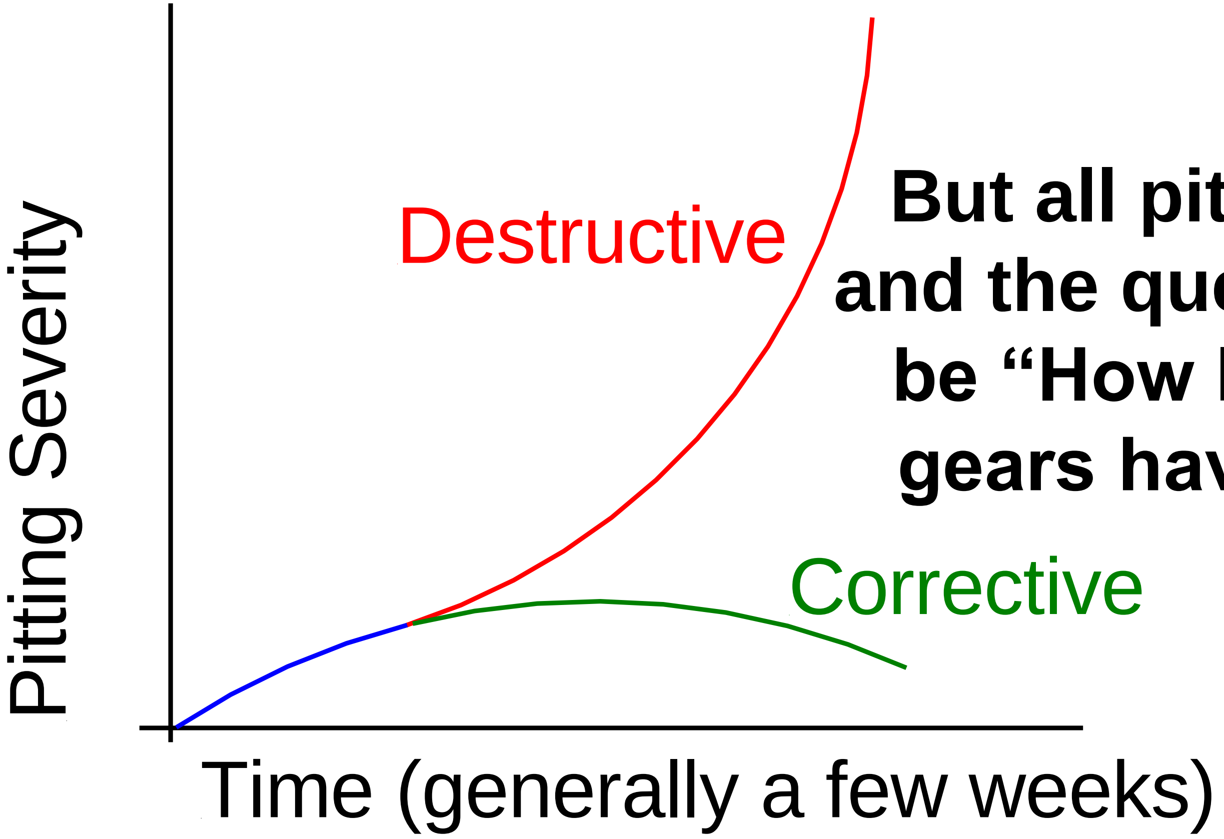
They all really just define the different wear rates.

Where Pitting is usually Found



Active profile!

Corrective vs. Destructive Pitting



But all pitting is wear and the question should be "How long do the gears have to last"?

Corrective Pitting

This is a large dragline gear – an open gear

- Usually small pits that allow the oil film to be developed.
- On through hardened gears it makes up for surface irregularities and misalignment.

Corrective Pitting

Usually small pits that allow the oil film to be developed. On through hardened gears it makes up for surface irregularities and misalignment.

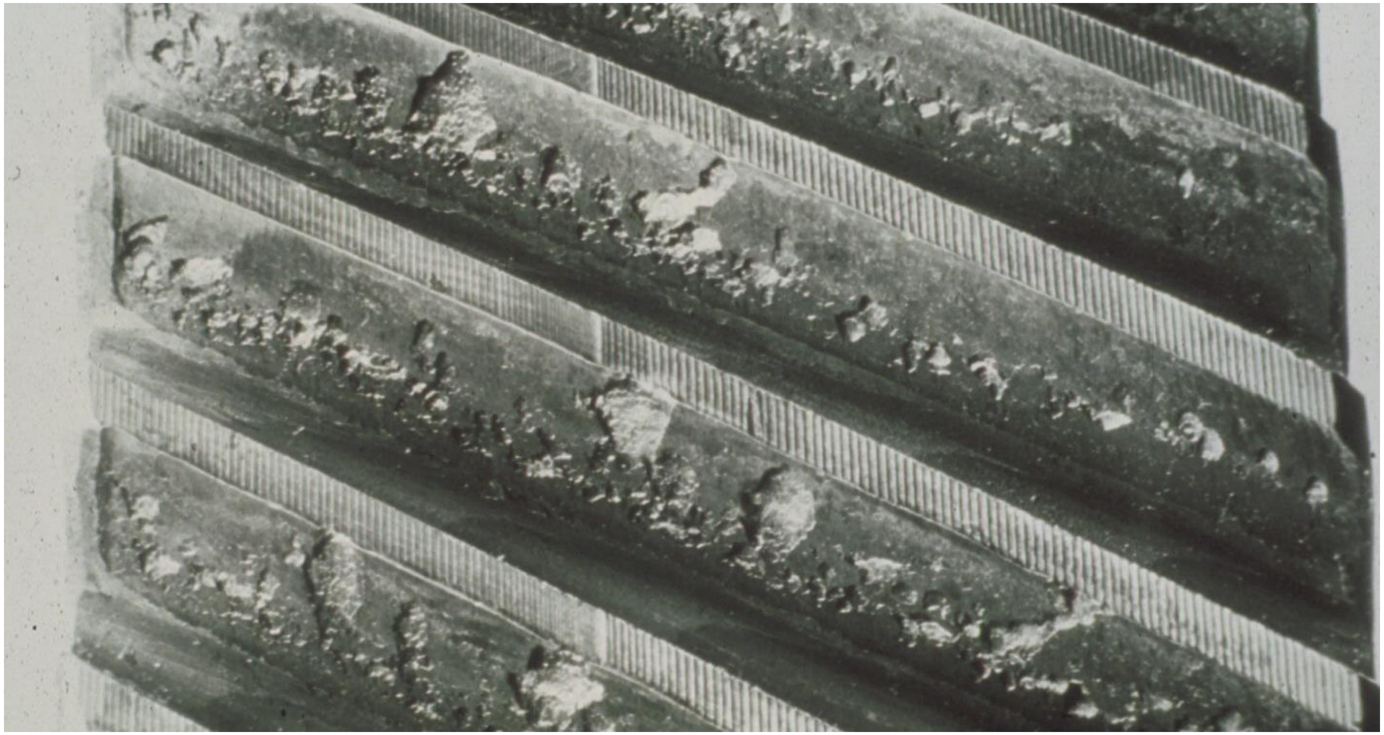
Normal Wear - Dedendum Pitting

Compressor drive gear after 10 years at 1800 rpm.

Yes, it will whine but does it have to be changed? What would you do?

