FAILURE ANALYSIS AND REPAIR TECHNIQUES FOR TURBOMACHINERY GEARS

by

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ABSTRACT

This paper covers the use of gears in turbomachinery applications. It reviews the contents of the American Gear Manufacturers Association (AGMA) and American Petroleum Institute (API) standards.

During the course of an engineer's career, he is called upon to examine gear failures. He must have a basic knowledge of gear failure modes and how they can be prevented. Sufficient background is necessary to detect early stages of gear damage so that they can be arrested before a complete outage occurs.

When gears do fail or are damaged, there are various proven repair techniques available. These methods can save much downtime. Through the reuse of salvageable parts, substantial cost savings can be realized.

INTRODUCTION

For practical and economic reasons, gears are used extensively in turbomachinery applications. The driving motor or turbine speed usually does not match the speed demanded by the driven compressor, fan, generator or pump. Gears are used to decrease or increase the speed of the driver to suit the driven machine's needs. Since the gear box delivers constant horsepower, the output shaft delivers torque inversely proportional to the speed change.

Most industrial gears are custom designed and manufactured. The original manufacturer usually does not have a spare gear set on his shelf and the user cannot afford to inventory spares for all of his equipment. Therefore, it is important for each user to be alert for potential gear problems. With tight money and a squeeze on profits, early failures are intolerable as they can keep a machine down for a long period of time.

Even with spares, the user must have sufficient knowledge of failure analysis so that the failure will not occur again. Without spares he must be familiar with acceptable repair methods and the quickest way to get back in operation.

Over the years the American Gear Manufacturers Association (AGMA) has established a series of gear rating standards which have been proven successful in permitting most gears to operate in severe applications for billions of cycles without failure. These ratings are being modified and updated as field experience and better analytical data become available.

The first step to insure that a gear drive performs as expected is to be sure that it has been selected properly for the job intended. Too many users have premature failures because they bought a machine package with a gear drive which had insufficient capacity for its application. Either the user must live with the mistakes of others or make costly modifications to the machine. When buying equipment the user should specify that the manufacturer supplies gears that are rated in accordance with established AGMA and American Petroleum Institute (API) standards. These standards gave proven successful for insuring long gear life.

SERVICE FACTORS

There are two main factors which determine how large and how strong a gear should be made. These are design parameters and service factors.

The design considers loading, face width, diameters, tooth sizes and geometry, materials, heat treatment, etc. If all of these factors could be optimized, which does not exist in practice, and the gears ideally manufactured, installed and lubricated, then the gears would last forever at the maximum design capacity.

Since perfection is not attainable, service factors are used which take into consideration the type of prime mover, kind of driven equipment and the amount of time the equipment is used. For example, a diesel engine driving a set of gears will create more shock and peak loads than an electric motor. Similarly, a reciprocating compressor is more severe on the gears than a centrifugal compressor would be. Also, a machine that runs 24 hours per day, 365 days per year requires tougher gears than one used in occasional service.

After the actual driving horsepower is determined, it is multiplied by the service factor to obtain the equivalent horsepower. It is necessary that the gears have a design rating equal to or in excess of the equivalent horsepower.

In effect, the service factor lowers the allowable unit load on the gear teeth. In general, gears are like bearings. If the gear capacity is doubled or the load is reduced by half, gear life would increase tenfold. Thus, higher service factors can improve gear life substantially.

Table 1 lists minimum gear service factors for various prime movers and driven equipment.

AGMA AND API STANDARDS

Adequate standards are available from the AGMA and API which present formulae for computing the rating, the surface

TABLE 1. MINIMUM GEAR SERVICE FACTOR (SF)

Driven Equipment	Prime Mover: Motor	Prime Mover: Turbine	Prime Mover: Internal Combustion Engine
Blowers			
Centrifugal	1.4	1.6	1.7
Compressors			
Centrifugal	1.4	1.6	1.7
Axial	1.4	1.6	1.7
Rotary Lobe (Radial, Axial, Screw, and So Forth)	1.7	1.7	2.0
Reciprocating	2.0	2.0	2.3
Fans			
Centrifugal	1.4	1.6	1.7
Forced Draft	1.4	1.6	1.7
Induced Draft	1.7	2.0	2.2
Generators and Exciters			
Base Load or Continuous	1.1	1.1	1.3
Peak Duty Cycle	1.3	1.3	1.7
Pumps			
Centrifugal (All Service Except as Listed Below)	1.3	1.5	1.7
Centrifugal — Boiler Feed	1.7	2.0	...
Centrifugal — Hot Oil	1.7	2.0	...
High-Speed Centrifugal (Over 3600 rpm)	1.7	2.0	...
Centrifugal — Water Supply	1.5	1.7	2.0
Rotary — Axial Flow — All Types	1.5	1.5	1.8
Rotary — Gear	1.5	1.5	1.8
Reciprocating	2.0	2.0	2.3

fatigue (pitting) resistance and the bending strength (resistance to tooth breakage) of the gear teeth. In these standards there are separate formulae which determine the surface fatigue resistance and bending strength of the gear teeth. The actual rating of the gears is determined by the formula which produces the lower rating. A typical set of gears covered by these standards is shown in Figure 1.

AGMA Standard 421.06, "Practice for High Speed Helical and Herringbone Gear Units", is used when pinion speeds are 3600 rpm and higher or gears are operating at pitch line velocities (PLV) of 5000 feet per minute and higher. From this standard the pitch line velocity is defined as

$$PLV = .262 \times d \times s$$

where PLV = pitch line velocity (feet/minute)
d = diameter of gear (inches)
s = revolution/minute of same gear.

Since most turbomachinery gearing operate in this speed range, this standard is widely used.

Other important features of AGMA Standard 421.06 are as follows:

1. Applies to helical and herringbone (double helical) external gears of the parallel shaft type for speed reducing or speed increasing service.
2. Allows gear materials of thoroughly hardened steels or surface hardened steels (carburized, nitrided or induction hardened). Flame hardened materials are not permitted.
3. Permits any practical combination of tooth height, helix angle and pressure angle within specified limits.
4. Specifies maximum shaft stresses in bending and torsion for various strength steels.
5. Specifies maximum allowable tensile stresses for bolts and studs.
6. Recommends lubricants and lubricating systems.
7. Suggests service factors for various applications.
8. Suggests special considerations be made to investigate critical speeds, noise levels, excessive shaft deflections and external thrust loads.

API Standard 613, second edition, "Special-Purpose Gear Units For Refinery Services", covers the minimum requirements for special purpose, enclosed, precision, single and double helical, speed increasers and reducers of the parallel shaft type for refinery service. Gears included have pinion speeds above 2900 rpm and/or pitch line velocities above 5000 feet per minute. Examples of gear driven applications are centrifugal and axial compressors, contactors, separators, blowers, centrifugal pumps, generators and fans.

