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SALVAGING LARGE GEARS BY NON-STANDARD RE-CUTTING

by

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SUMMARY

This paper describes the experience of the authors in using non-standard cutting geometry to salvage large, expensive gear-sets. As time passes, even the most conservatively designed gear-sets may become damaged or worn, and replacement gears may be prohibitively expensive. However, it is not widely known that large gears can frequently be re-cut to a non-standard tooth size which can be equal in strength to the original gear. This procedure salvages the original gear blank and saves up to 75% of the cost of the new gear. However, it involves geometric, kinematic and strength changes that may limit its use in certain cases. These limitations are explained in this paper, and guidelines are given to judge when a gear can be re-cut or when it must be replaced.

1. INTRODUCTION:

Large-diameter gear-sets can be very expensive. They are commonly found in manufacturing machinery, such as large stamping presses, where gear diameters of 7 or 8 feet are common. As time passes, these gear-sets may become damaged or worn, particularly if the gear-teeth are not sufficiently hard or if the contact lubrication has been inadequate. To restore the machine to its original state of operation, the owner is usually faced with the purchase of an expensive set of replacement gears; however, it is not widely known that large gears can frequently be re-cut to a non-standard tooth size which can be equal in strength to the original gear. This procedure salvages the original gear blank and saves up to 75% of the cost of a new gear.

However, re-cutting involves changes, depending on the case, that may limit its use. For example, in some cases, it may be necessary to alter the speed ratio slightly or to change the center distance of the gears. To restore full strength, hardening of the teeth may be required after re-cutting. The implications and limitations involved in re-cutting large gears are explained in this paper, and guidelines are given to judge when a gear can be re-cut or when it must be scrapped.

Large gears (or gear segments) are also found in movable structures, such as lift-bridges, and although the authors have not seen this type of gear re-cut, the principles apply equally to this application, and the significance of the cost saving may not be widely known.

2. TYPES OF GEAR DAMAGE:

It is important to detect faulty or damaged gears before the damage is too severe to salvage the gear-set. It is also important to identify the cause of the damage, so that the re-cut gear will not see a future failure of the same sort. This is particularly important when the cause of failure is something (such as the lubrication or alignment) which can be easily remedied during the renovation of the gear-set. Some typical types and causes of gear damage are therefore reviewed in the following paragraphs:

In high-speed gear-sets, evidence of gear damage is usually observed as vibration which can be felt or heard as noise. An increase in gear-box temperature may also be a signal that tooth damage has advanced to the point where failure is imminent. In slow-speed gear-sets, such as those commonly found in large movable structures, serious gear damage can usually be observed with the unaided eye. Gear damage can be classified as one of four types: wear, plastic flow, surface fatigue or breakage [1,2]. Each of these is discussed briefly below:

Wear is defined as the removal of small amounts of surface material, in layers. The motion of gear-teeth in contact almost always results in some wear because of the rolling and sliding action of the involute tooth profile; only at the pitch point does pure rolling occur. Light wear can sometimes be beneficial, as when two contacting surfaces "wear-in" to create a polished surface which distributes the contact load more evenly; however, if the particles are not removed, an "abrasive wear" can result, in which the removed particles act as an abrasive to remove more material, at an even faster rate.

Lubrication failures can lead to a form of wear known as "scoring", in which the failure of the oil film has permitted direct metal-to-metal contact to occur. This causes welding and tearing of the two surfaces in contact. Misalignment may also cause a form of scoring to occur, in which heavy pitting exists at one end of the teeth.

Occasionally, gears can fail through overload, causing plastic flow of the surface material to occur. This is more common in soft or medium-hard materials, and may result from severe static or dynamic overloads being transmitted. Occasionally, plastic flow may be the end-result of severe scoring which has damaged the involute tooth profile so severely that the conjugate action of the teeth can no longer occur.

The surface of the teeth may also fail even if the applied loads are well below the stresses needed to cause plastic flow, if the stresses are applied very many times. This is called "surface fatigue" or "pitting" and results from the very high compressive stresses between the teeth in contact. A special type of surface fatigue, called "spalling", occurs when the fatigue failure begins slightly below the surface, at the interface between the hardened outer case and the softer inner core. Spalling and pitting may, in severe cases, spread across the contact area of the teeth, causing obvious damage and resulting in very rough running. Spalling and pitting are usually the result of inadequate surface hardness, and the although they are a form of fatigue failure (and may take many years to develop in the re-cut gear) it may be desirable to harden the gear-teeth after re-cutting.