Normal dedendum wear of a through hardened gear

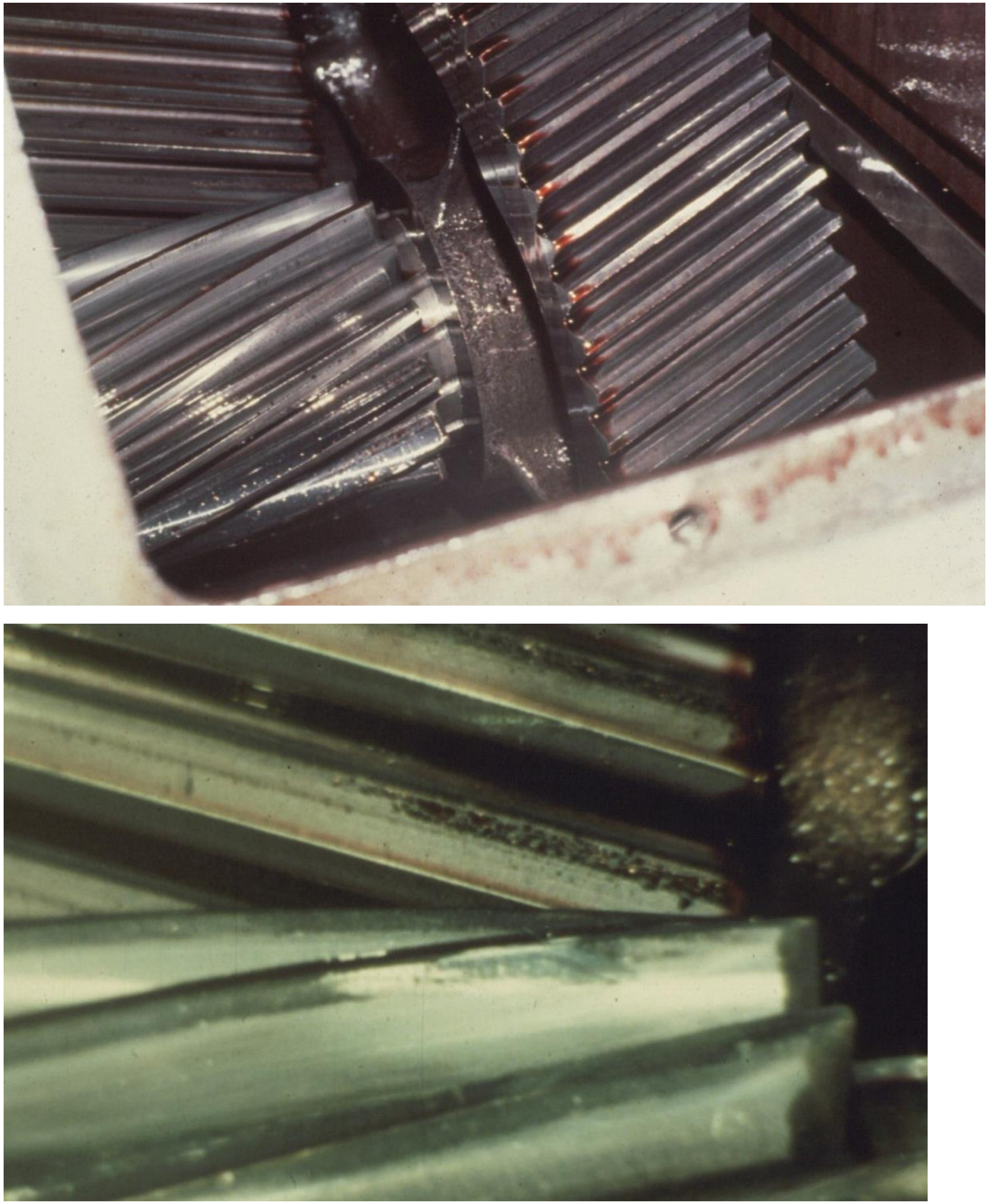
Destructive Pitting



Can't develop a lubricant film. As a result the gear wears rapidly and gets progressively rougher and noisier.

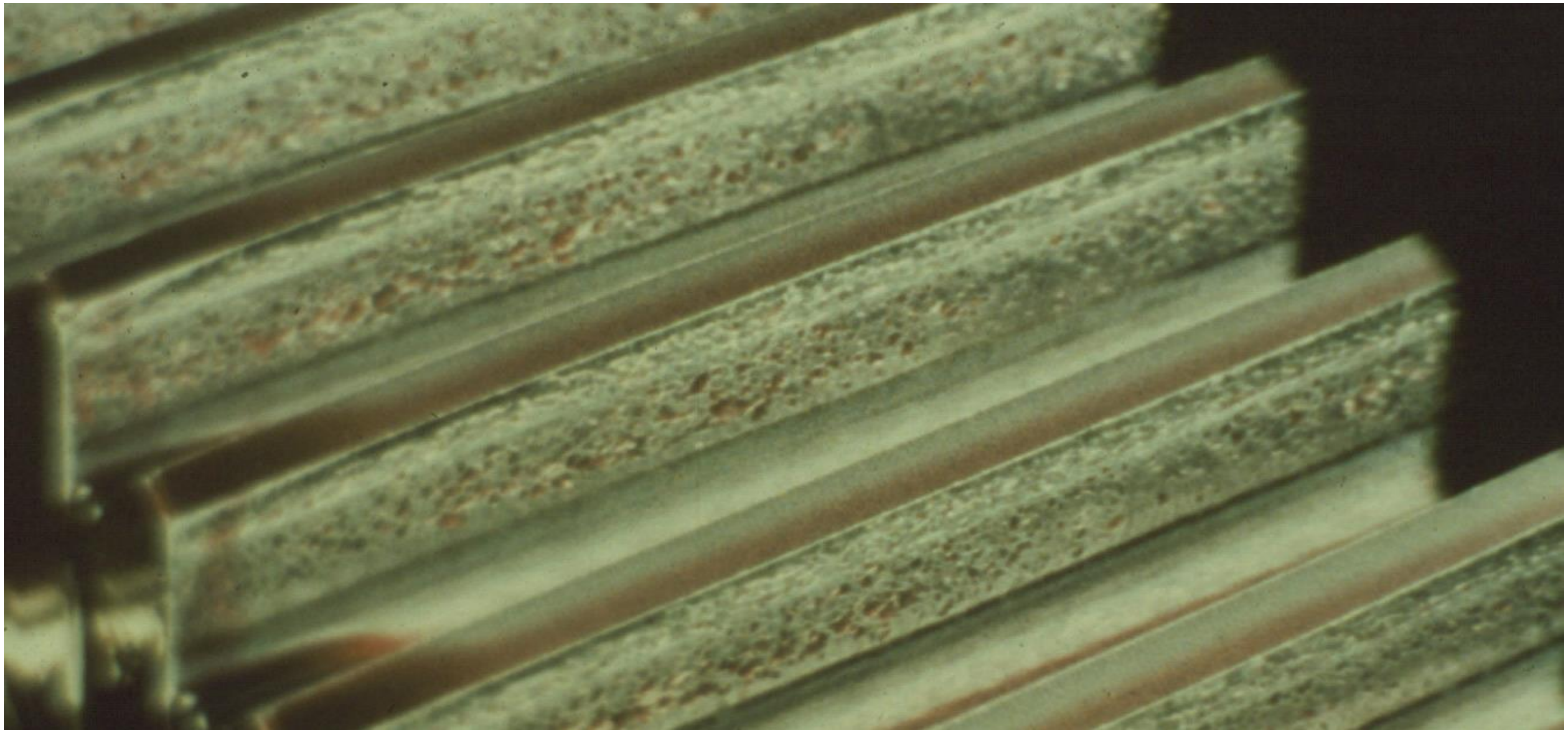
A Falk photo.