While the gear rating formulae for computing pitting and tooth strength are different than the AGMA approach, the final results are the same. Important features of API 613 are as follows:

1. Specifies other applicable standards of AGMA, API, ASME, etc.
2. Specifies basic design criteria such as sound level,

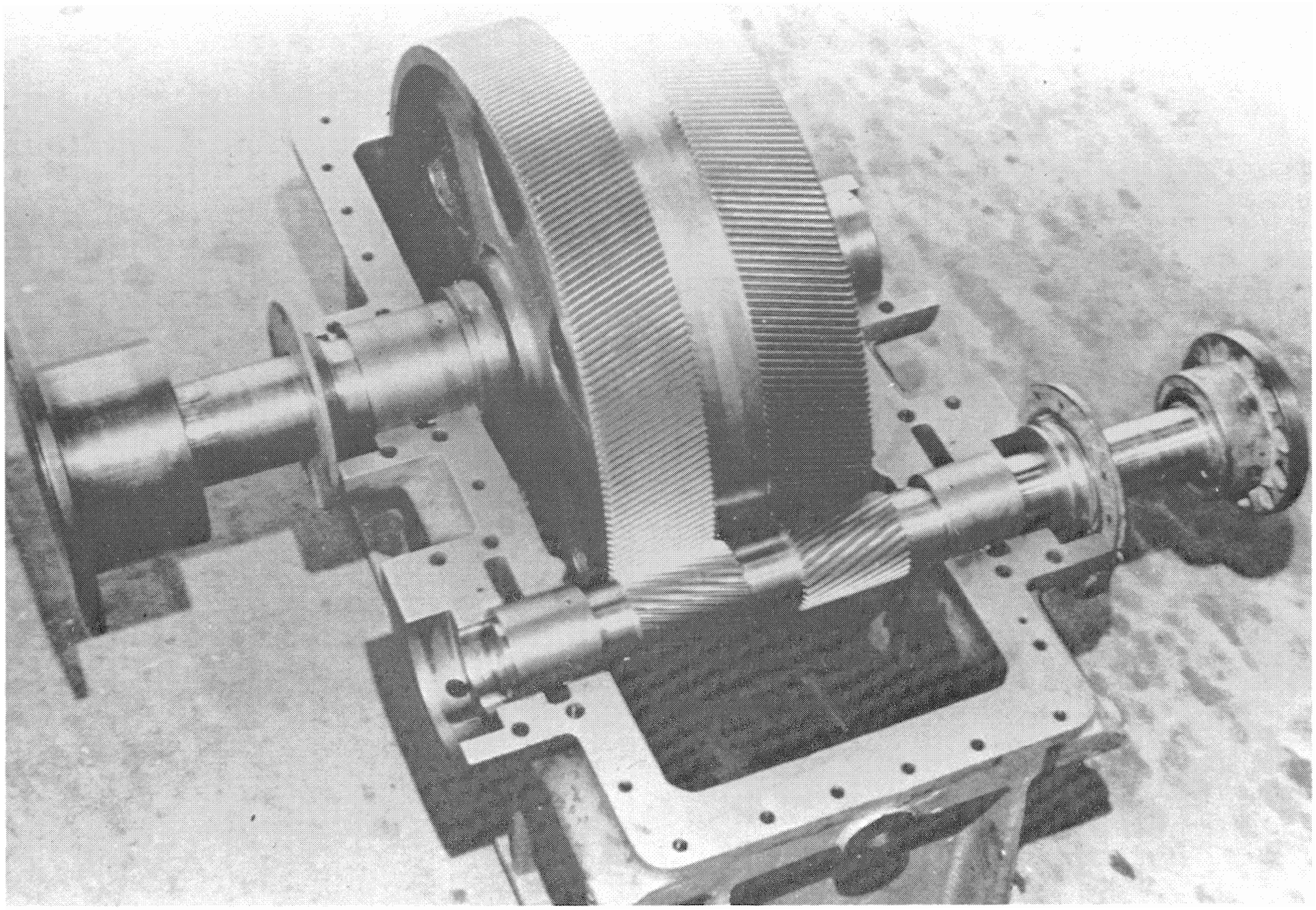

Figure 1. Typical Gear Set Used in Turbomachinery Service.

cooling water systems, electrical codes, lubrication, maintenance, etc.

3. Gives design parameters for gear housings, pipe, and flanged and threaded connections.
4. Covers minimum design and manufacturing processes for the gear elements.
5. Gives quality assurance methods for checking manufacturing tolerances, welds, and materials.
6. Specifies dynamic balancing requirements and critical speed considerations.
7. Provides guides for gear data, coupling selection, load curves for shoe thrust bearings, material specifications, a lateral critical speed map, and shaft assembly designations.

GEAR FAILURES

Failures are rare when considering the vast number of gear sets which operate trouble free for the life of the machines of which they are a part. However, under unfavorable conditions gear teeth do fail in service.

When failures do occur, it is important to find out why. When confronted with a gear problem, it is easy to become confused by the various appearances that are common. The problem is much simplified, however, by the realization that most failures can be attributed to three basic causes:

1. Surface Fatigue (Pitting).
2. Tooth Breakage.
3. Lubrication Failure (Scoring).

Surface Fatigue

Pitting occurs due to surface fatigue. Under load, gear teeth are subjected to high compressive stresses. If the endurance limit of the gear material is exceeded then cavities or pits form on the surface of the teeth.

There are two kinds of pitting, initial pitting and destructive pitting.

Initial Pitting

In most cases, initial pitting is not considered serious. It frequently occurs on the teeth of new gears due to high spots and roughness on the tooth surfaces. The pitting is usually small in size and extends in a narrow band near the pitch line of the tooth as shown by Figure 2. The over-stressed areas can experience fatigue in relatively few cycles, thus, initial pitting can be observed in a few days or even several hours after start-up.

Once the over-stressed areas have been removed, the loads are redistributed more evenly and the pitting stops.

This type of pitting can be prevented by providing gears with smoother surfaces such as by lapping, shaving, or grinding them. Also, a more accurate tooth profile will reduce the probability of highly stressed areas and dynamic loads on the teeth.