Finally, the gear failure may occur through "breakage", which is the loss of one or more teeth, through overload or fatigue failure. Although it is possible to repair broken teeth by inserting material, this process is not recommended, and (if the rim is wide enough) it is preferable to remove all of the teeth, or to cut the teeth on a replacement rim which is shrunk onto the old blank (as discussed below in more detail).

3. *THE RE-CUTTING PROCESS*

Re-cutting a large gear usually involves three steps: preparation, re-cutting and heat-treating.

(a) Preparation: It is necessary to examine a gear thoroughly before re-cutting, to ensure that the teeth are not cracked or damaged too severely. Occasionally non-destructive testing methods, such as magnetic flux methods, are used to check that the teeth are fundamentally sound. Gears which were hardened during their original manufacture may be too hard to re-cut, and may require annealing. It is important, also, to investigate the geometric, kinematic, strength and economic implications of re-cutting, as discussed in this paper, prior to selecting a course of action.

(b) Re-cutting: The re-cutting process is similar to the original cutting of the gear, although it is performed usually on a generating shaper, with either a rack or pinion cutter. In most cases, the large gear is re-cut, with the same number of teeth, on a pitch circle which is slightly smaller. (This inevitably implies the use of non-standard tooth sizes.) The pinion, or small gear, is usually discarded and a new pinion is cut, although in some cases, it is possible to re-cut the pinion also.

(c) Heat treating: After cutting, the gear teeth may, if necessary, be hardened to increase the strength and durability of the teeth. For steel gears, this requires flame-hardening or induction hardening on a tooth-by-tooth basis. Some cast iron gears cannot be hardened. However, as discussed below in this paper, hardening is not always necessary, and is not frequently done for re-cut gears.

4. STANDARD AND NON-STANDARD GEAR TEETH:

Gear teeth are usually cut in specific sizes, designated by the "Diametral Pitch" in the English unit system and by the "module" in the metric (or SI) system. Standardizing the number of tooth sizes has two purposes: the number of cutting tools needed is greatly reduced, and the resulting gears are interchangeable. The American Gear Manufacturers Association has long-established standards for gear size, shape and strength. These standards are particularly useful where replacement parts must be interchangeable. (For example, in the automotive industry.)

However, very large gears are almost always custom designed, interchangeability is not an issue, and there is no obstacle to using non-standard tooth sizes and shapes, if the tooling, time and expertise are available to complete the job.

Nevertheless good gear design involves many geometric, kinematic and strength constraints which were undoubtedly considered during the manufacture of the original gears and which must be examined for the re-cut gears. These factors are discussed in the next three sections.

5. GEOMETRIC CONSTRAINTS:

When a large gear is considered for re-cutting, the geometric constraints must be examined first, and usually require a choice between maintaining the center distance or maintaining the speed ratio of the gears.

The speed ratio is given by the equation:

$$\text{speed ratio} = N1 / N2$$

The center distance is given by the equation:

$$C = (N1 + N2) / (2P) \text{ where:}$$

C is the center distance (inches),
N1, N2 are the number of teeth in gears 1 and 2, respectively,
P is the diametral pitch or tooth size (teeth/inch).

When a gear is re-cut, the new teeth must obviously be slightly smaller, so the diametral pitch (P) will change. The above equations illustrate the dilemma: if N1 or N2 is changed to keep center distance (C) constant, then the speed ratio will also change. These geometrical constraints on speed ratio and center distance are discussed below in more detail:

***(a) Maintaining Center Distance by Altering Speed Ratio*:**
In some machinery, synchronization is critically important, whereas in others a wide range of speed ratios may be acceptable. If the speed ratio can be varied, then the larger gear can usually be re-cut and matched with a new pinion (with an increased diameter, to keep the center distance constant). However, if the speed ratio cannot be varied, even a small amount, then the number of teeth on the pinion and gear must remain constant.