Corrective Pitting Example



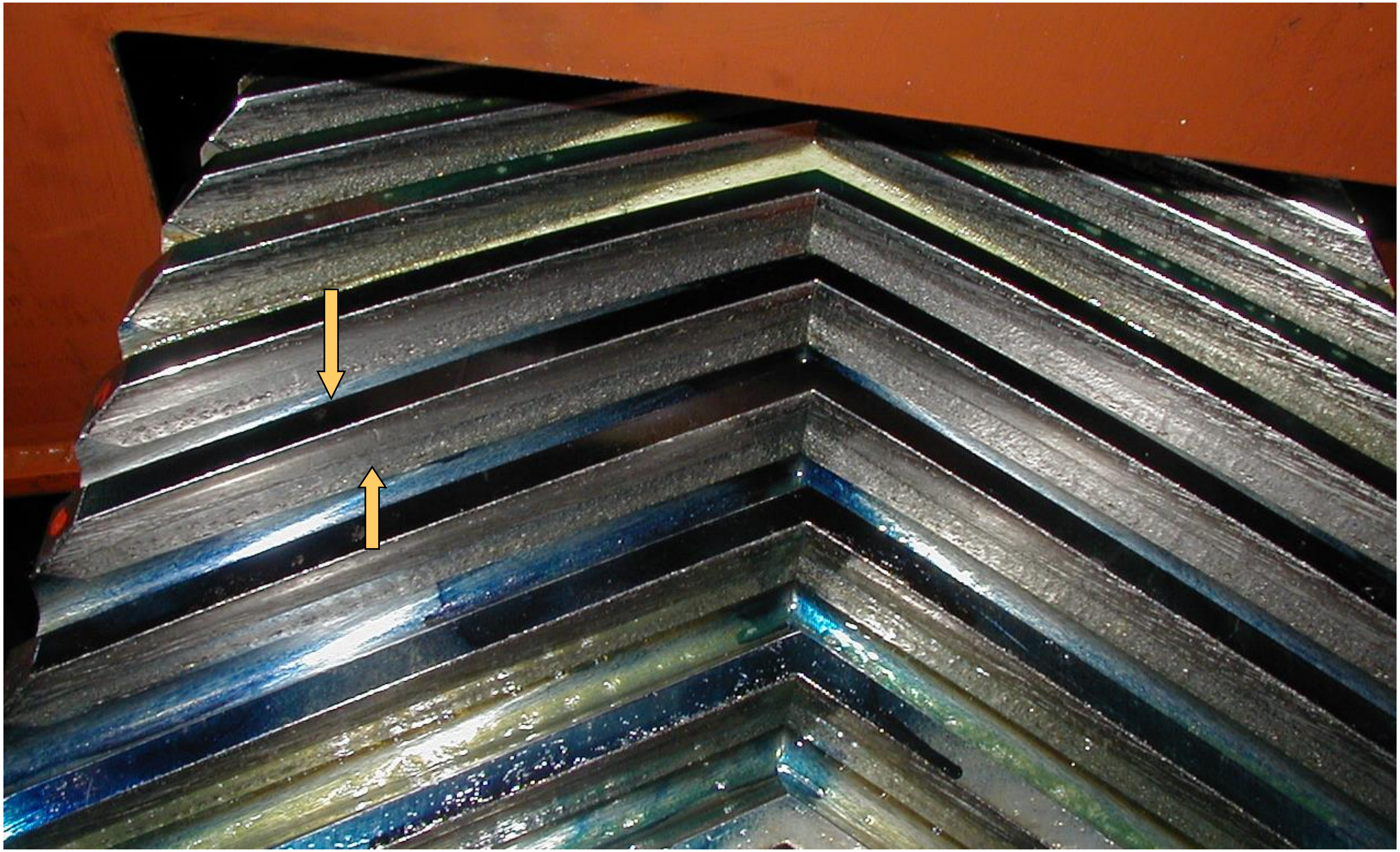
Double reduction reducer with corrective pitting on low speed gear. Original gears only lasted three years.

Continued...



- Causes - lots, including undersized reducer and "dynamic soft foot", i.e., misalignment
- Revisions included installing "softer" couplings and increasing the oil viscosity
- New expected life - 18 years from micrometer data

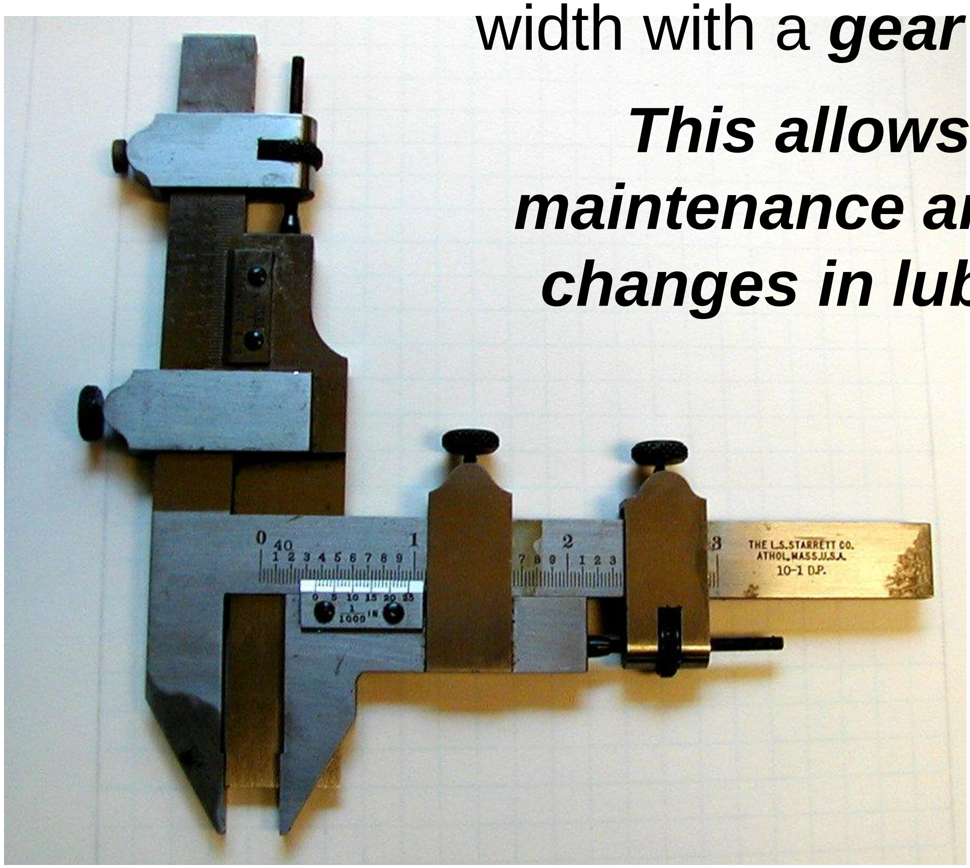
Monitoring normal dedendum wear on through-hardened gears

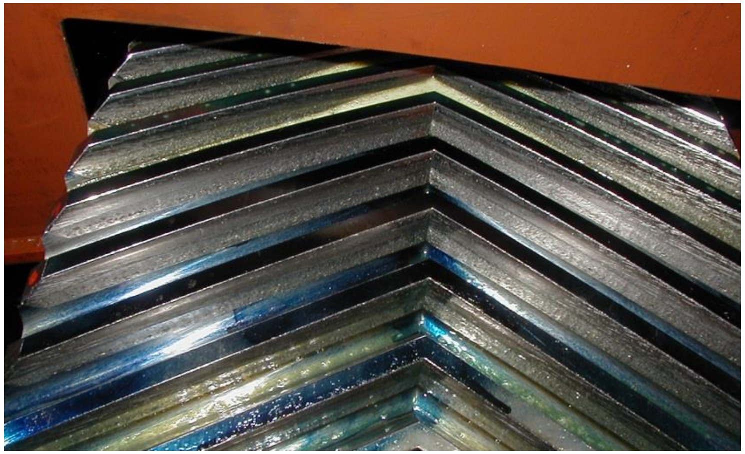


Monitoring normal dedendum wear on through-hardened gears

Set the depth about 10% below the pitch line and periodically measure the tooth width with a ***gear tooth micrometer***.

This allows you to do predictive maintenance and monitor the effects of changes in lubrication and operation!





Alignment Disaster

A. The choice is either broken teeth or rapid wear
B. Don’t forget the two basic metallurgies

More on Alignment

When we started working on gears, with open gear sets, 1/2 tooth contact was OK. Later we realized the how important good alignment is.

Now, on running gears, we use an infrared scanner and try for no more than a 10^0 F difference across the face of the pinion.