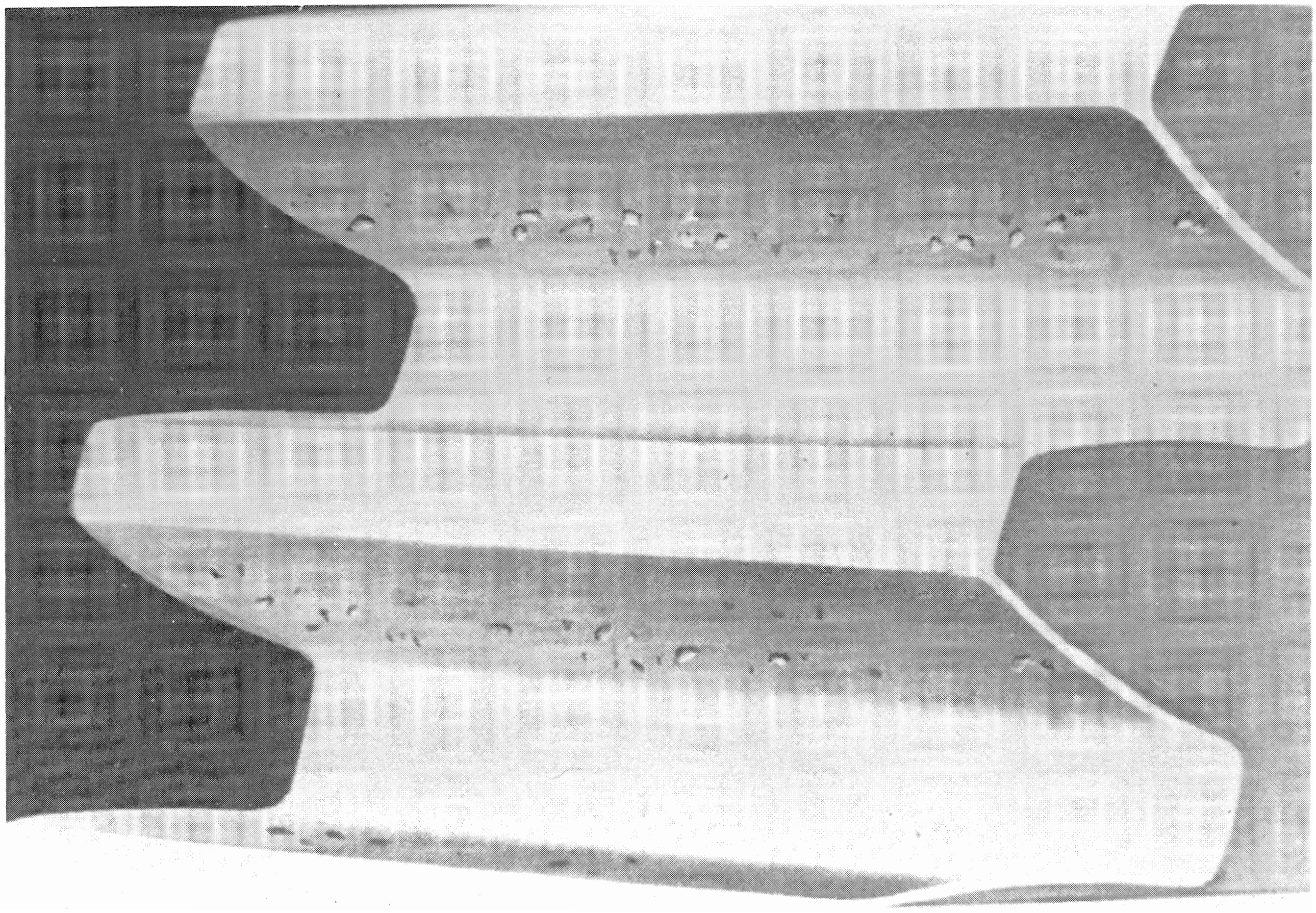

Figure 2. Initial Pitting.

Destructive Pitting

In this type of pitting the pits are larger in diameter than those associated with initial pitting (see Figure 3).

Usually, the dedendum areas of the drive gear are the first to experience serious damage by pitting; however, as operation continues, pitting extends over a majority of the tooth surfaces. In destructive pitting, the pits continue to form and enlarge as they break into each other. Eventually the tooth shape has been destroyed and the gears become noisy and rough running. Since the pits have rough surfaces, they have ideal stress concentration areas from which a bending fatigue crack can originate and cause a tooth breakage failure.

Cause and Correction of Pitting

Since pitting is a fatigue failure caused by too much compressive stress, either the gear loads must be reduced or the compressive strength of the gear material must be improved.

The gear user has a few options available if destructive pitting is detected:

1. Use a larger gear box. The gears in a larger box would have greater diameters and wider face widths. This would result in lower unit tooth loadings.
2. Use gears with higher strength gear materials. This is usually the most practical method since no dimensional changes would be required. A substantial improvement in the pitting resistance of a gear can be produced by increasing the hardness of the material. Hardness, measured in Brinell, is approximately proportional to compressive strength. Therefore, increasing the hardness of the teeth, through the proper selection of materials and heat treatment, is a very important factor for improving pitting resistance in gears.
3. Use a better lubricant. Although pitting is not caused by a failure of the lubricant, it can be retarded sometimes by using an oil of higher viscosity or with extreme pressure (EP) additives. A thicker and stronger oil film has a load spreading effect that reduces the unit loads. Caution must be used if a higher viscosity oil is tried since heavier oils tend to increase operating temperatures due to the increased shearing of the more viscous oil. Since viscosity decreases as temperatures rise, the benefit can be lost unless additional oil cooling is employed.

When oils with EP additives are used, temperatures should be maintained below the maximum allowed by the manufacturer so that the oil does not break down and cause the additives to form very active corrosive agents. Also, the entire lubricated system should be checked for any materials which are susceptible to chemical attack from the oil additives.

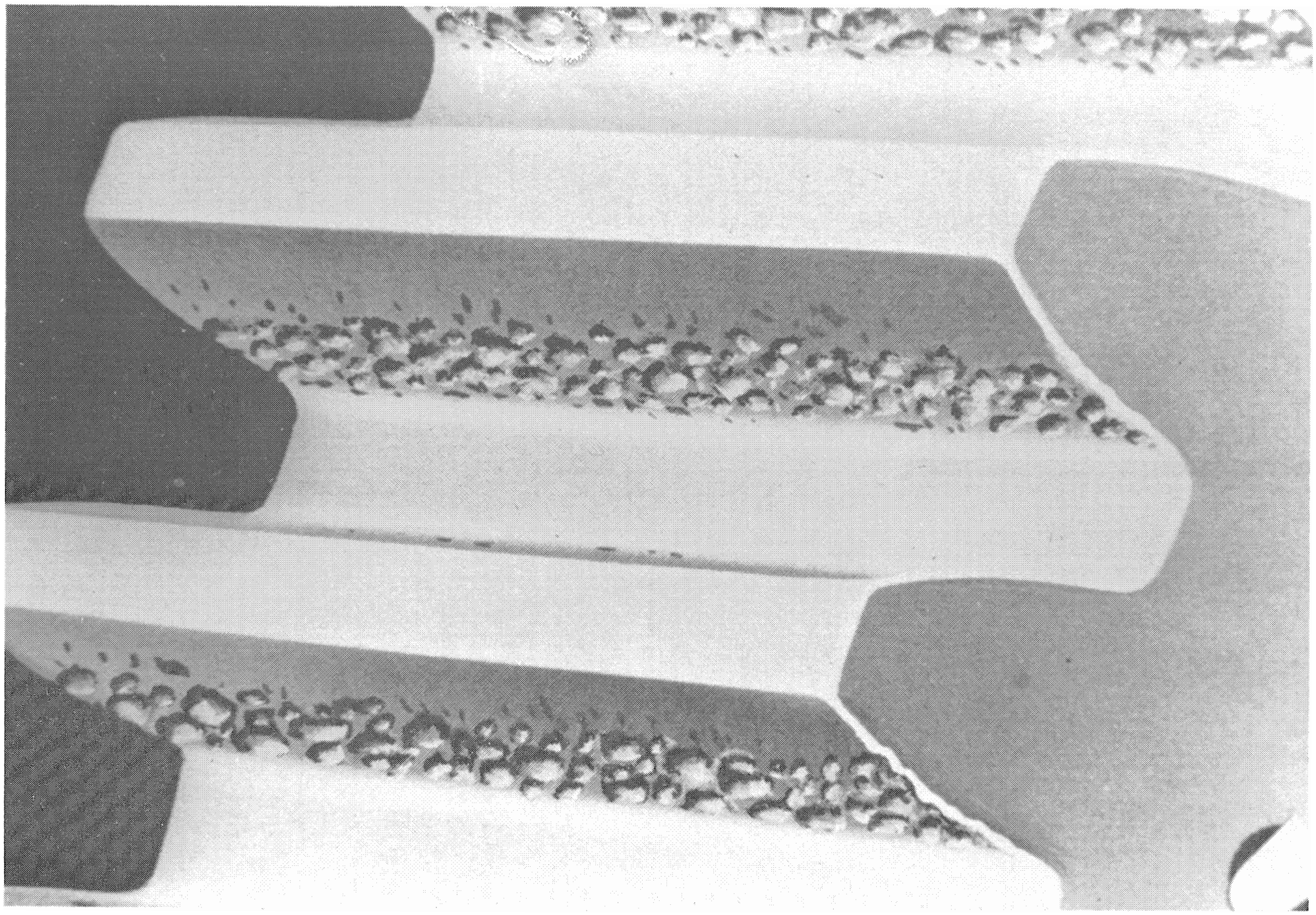

Figure 3. Destructive Pitting.