***(b) Maintaining Speed Ratio by Altering Center Distance*:**
When the machine is constructed (or can be modified) so that the center distance can be adjusted, then the problem is somewhat simpler, since the re-cut gears (although slightly smaller) can have the same number of teeth as the original gears, and the speed ratio will be maintained. In this case, it is usually economical to re-cut the pinion as well as the large gear, for a further saving.

***(c) Maintaining Both Speed Ratio and Center Distance*:**
When both the center distance and speed ratio must be maintained, the solution requires more imaginative action. If the rim of the gear is sufficiently thick (in the radial direction) to permit the gear teeth to be completely turned off, then the old gear can be used as a hub. A hardened ring is shrink-fitted to the hub, and the teeth are cut in the ring. This is similar to cutting a completely new gear; the teeth can be identical to the original, and non-standard teeth are not needed.

6. CHANGE IN CONTACT RATIO:

In addition to satisfying the geometric constraints, the re-cut gear must satisfy some kinematic conditions, to guarantee proper meshing and smooth running of the renovated gear-set. The most important indicator of smooth running is the contact ratio, which is defined precisely as the "number of normal pitches in the interval of contact" [1], or loosely as the "weighted average" number of teeth in contact during one cycle of contact. This is illustrated in Figure 1, which shows two teeth coming into contact at point B and leaving contact at point C. The contact ratio (m) is defined as:

Contact Ratio: m = (Distance BC) / (Base circular pitch)

where: Distance BC is the "interval of contact", and the
Base Circular Pitch is the distance from a point on one tooth to the corresponding point on the next tooth, as measured along the Base Circle (as shown in the figure).

Obviously, the contact ratio must be at least equal to 1.0 for smooth operation of the teeth to occur, and in practice, ratios less than 1.2 are rarely permitted. When gears are re-cut, the teeth are generally smaller. However, it is interesting to note that the contact ratio is independent of the tooth size, and depends only on the number of teeth and tooth profile.

Therefore, if only the tooth size changes, then the contact ratio will remain constant. In fact (as the example later in the paper shows), if the re-cut gear is paired with a larger pinion, the contact ratio could even increase!

In some cases, it may be necessary to change the shape, as well as the size of the re-cut teeth. (In the example which follows, stub tooth shapes were used when re-cutting.) Reducing the tooth height can cause a reduction in the contact ratio, and rough running could result, so the contact ratio should be calculated. However, in large gears, the interval of contact is usually fairly long, and the contact ratio is usually fairly large. Typical ratios would be in the range of 1.5 or 1.6 , and small reductions in these ratios would still be well in excess of 1.2, indicating that smooth operation could be expected.

7. STRENGTH CONSIDERATIONS:

The re-cutting process generally results in slightly smaller and therefore usually weaker teeth. This reduction in tooth strength may however, be completely acceptable! This interesting result is again not widely known, and can be easily explained by examining the strength calculation procedure. In the AGMA (American Gear Manufacturers Association) procedure for strength calculations, gear-sets are examined for three modes of failure:

* Static failure (instantaneous tooth breakage due to overload),
* Fatigue failure (crack development after many millions of cycles),
* Surface wear failure (surface pitting after millions of cycles).

In the original design of a gear-set, the governing mode of failure is most commonly fatigue failure (due to tooth bending) which would occur only after many millions of cycles. The factors of safety against static and surface failure are usually much larger than needed. Therefore, after re-cutting, the factors of safety against static and surface failure will probably still be greater than the AGMA requirement.

The fatigue factor of safety may, however, be less than the AGMA recommendation. However, this does not mean that failure is imminent, but that the life expectancy is less. The life expectancy may still be more than adequate, however, since the surface layer that has

FIGURE 1:
Sketch of a Typical Gear Mesh

The gear teeth make contact at point B and end contact at point C. Line BC is the "interval of contact".