Speaking of alignment…

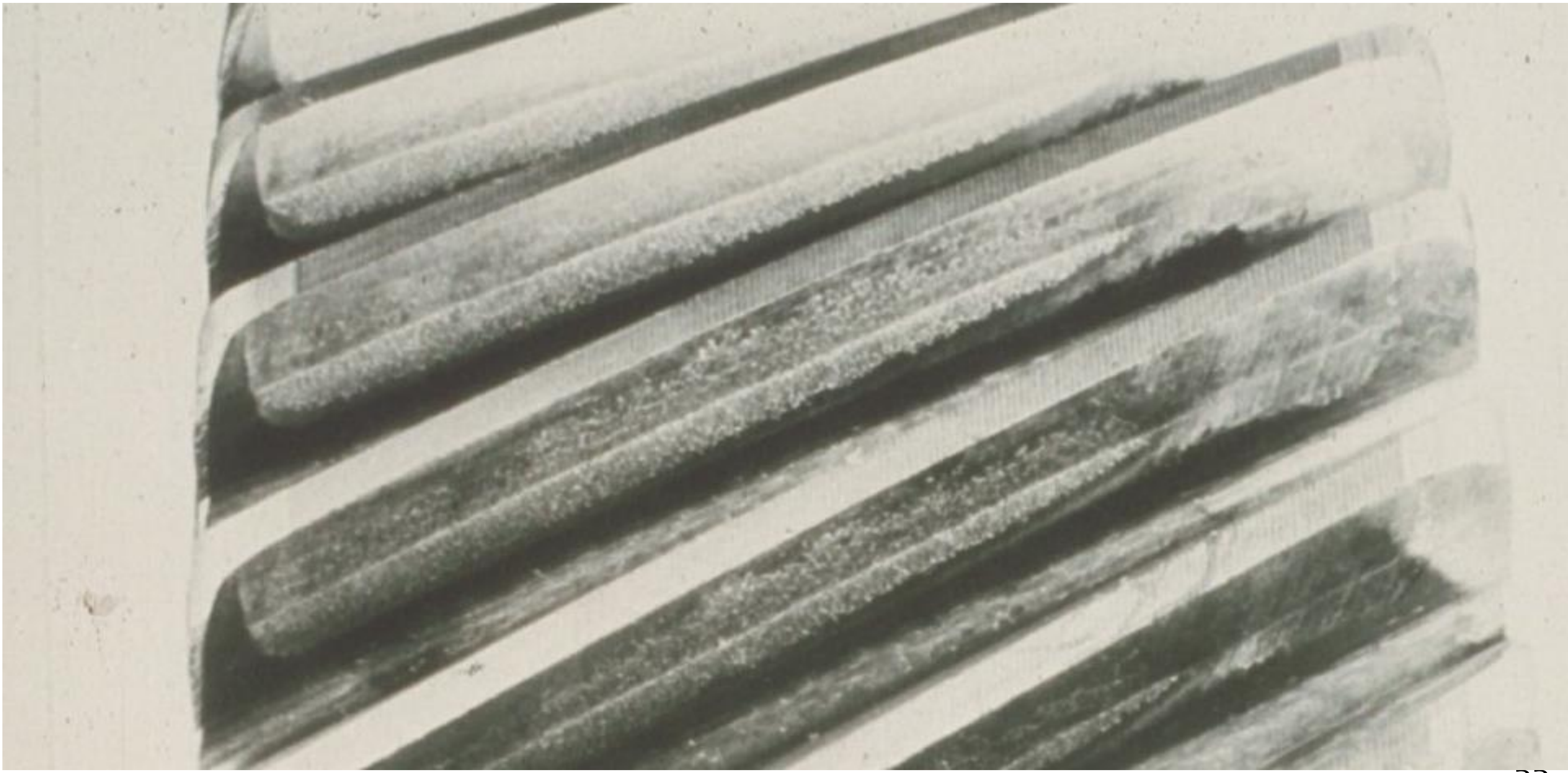
Case Hardened Tooth

Where did the cracking start?

How good was the alignment?