Tooth Breakage

Breakage of a gear tooth, as in Figure 4, is considered the most serious of the other forms of failure since it usually renders the gears unsuitable for continued operation.

Even if only a portion of a gear tooth breaks off, heavier unit loads are transferred to the remainder of the tooth with increased risk of complete failure. Dynamic unbalance will result and cause potential damage to other elements in the drive system. Many times the broken tooth will be caught in the mesh and damage to the other element will occur.

To understand how tooth breakage occurs, consider the tooth to be a tapered cantilever beam. A load on the tooth creates bending stresses which are greatest at the base of the tooth, at the root fillet.

Tooth breakage can be classified as fatigue breakage or overload breakage.

Fatigue Breakage

This form of failure is the result of many cycles of bending stresses that are above the fatigue strength of the material. A fatigue crack usually starts in the root section. It gradually enlarges until the weakened tooth breaks off. A fatigue break is often smooth and there usually is an "eye" or focal point where the crack originated. Generally, there is a smaller area of the broken tooth that has a jagged, rough appearance. This is the last portion of the tooth to break away.

Excessive bending stresses can be due to inadequate tooth design. A tooth with a larger pressure angle will be heavier at the base and therefore, stronger. Sometimes, larger teeth can be substituted for smaller ones. Also, a full fillet radius tooth has greater capacity than a tooth having sharp fillet radii.

Many times some sort of "stress riser" will aggravate the situation and cause higher stress levels than would normally be predicted. Such risers include tool marks, quenching or grinding cracks, metal inclusions, and residual stresses.

The best way to avoid fatigue breakage is to have gear tooth elements which will produce stresses well within the fatigue limit of the material. Also, a higher strength material can be used. It is important that the material be properly heat treated for the best structure and to minimize harmful residual stresses.

Overload Breakage

Failures of this type occur as a result of sudden overloads that produce stresses which exceed the tensile strength of the material. The surfaces of the fracture will appear much coarser and granular than a fatigue break. The break shows evidence of having been pulled or torn apart abruptly.

When several teeth or parts of teeth break out, examination may show that the first break was due to fatigue and the other breaks occurred subsequently as a result of the shock loading caused by the original broken teeth.

Overload breakage may result from a bearing seizure, failure of the driven equipment, foreign material passing

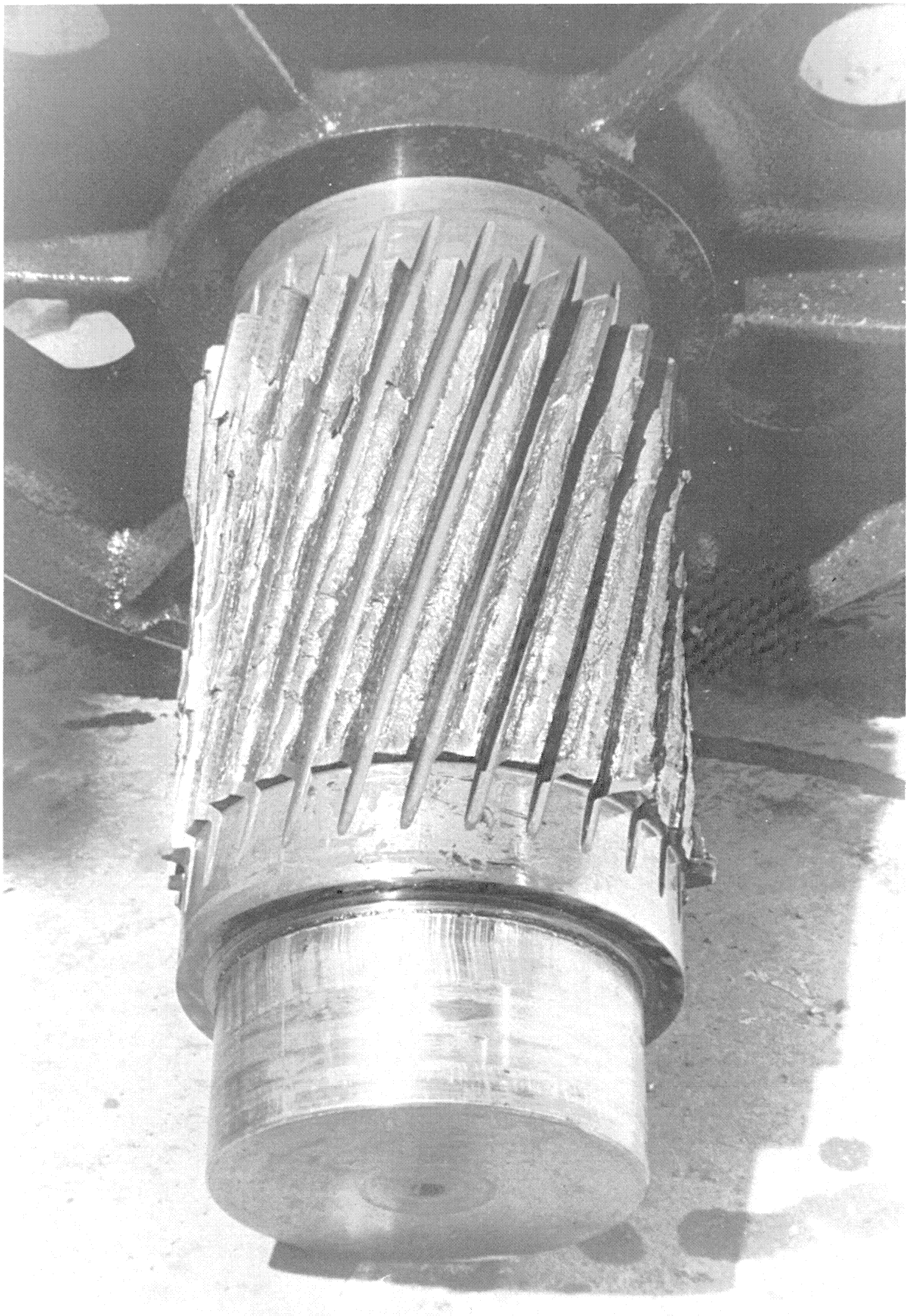

Figure 4. Failure Due to Tooth Breakage.

through the mesh, or sudden misalignment due to a gear bearing failure.

Lubrication Failure (Scoring)

When gears operate, the gear teeth are subjected to rolling action with sliding added. Pure rolling occurs only at their operating pitch diameters. Sliding takes place above and below this location and increases in proportion to the distance from the pitch line. Thus, the maximum sliding on a gear tooth occurs at its tip and at the lowest point of contact with the tip of its mating tooth.

Theoretically, the lubricant forms an oil film which prevents metal to metal contact when the gear teeth slide. No wear occurs and the original tool marks can be seen even after long periods of operation.

For various reasons, the oil film may not be thick enough to prevent metal to metal contact. Under the high pressure of gear tooth loading, the contact produces alternate welding and tearing in the direction of sliding as shown in Figure 5. Often material is displaced over the tips of the teeth causing a "feather edge." Considerable material is removed above and below the pitch line. The tooth profile is destroyed and the gears run with severe vibration and noise.

Since sliding is greatest at the tips of the teeth, scoring starts there. If it can be caught and diagnosed before it proceeds further, the gear can be saved. Thus, if radial scratches or tears are noticed at the tips of the teeth, the lubrication conditions causing failure can be identified and corrected before the gears are seriously damaged.

Often the gear lubricant is not at fault. Oil viscosity is an important factor. More viscous oils maintain a thick oil film and have greater resistance to being wiped away or squeezed out of pressure areas. Figure 6 shows gear teeth that scored severely in a few weeks because a lower oil viscosity than recommended was used.