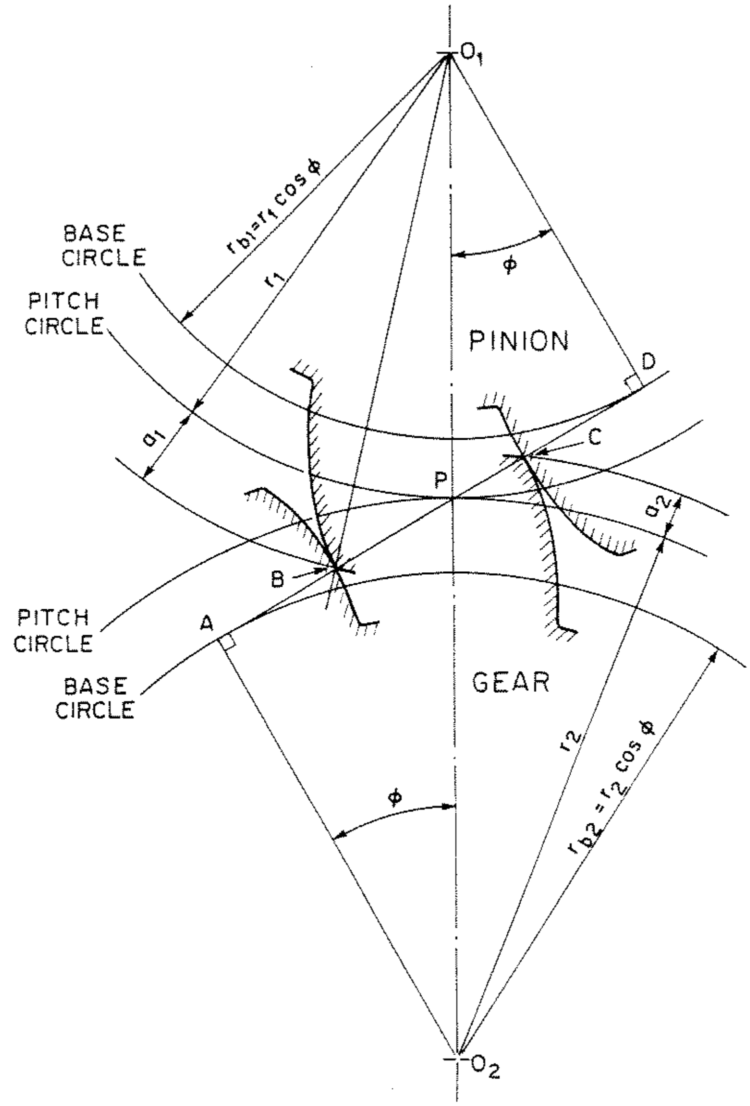
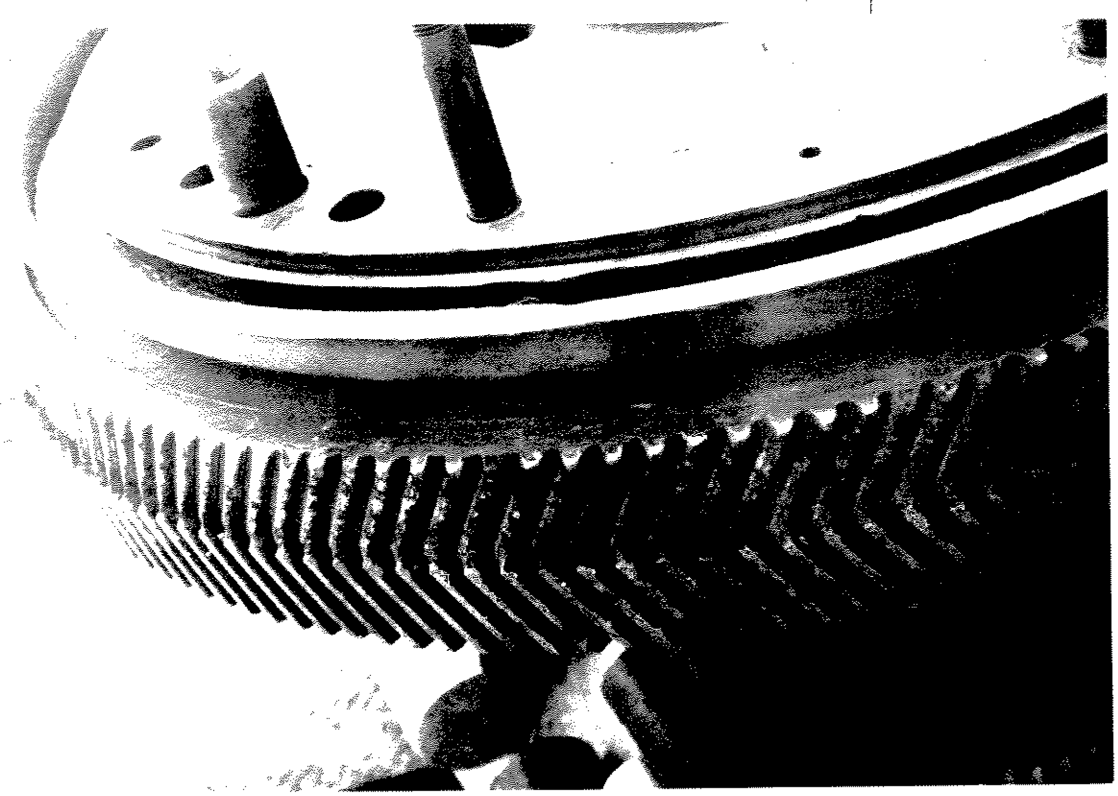