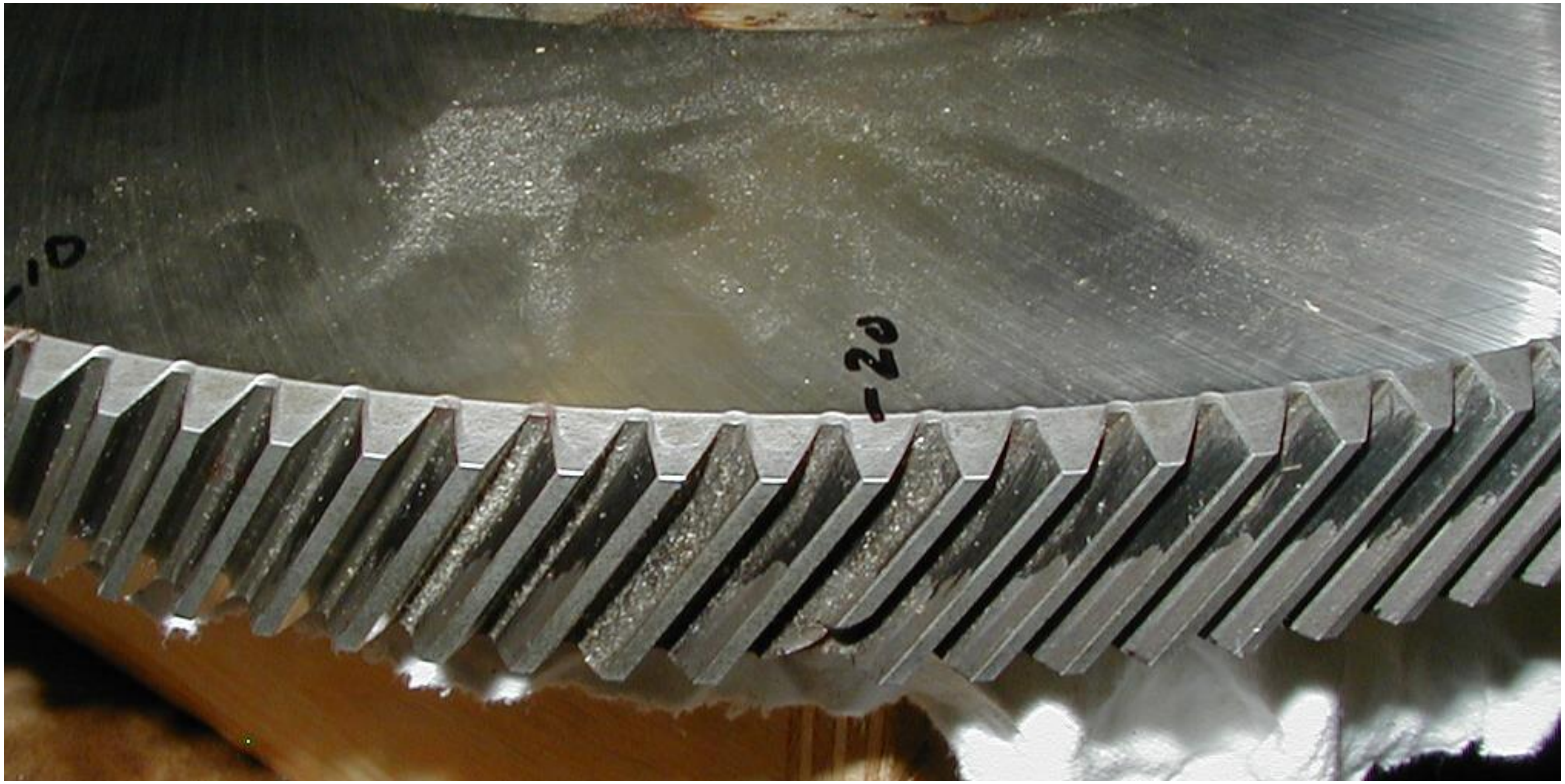
Surface (Case) Hardened Gears

Micropitting - from heavy loads, hydraulic action, and Hertzian fatigue

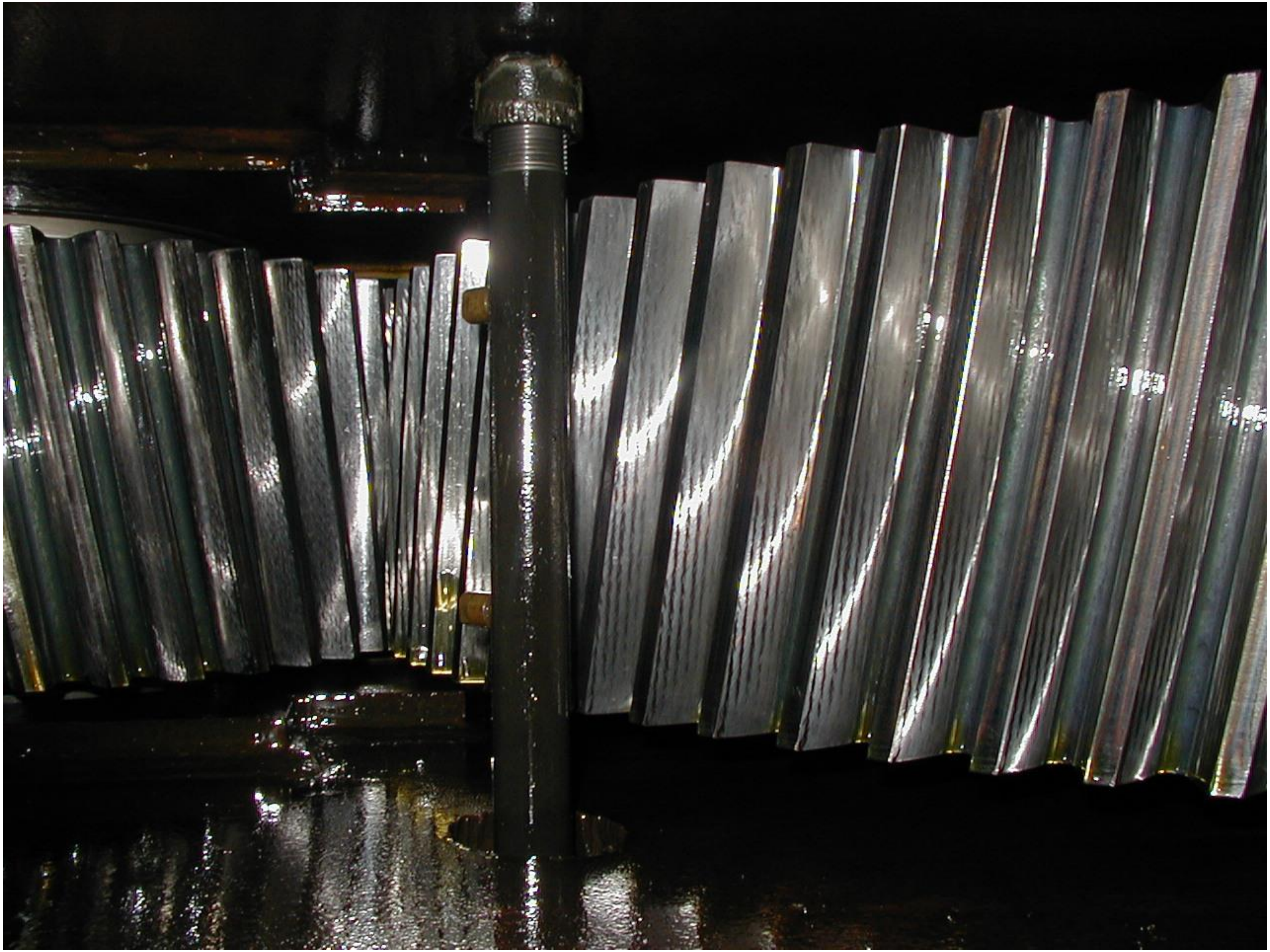


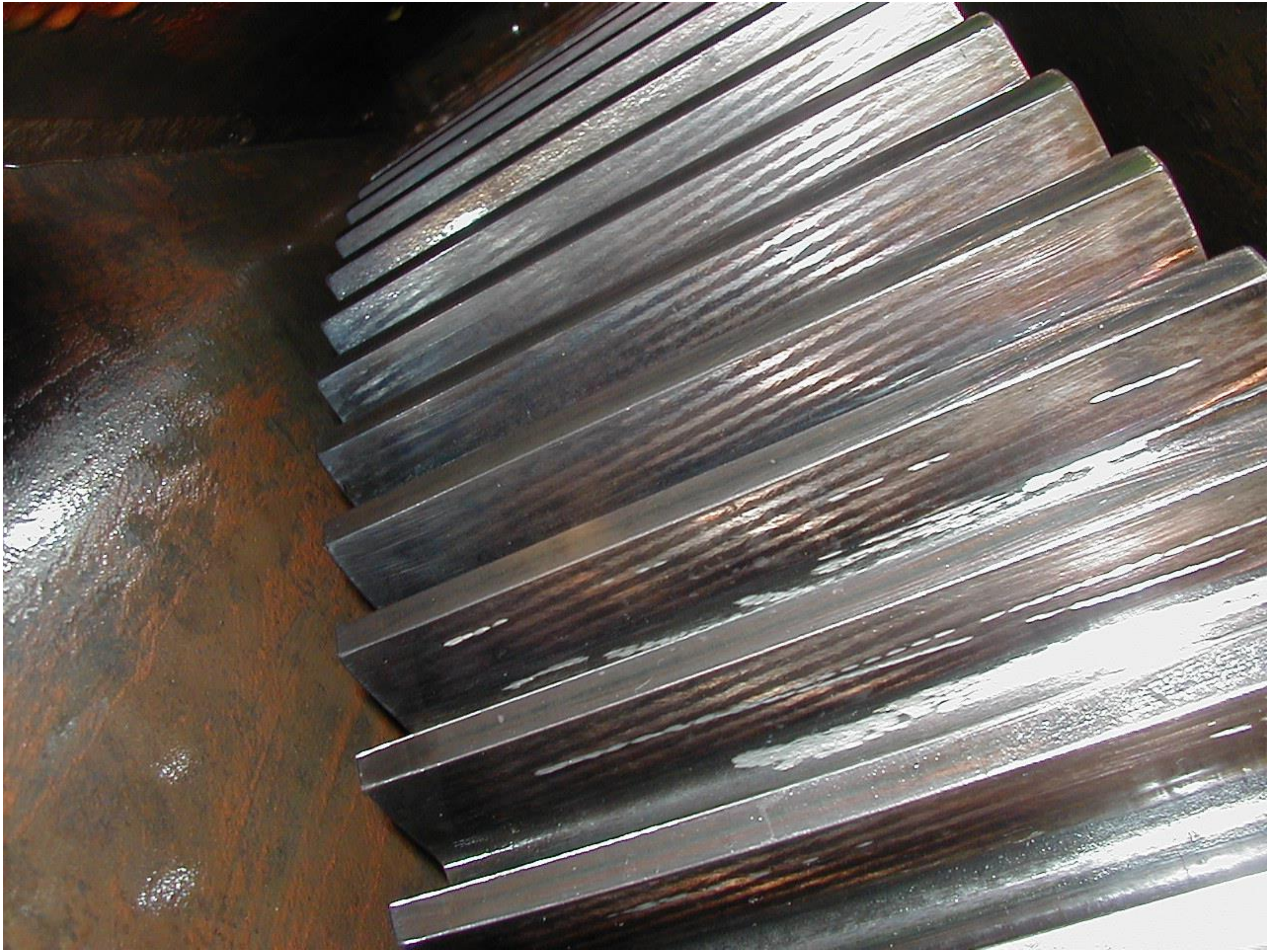
Micropitting on a Case Hardened Gear