The gear box must not be permitted to run at excessive temperatures. Extreme temperatures will cause the oil to thin out which can permit metal to metal contact. Excessive temperatures can be the result of failure to maintain proper oil level, flow, or distribution across the face of the gears.

In some instances the workmanship or application of gears result in conditions that no lubricant could withstand. These include excessive surface roughness, vibration, and shock loading in combination with high sliding speeds.

Sometimes scoring can be arrested by using an oil of higher viscosity than the one in use. Where straight mineral oils are in use, it may be desirable to use a lubricant with extreme pressure (EP) additives.

RECORDING SURFACE DAMAGE

Often it is desirable to record the progress of surface damage of gear teeth due to pitting or scoring. Pick a gear tooth that you want to periodically check. Mark it at the top or side for future reference. If you can get close enough, a photograph

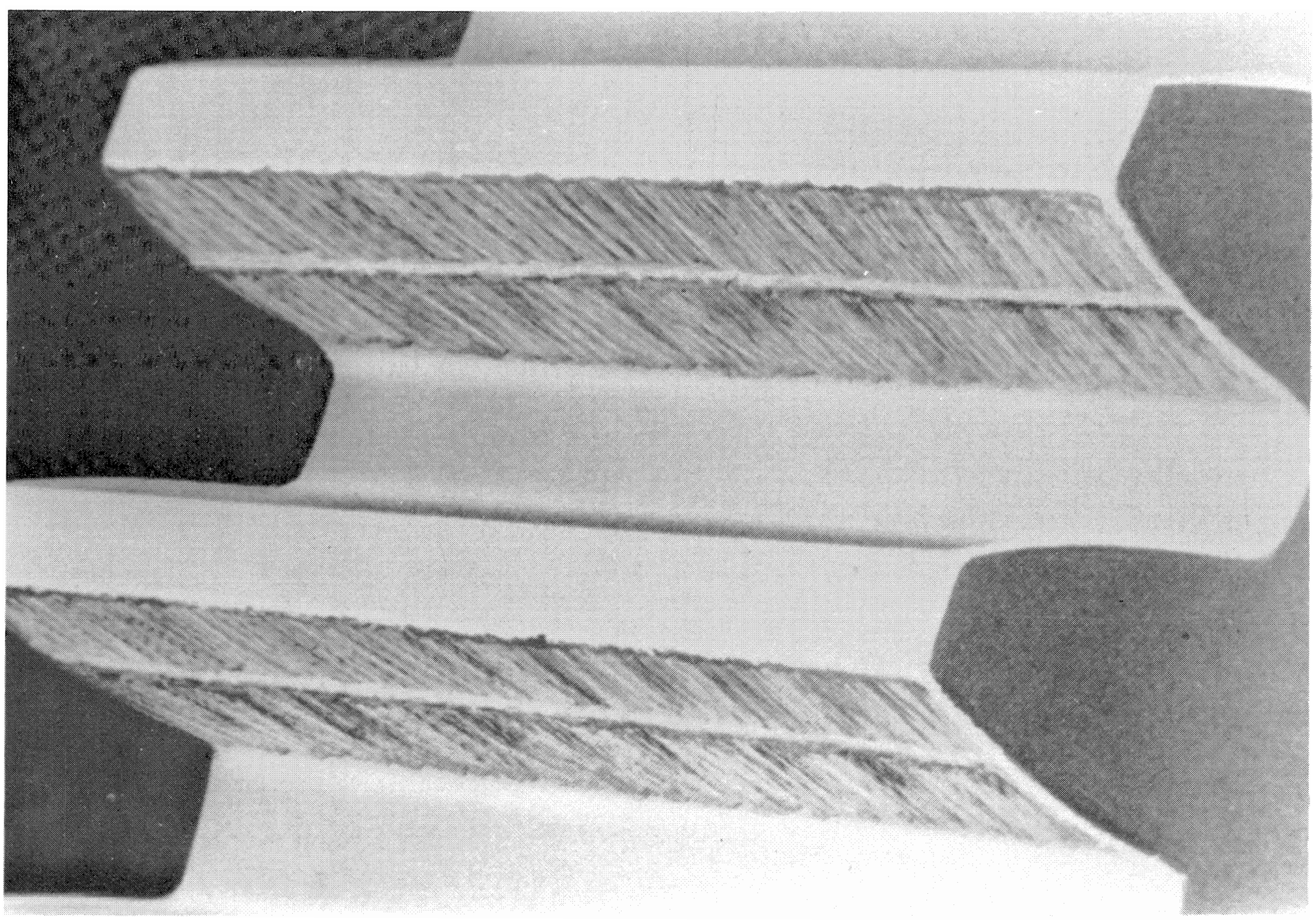

Figure 5. Lubrication Failure (Scoring).