FIGURE 2:
A Typical Damaged Gear



suffered the most fatigue damage has been removed during re-cutting. For example, a gear-set that was designed originally for a fatigue life of 20 years may, after re-cutting, have an additional life expectancy of only 10 to 15 years, but this might be fully acceptable, in view of the cost savings.

When a reduction in strength (of any sort) is not acceptable, then the gear-teeth can usually be hardened after re-cutting. This increases the strength against all three modes of possible failure. Although some materials (some types of cast iron, for example) cannot be hardened, the carbon steels typically used in large gears can almost always be hardened. Heat-treating to harden the teeth reduces the cost savings, however.

8. COST SAVINGS:

The cost of manufacturing a large gear depends on the cost of the material, plus the cost of machining and heat-treating. These operations are listed below:

(a) stress relieving or annealing the blank to remove residual stress,
(b) machining the blank to lighten the web,
(c) turning the hub and rim,
(d) slotting the hub for a keyway,
(e) adding bolt holes, etc., for attachments (clutches, brakes, etc.),
(f) cutting the teeth,
(g) where necessary, hardening and grinding the teeth.

Five of the seven operations listed above must be performed on a new gear-blank, but are not necessary when a used gear is is being re-cut. Cost savings would, of course, vary from job to job, but experience has shown that purchasing and preparing the blank for cutting the gear-teeth amounts to about 75% of the cost of a gear that does not need a final hardening. If hardening is necessary, the savings would be slightly less, probably about 60% of the new cost.

The gear in Figure 2 illustrates the type of damage that can be remedied by re-cutting and shows some of the potential savings: fittings for the auxiliary equipment on the gear are not damaged, and can be re-used if the gear is re-cut.

9. EXAMPLE:

As an example of the process of re-cutting, consider the gears shown in the photograph in Figure 3. A set of two fairly large gears (7 feet in diameter) required re-cutting, along with their pinions. The gears were part of a stamping machine and were severely damaged, requiring removal of over 3/4-inches of material on the diameter of the large gear. Two cases were possible: the gears could maintain a constant center distance or a constant speed ratio. Both cases were examined, and the data is summarized in the chart on the following page.

In case (A), the center distance could be kept constant (within .015 inches of the original value), however, the speed ratio would decrease about 13.4 percent. The speed reduction was not desirable. Moreover, the rim thickness of the gear was not large, and the use of full-depth teeth would weaken it. Consequently, another alternative was considered:

In case (B), shorter "stub" teeth were proposed, which would not weaken the rim as much. Fortunately, the stamping machine design could permit small alterations in center distance, so the tooth numbers (and speed ratio) could be maintained constant. The teeth were re-cut on both the gears and the pinions, and they were re-installed with the center distance reduced from 47.0 to 46.515 inches.