Micropitting from heavy loads caused by poor alignment

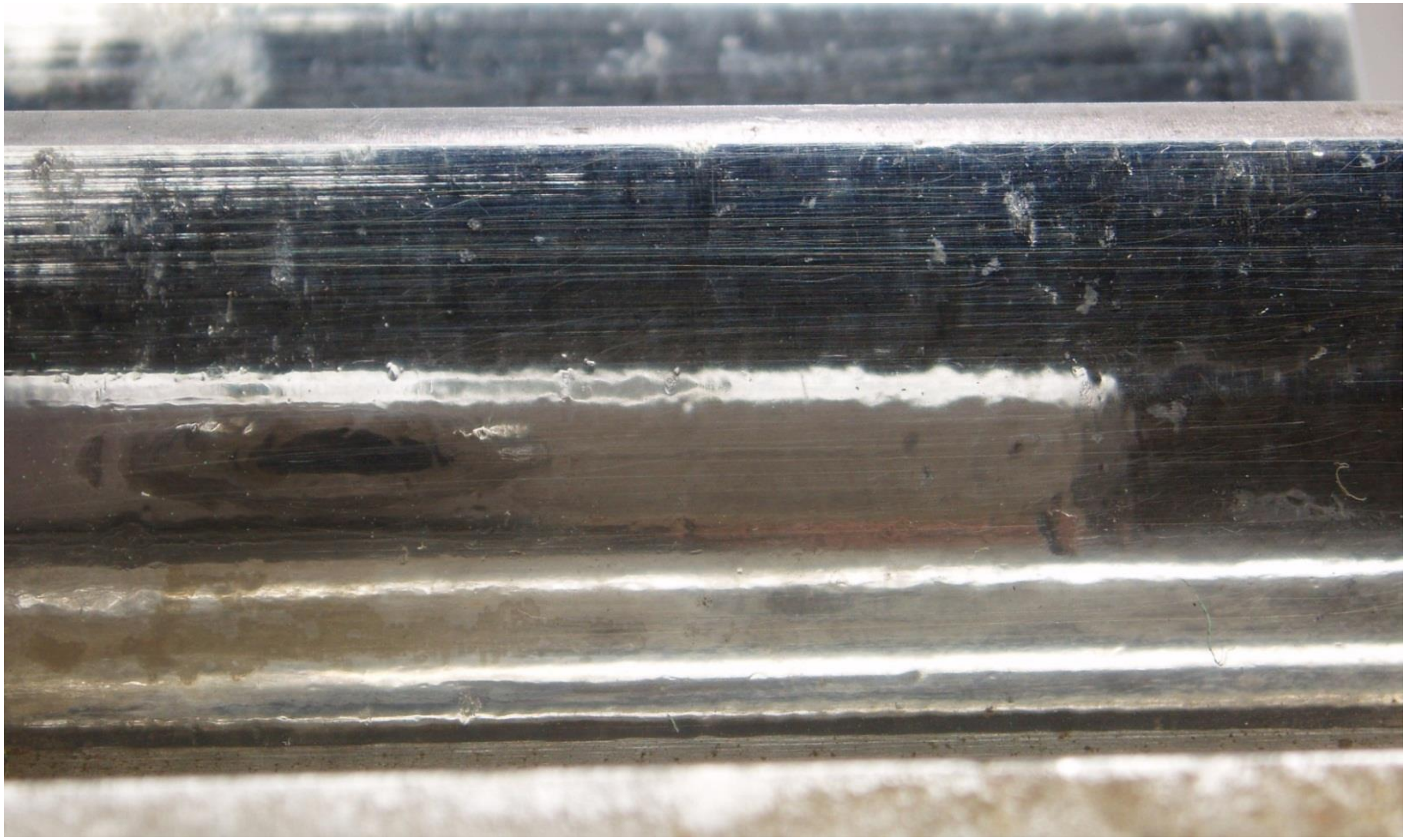


Uniform Micropitting Bands





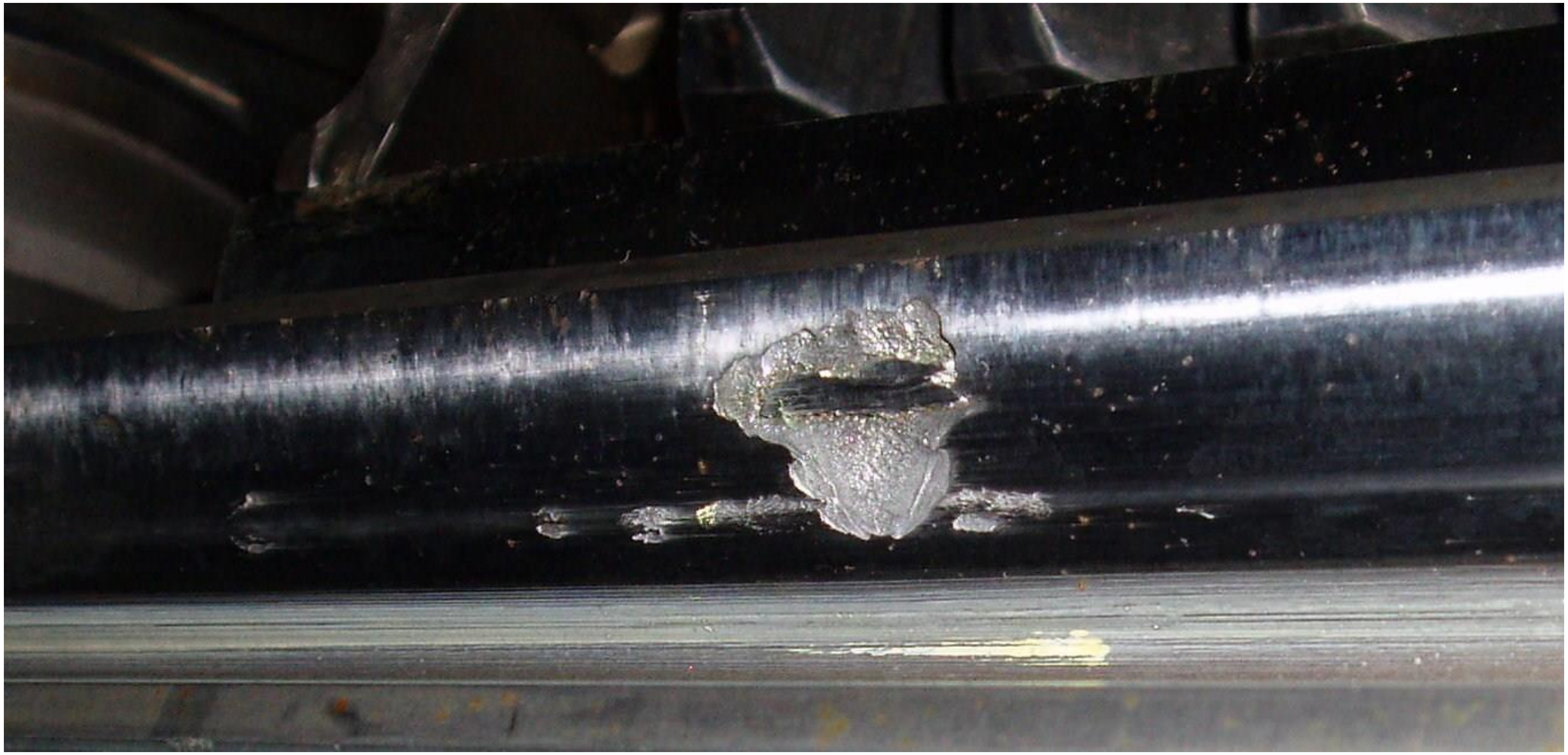
Rippling of a Case Hardened Gear



Can you see the distorted reflection of the camera?