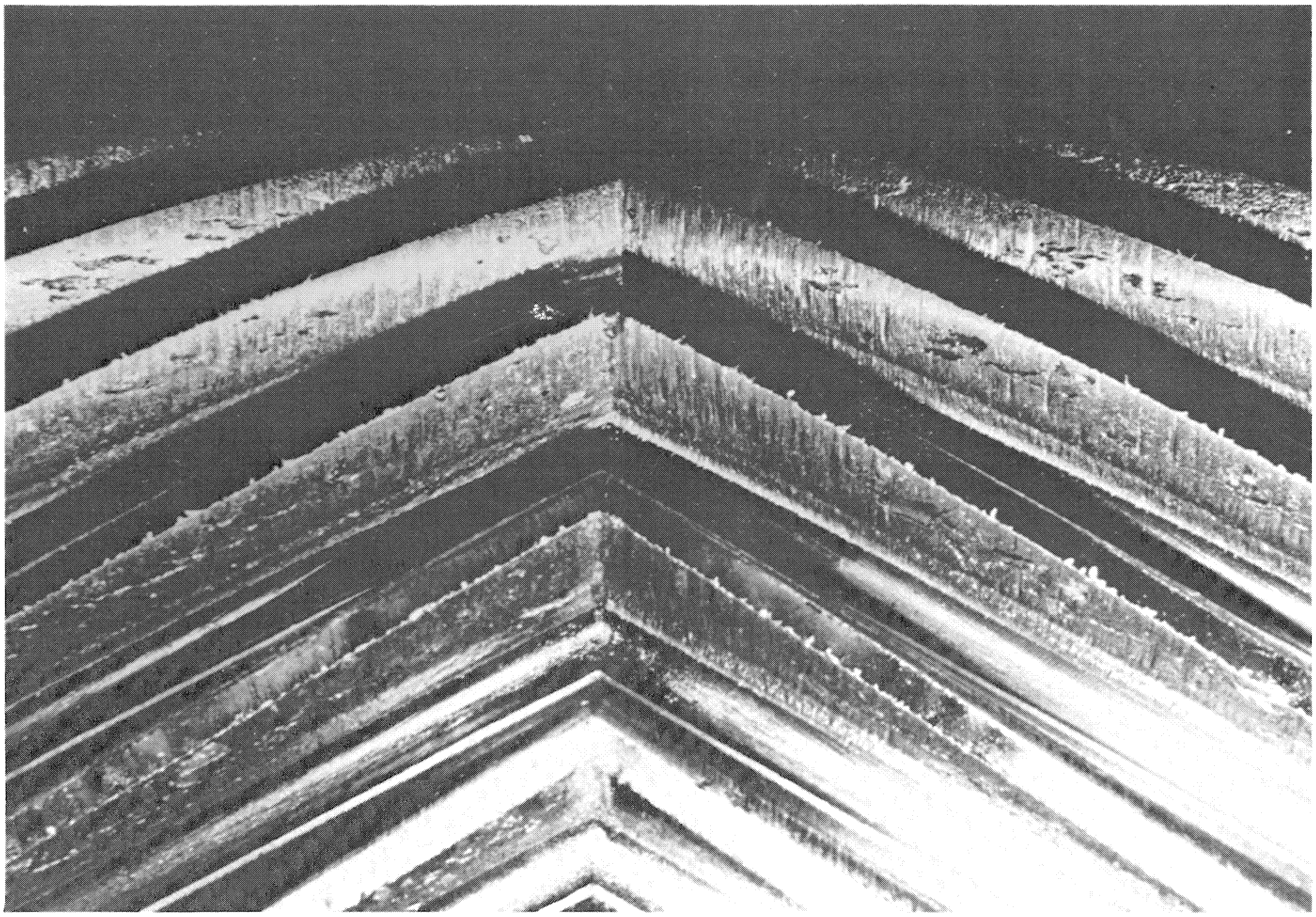

Figure 6. Scoring Caused by Improper Oil Viscosity.

will make a good record. If that is not possible, the following method can also be used at intervals to record progress of damage:

1. Clean the tooth surface and remove most of the oil.
2. Apply a thin coat of "Prussian blue" or other non-drying colored substance which has a consistancy of a light paste.
3. Wipe off the excess with a soft tissue.
4. Apply pressure sensitive transparent tape, adhesive side down, on the tooth surface. With a pencil eraser or fingers, rub the tape so that it adheres to the surface.
5. Strip off the tape and apply to a sheet of white paper. The surface condition is then permanently recorded.

MISALIGNMENT OF GEAR TEETH

A common cause of trouble in gear boxes results from misalignment between the pinion and gear. Pitting, scoring and tooth breakage can occur if the load is not evenly distributed across the face width of the gears. The gear rating standards of AGMA and API do allow for a small amount of misalignment, since perfect alignment does not exist in practice.

The load capacity of a gear set is proportional to its face width. If part of the tooth surface carries only a small amount or none of the load due to misalignment, then tooth loading on other portions will be greater than the design load. Usually the highest loads are at the ends of the teeth which are susceptible to breakage. Figure 7 shows pitting of gear teeth due to misalignment.

There are three types of causes of misalignment. These are manufacturing errors, design conditions, and installation problems. Manufacturing errors occur at the time the gears, bearings, and housing are produced. These include inaccurately cut gears with helix angle errors, eccentricity of bearing bores to outside diameters, and inaccurate boring of housings. If the gear box manufacturer employs suitable quality control procedures, these problems can be minimized and eliminated.

Design conditions refer to deflection under load. A pinion that is wide and small in diameter can deflect out of mesh through bending and torsion. Fortunately, the designer usually uses reasonable pinion proportions and relies on proven analytical methods and field experience to keep pinions and shafts within satisfactory deflection limits.

For the user, installation tends to cause most of the misalignment problems. Many people are unaware how precise a set of turbomachinery gears are and how important it is to maintain them in proper alignment. Problems with gear misalignment are the following:

1. Improper Housing Bolting to Base.
2. Misalignment of Couplings.
3. Bearing Problems.

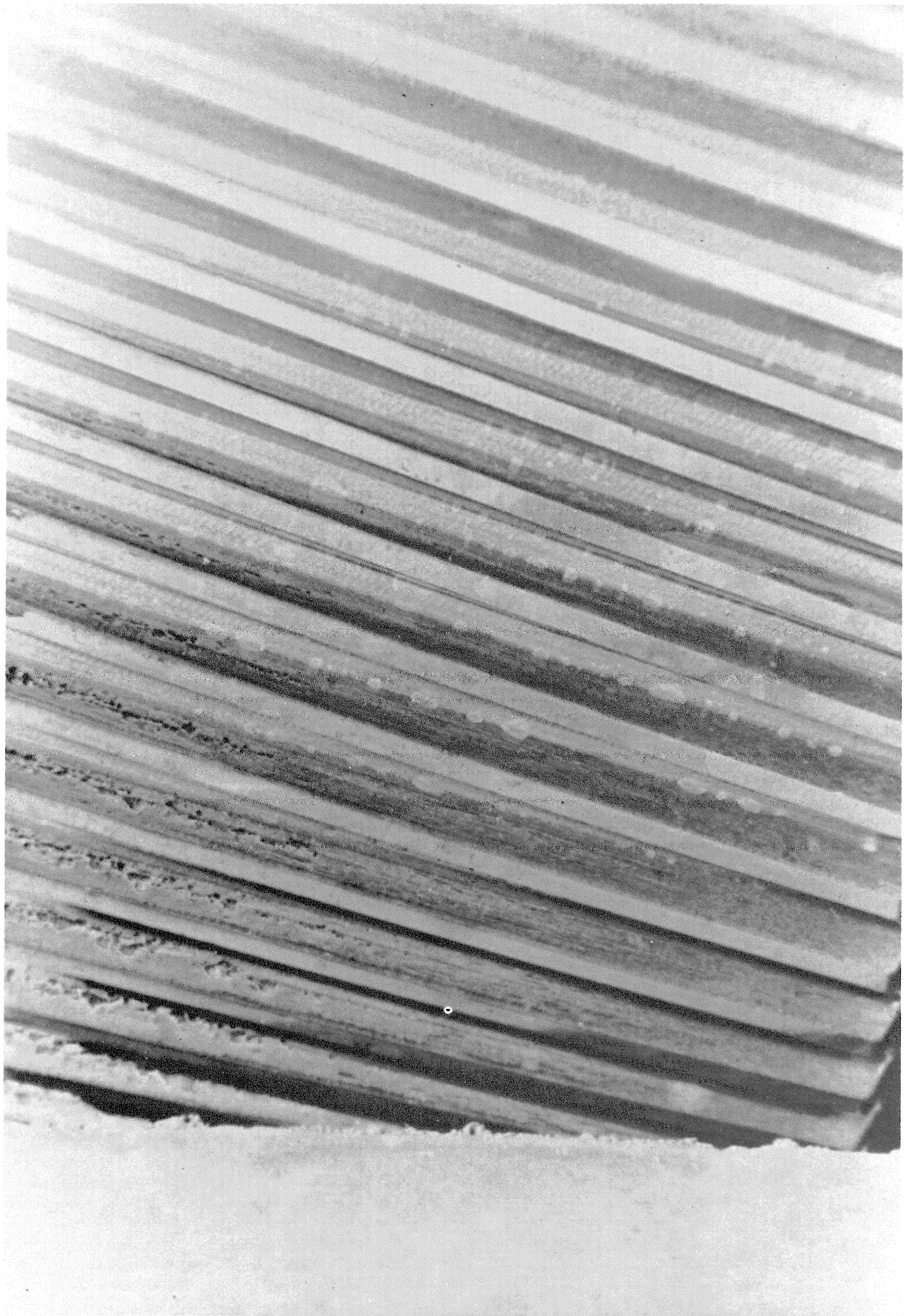

Figure 7. Pitting of Teeth Due to Misalignment.

Improper Housing Bolting to Base

When a gear case is bolted down to its base, care must be taken to insure that no twisting of the housing occurs. This can happen due to a "soft foot." A gap can exist between the base and one of the housing's feet. When bolts are tightened, the housing is distorted which takes the bearing centers out of parallel, thereby misaligning the gears.