TABLE 1: DATA FOR EXAMPLE (Dimensions in inches)

	ORIGINAL		*CASE (A)*		*CASE (B)*	
	Gear	Pinion	Gear	Pinion	Gear	Pinion
Number of Teeth	169	19	169	22	169	19
Nominal DP	2	2	2.03125	2.03125	2	2
Pressure angle	20	20	20	20	20	20
Nominal Pitch Dia	84.5	9.5	83.2	10.831	84.5	9.5
Operating Pitch Dia	84.5	9.5	83.2	10.831	83.628	9.402
Addendum	0.5	0.5	0.4923	0.4923	0.411	0.389
Dedendum	0.5785	0.5785	0.5696	0.5696	0.539	0.561
Whole Depth	1.0785	1.0785	1.0619	1.0619	0.95	0.95
Center Distance	47.0		47.015		46.515	
Speed Ratio	8.8947		7.6818		8.8947	
Contact Ratio	1.722		1.741		1.406	
Fatigue Stress (relative)	100 %		107 %		105 %	

The problem of smooth running can be checked by examining the contact ratios for the two cases. In case (A), the contact ratio was actually increased (from 1.722 to 1.741) by re-cutting, since a 22-tooth pinion was needed to maintain the center distance constant! However, in case (B), which was actually followed, the contact ratio dropped to 1.406 because of the use of the shorter "stub" tooth profile. Note that the value of 1.406 is still well in excess of 1.2, which is the usual minimum value.

The stresses on the re-cut teeth increased slightly. The full-depth teeth in case (A) were estimated to have about a 7% increase in stress, whereas the "stub" teeth in case (B) have about a 5% increase. The stress calculations are difficult to perform for non-standard teeth, and require a computer program which calculates non-standard form factors (although good estimates can be obtained by multiplying standard form factors by the ratio of the square of the tooth thicknesses). In this example, the static and surface factors of safety were well in excess of the AGMA requirements, and the 5% increase in stress is believed to have a negligible effect on the life expectancy of the re-cut gears.

Significantly, the cost savings through re-cutting were estimated at about 75 percent of the cost of new gears. Moreover, since the tooth numbers remained the same, the pinions were also re-cut, saving the cost of both pinion blanks.