Case Hardened Gears

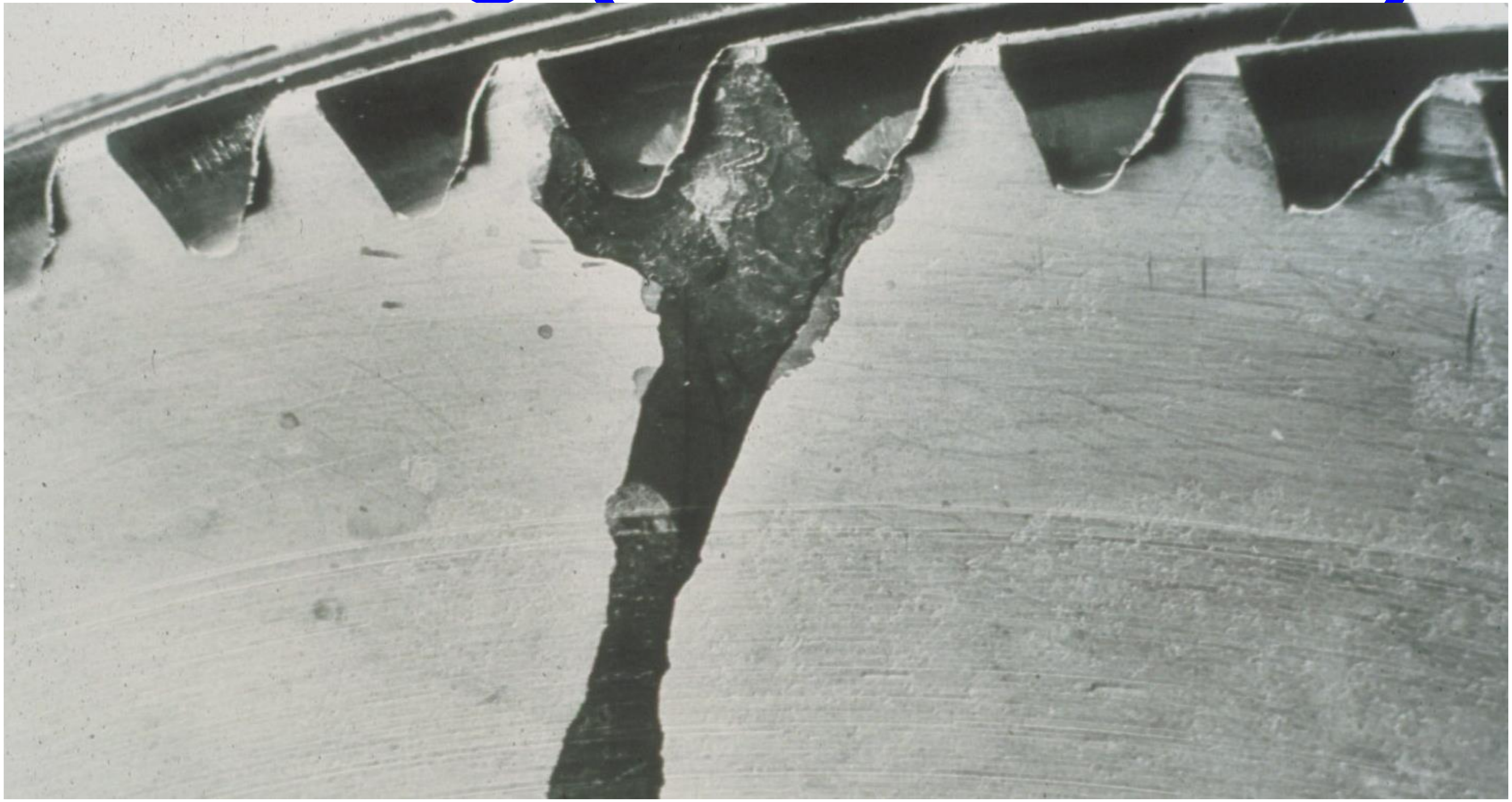
Rippling that has progressed to pitting and serious spalling



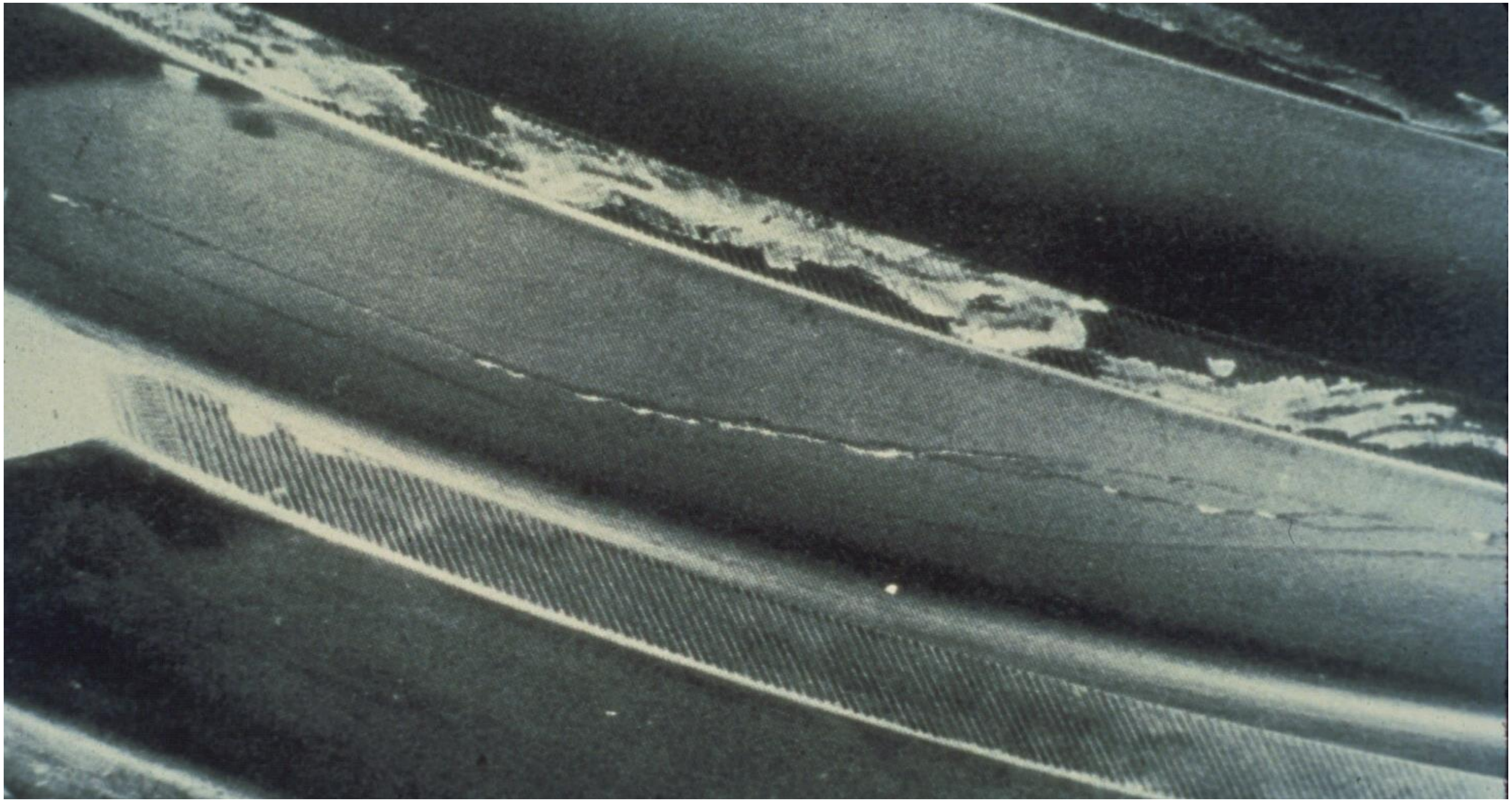
Comparison Review

- **Through Hardened -** Tough, good impact resistance, relatively tolerant of poor lubrication and abuse, corrective pitting can improve contact pattern, larger gear to handle the same loads.
- **Surface Hardened -** More power in same package, requires ***very*** good alignment and lubrication, pitting is a sign of excessive loads and can be a danger warning.