After bolting down, it is good practice to check the alignment of the gears with a blueing check. Apply a thin coating of blueing to one member. Roll the gears back and forth together and check the transfer of the blueing to the other. This test will indicate whether the gears are sufficiently well matched.

Misalignment of Couplings

This is important if the natural running position of the shaft journals in their bearings is disturbed resulting from outside forces imposed by misaligned couplings. It is important to maintain coupling alignment within the specified level.

Thermal growth of all elements must be considered. Coupling alignment should be rechecked after all machine components are at operating temperatures.

Relative to the cost of the gears, most couplings are inexpensive. If the condition of a coupling is poor, it makes good sense to change it. For example, a flexible coupling with worn teeth can apply extra loads on the gears and bearings which can cause them to fail prematurely.

Bearing Problems

If journal bearings are not bored concentric with their outside diameters, they can cause gear misalignment similar to an inaccurately bored housing. Housing bores must fit evenly and snugly with the bearings.

Rolling element bearings, particularly the tapered type, must be adjusted with the proper end play. Too much looseness will allow the shafts to operate misaligned.

Another important condition often overlooked is that the clearances between the shaft and journal bearing should be the same for both bearings that support the shaft. Different clearances will allow one end of the shaft to run more off center creating a misaligned condition.

GEAR REPAIR METHODS

When a gear set has failed for reasons previously discussed (pitting, scoring or tooth breakage), repair of the gear set should be considered before it is sent to the scrap heap. There are two good reasons for determining if a repair job is desirable. They are time and cost.

When a gear set needs replacement, especially in a critical application and there are no spares, it is crucial to get back in operation as soon as possible. Repair methods are available which can restore the gears to their original condition and minimize downtime. Days and even weeks can be saved by reusing the undamaged parts of a gear set. For example, if the teeth on both gear and pinion have failed, it may be possible to salvage the gear hub and low speed shaft, thereby saving much machine time.

Naturally, costs can be reduced if certain parts of a gear set are not damaged and can be reused. It makes no sense to scrap perfectly good parts of a gear set when it has been determined that they have no defects.

Gear Grinding

After the teeth are cut, grinding of the gear tooth is used to improve the finish and improve accuracy. Grinding is usually regarded as the most accurate method of producing gear teeth. Besides accuracy, it has the versatility of finishing teeth of any hardness level.

When the tooth profile has only minor wear, such as from slight scoring or pitting, a quick and relatively inexpensive repair method is to grind the teeth in order to remove the damage. Usually the ground teeth are an improvement over the original gears since most were not ground.

Even though grinders are expensive, gears can be ground for a fraction of the cost of a new set and much time can be saved. Less than one thousandth of an inch to as much as several thousandths of an inch can be removed from the thickness of a tooth, depending on the amount of damage. Although the gears will have more backlash than before grinding, this usually is not critical since most turbomachinery gears run in one direction and a little extra backlash is not critical. Figure 8 shows a gear grinder in operation.

Before it can be decided if grinding the teeth is an acceptable repair method, the worn teeth must be checked carefully for cracks. Magnetic particle inspection methods are usually employed. If a crack on even one tooth is discovered, grinding is not the repair solution. Cracks are usually too deep to be ground out and there is high probability that a residual crack will continue to grow, causing quick failure of the gears when reinstalled.

In certain petrochemical environments, gears in storage and operation are attacked by corrosive agents which can destroy the tooth profiles. If the corrosion is not too deep, grinding can remove the corrosion and restore the teeth to new condition.

Typically, a gear set can be ground for one-fourth to one-third the cost of a new set. In regards to time savings, a new set may require at least several weeks to manufacture, especially if materials must be purchased. Grinding the teeth of an existing gear set can usually be complete in two or three days with all out effort.

Recutting Gear Teeth

Sometimes teeth are worn so badly that grinding is not feasible. If the low speed gear has been found to have teeth with no cracks, the diameter of the gear can be turned down and the teeth recut. Since the gear is always larger than the pinion, time and expense can be saved by remachining and recutting it.

Materials for a pinion are usually available. When the gear is turned down, the pinion diameter is made larger by the same amount that the gear diameter was reduced. An undersize gear and oversize pinion is a perfectly legitimate gear system and is called "long and short addendum modification." Since both gear and pinion have the same numbers of teeth, there is no change in the gear ratio. By enlarging the pinion the same amount that the gear is reduced, the original operating center distance and backlash is maintained.

When speeds are high and noise levels are critical, the recut gear and new pinion can be ground for highest accuracy.

When a gear is turned down for recutting, the amount usually is no more than one addendum on the diameter. Speed reducing drives are commonly designed originally with an addendum modification such as this.

The kinematics of speed increasing drives is different. A gear tooth driving a pinion is like the case of where the boy pushes a stick ahead of him; it tends to gouge into the ground. This situation can be a problem with speed increasing gearing using long and short addendum modifications. Therefore, this repair method should be used for speed reducing drives only.