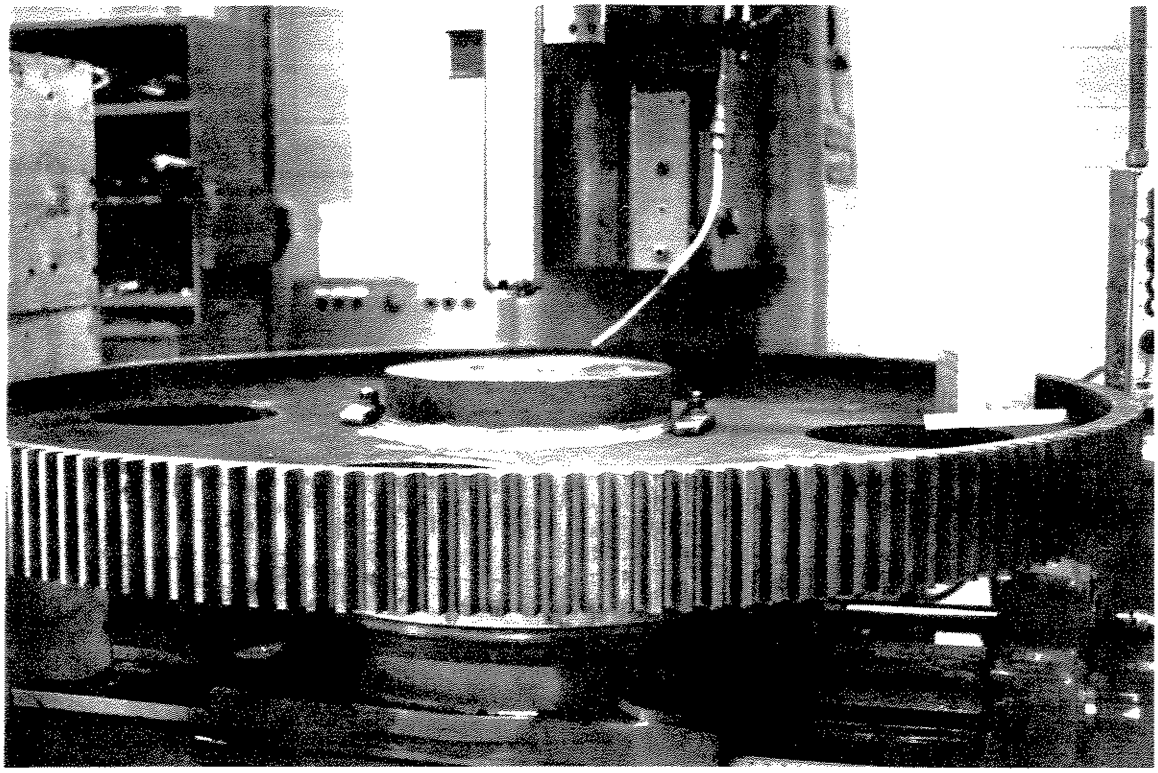


FIGURE 3: Gear Described in Example Being Re-cut

The cross-hatching shows the material removed by re-cutting.

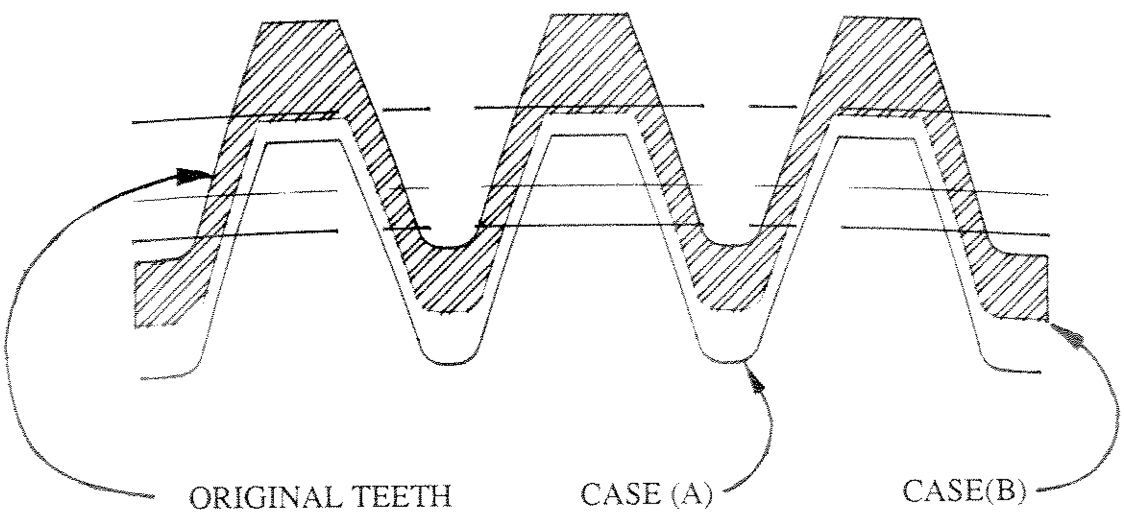


FIGURE 4: Relative Sizes and Shapes of the Gear Teeth in the Example

10. SUMMARY OF GUIDELINES:

In summary, it is possible to save a great deal of time and money when renovating large gear-sets, by re-cutting the large gear (and, if possible, the pinion also). The guidelines for making such a decision are summarized below:

(a) The cause of the damage should be identified, so that it will not cause similar failure of the re-cut gear-set.

(b) The tooth size will be slightly smaller and the stresses will therefore be slightly higher. The factors of safety will usually be adequate for static and surface strength, although the bending fatigue life will probably be reduced. If the fatigue life reduction is not acceptable, the re-cut gear-set can be hardened to increase the fatigue strength.

(c) If it is possible to adjust the center distance between the gears, then both the gear and pinion may be re-cut, resulting in increased savings. This also permits the speed ratio to remain constant.

(d) If the center distance must remain constant, then the large gear may be re-cut, but a new pinion will be required, with more teeth, to satisfy the center distance equation. The new gear-set will have the same center distance, but a different speed ratio.

(e) When both center distance and speed ratio must remain constant, more creative methods are called for. One method is to strip all teeth from the large gear and use it as a hub by shrink-fitting a steel rim or sleeve over the hub. The re-cut gears will be identical to the original gear-set.

11. CONCLUSION:

This paper has reviewed the geometric, kinematic, strength and financial implications of re-cutting, rather than replacing, large, expensive gears which have significant tooth damage. The importance of this method of recycling resources will undoubtedly increase in the years ahead.

ACKNOWLEDGEMENT:

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