Overload resulting in Rolling (Plastic Flow)



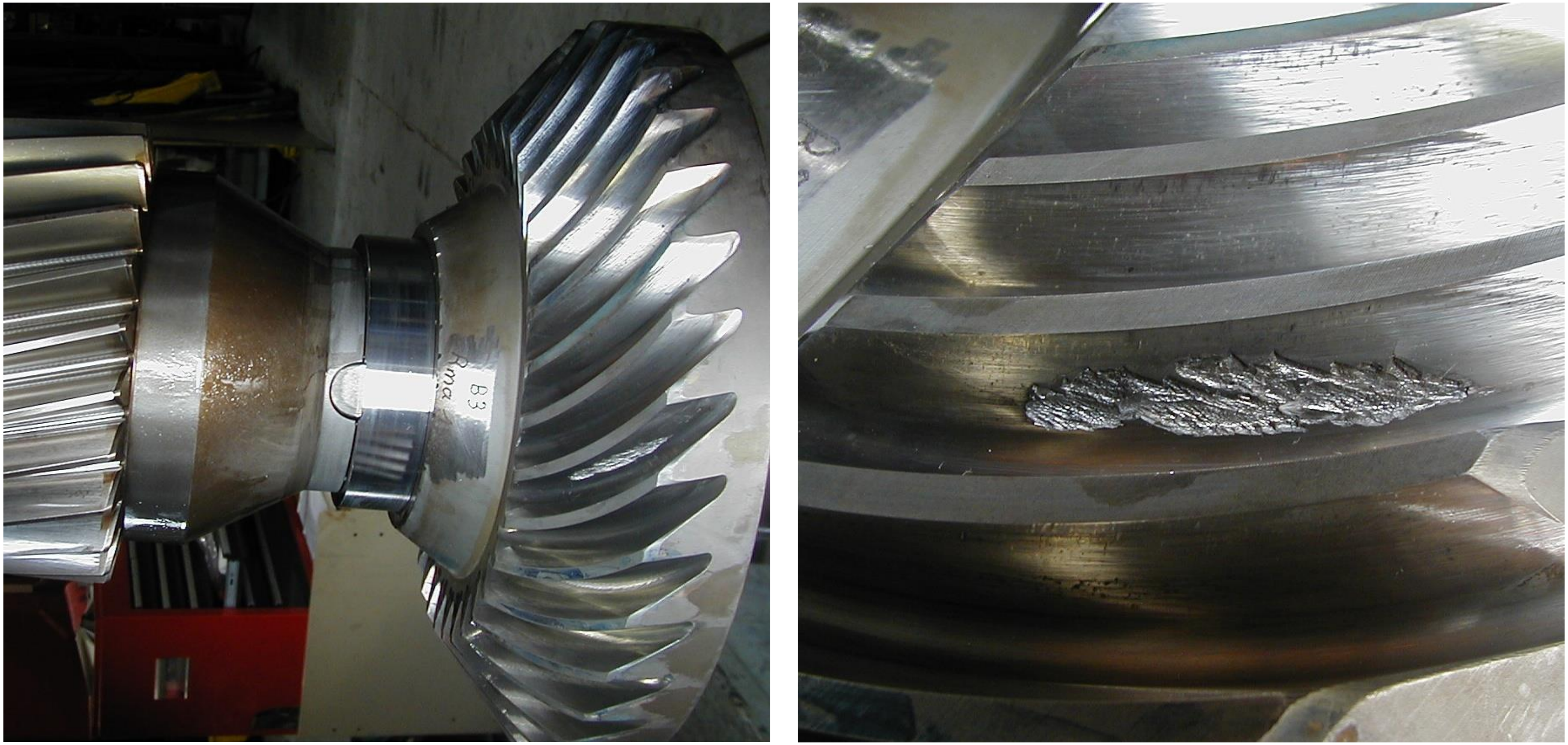
Case Crushing from Overload



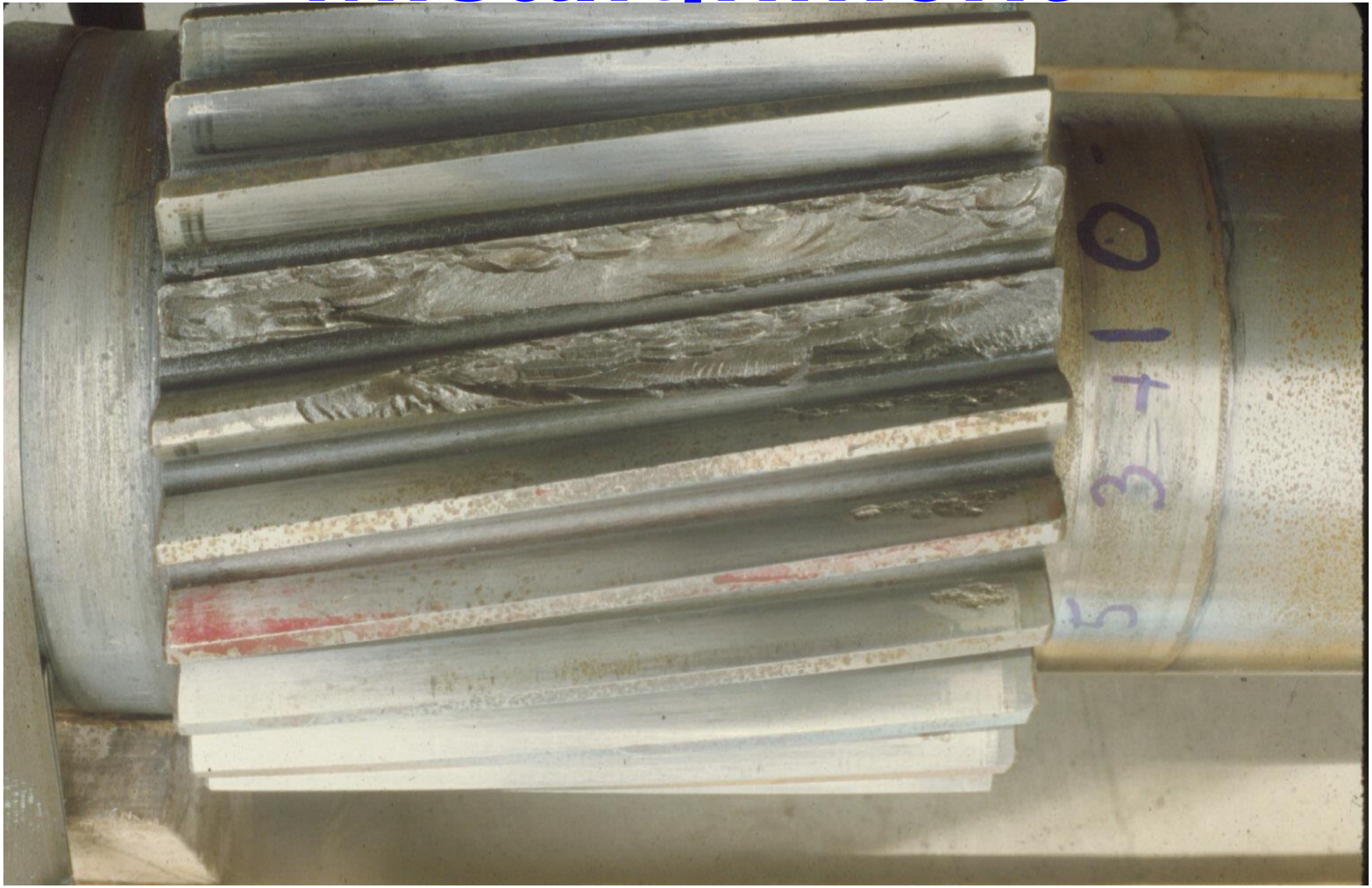
This large spall indicates a metallurgical problem

Manufacturing Problem

with an intermediate Pinion Gear



Misalignment



… with serious micropitting

Quiz questions

1. What is the basic metallurgy used for most modern industrial and transportation gears?
2. What is the ***diametral pitch***?
3. What is the gear ***module***?
4. There are several common ways of sizing gears. What are the primary differences between the ***AGMA 2001*** and the ***ISO 6336*** methods?
5. With what type of industrial gear metallurgy is pitting ***not*** of immediate great concern?
6. When pressure is put on oils, what happens to their viscosity?
7. In the shop, how should you check for the proper gear alignment of a set of gears in a reducer that has been in use?

Thank you for listening!

Any questions??