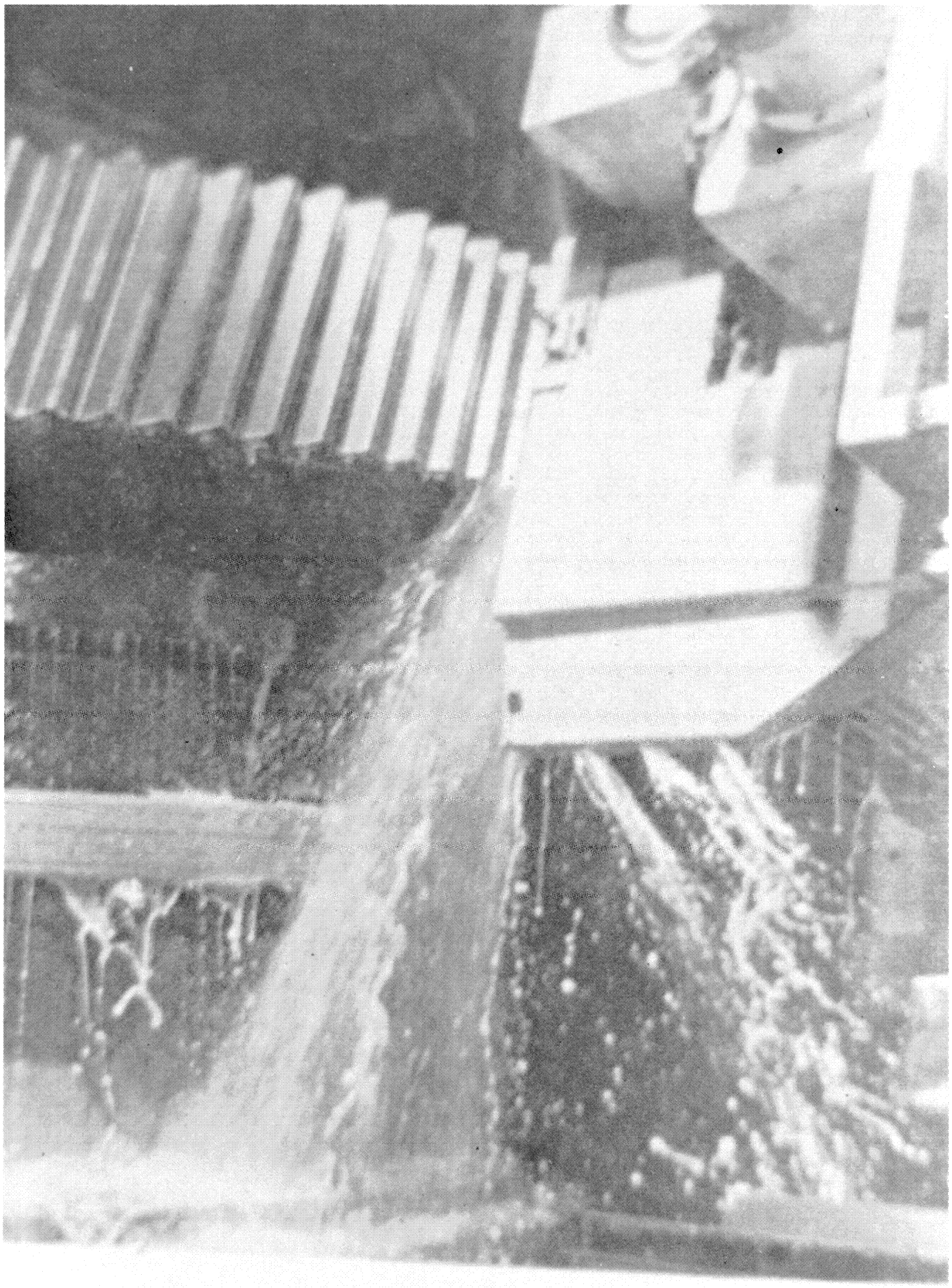

Figure 8. Gear Teeth Being Finished by Grinding.

If a gear can be repaired by machining and recutting and an oversize pinion made, a usable gear set can be completed in two or three days versus several weeks for a complete new gear set. Dollar savings also are substantial. A gear set repaired by this method will cost about half that of a new set.

Rebanding the Gear

When the teeth in the gear are broken, severely damaged, or have cracks, then neither grinding or recutting will repair them properly. If the gear is reasonably large in diameter, say over 20 inches, than rebanding can be the solution.

Rebanding is a repair method in which the gear is turned down sufficiently below the roots of the original teeth. Then a band of new steel, with the proper material specifications, is shrunk and dowelled to the gear center. Figure 9 shows a gear and shaft assembly suitable for rebanding.

Depending on the material of the gear hub, a band is installed with a shrink fit between .0005 in and .001 in per inch of diameter of the band inside diameter. Usually the fit is more than sufficient to insure turning of the band on its center under load. Dowels can be used for insurance.

After the band is installed, the gear and shaft assembly are put in a lathe and finish turned so that the gear sides and outside diameter are perpendicular and concentric with the shaft journals.

After finish machining, teeth can be cut in the new band. Teeth can be ground, if necessary. While the gear assembly is being repaired, a new pinion can be made. This repair method permits salvage of the gear center and shaft. Bands are typically kept in stock up to 46 inches in diameter and 13 inches wide. They have specifications that usually exceed those of the original material.

Gears that require rebanding can be manufactured in a week or less with an all out effort. Cost savings are typically from 25 to 40 percent of a complete gear set.

CONCLUSION

The AGMA and API have proven rating standards which permit trouble free operation of most gear installations. Service factors must be applied properly for severe or critical service applications.

Gear failures in turbomachinery usage usually occur due to pitting, tooth breakage or scoring. Early detection of gear damage can prevent premature failures.

Misalignment causes many gear sets to fail by overloading a section of the gear teeth. Inaccuracies in the housing, bearings or gears are possible causes. Improper installation can cause housings to twist. Misaligned couplings, improper bearing clearances or settings and failure to make adequate quality control checks are other factors that can cause premature damage.

When gears do fail, certain repair techniques are useful in reducing downtime and cost. If damage is not too severe, grinding the teeth is common practice. Some damage can be repaired by recutting the gear teeth deeper and making an oversize pinion. Where the teeth on the gear are cracked or broken, the gear assembly can be salvaged by turning off the old teeth and shrinking on a new band.

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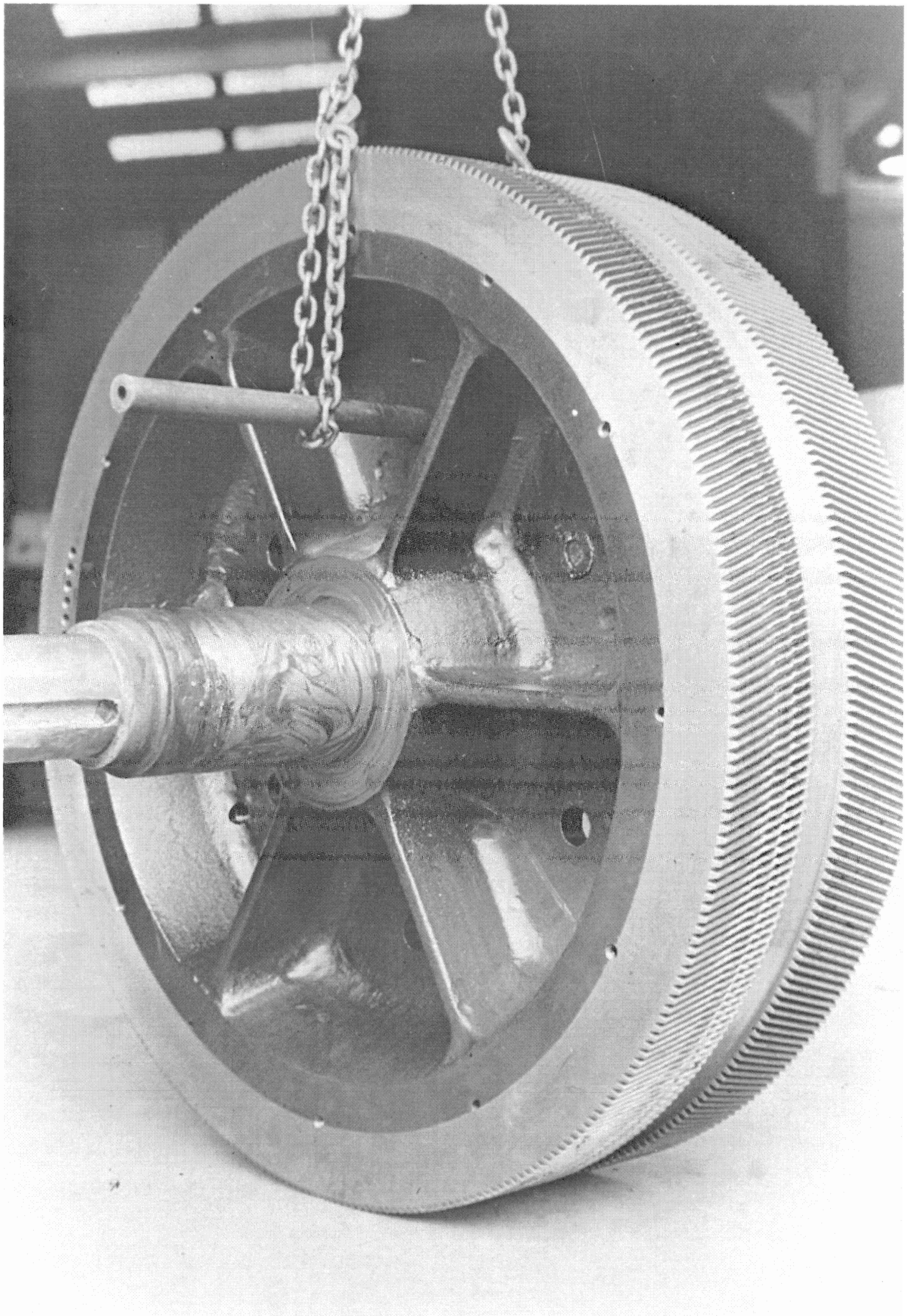

Figure 9. Gear Assembly Which Can be Salvaged by Rebanding.