The Effect of Material Defects on Gear Performance—A Case Study

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Abstract

The quality of the material used for highly loaded critical gears is of primary importance in the achievement of their full potential. Unfortunately, the role which material defects play is not clearly understood by many gear designers. The mechanism by which failures occur due to material defects is often circuitous and not readily apparent. In general, however, failures associated with material defects show characteristics that point to the source of the underlying problem, the mechanism by which the failure initiated, and the manner in which it progressed to failure of the component.

In this case study, the authors examine the failure of a medium-sized pinion used in a mining application. The mode of failure was rather catastrophic in nature but did not follow any of the typically understood mechanisms such as tooth bending, surface distress, wear, etc. Often, as was the case for the subject pinion, material defects do not manifest themselves in these more typical tooth oriented failure modes, though the initial presentation of the failure often suggests more classical origins.

A complete shaft fracture was the ultimate cause for the pinion's removal from service. Initial inspection of the failed pinion indicated the presence of cracking in the toothed area. This cracking appeared to have progressed through the pinion and resulted in the shaft fracture, which caused the pinion to cease transmitting torque. In order to avoid a recurrence of the problem in this very critical application, it was very important to fully understand the failure including its cause and progression mechanism.

This paper presents a summary of the failure, its investigation, and the methods proposed for its resolutions. The data is presented in tutorial format so that the basic effect of the identified material defects can be better understood and used in future designs.

Fig. 1—Distress observed on ball mill pinion during 1994 visual evaluation.

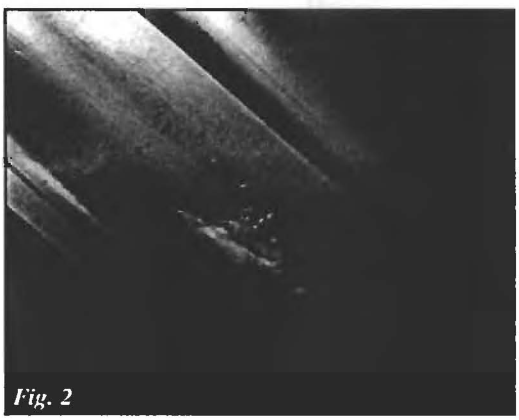

Fig. 2—Close view of distress observed on ball mill pinion during 1994 inspection.

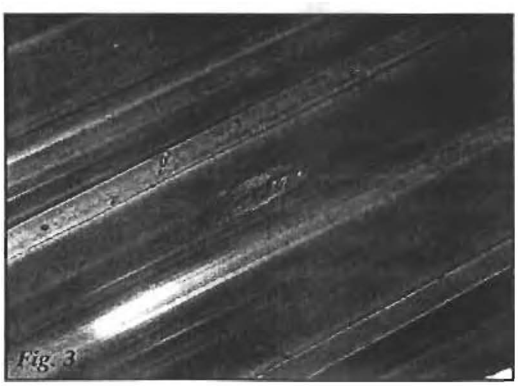

Fig. 3—Currently installed ball mill #2 pinion showing region (near midface) which has been ground out to remove pitting and surface cracks and then restarted.

Introduction

In 1992, two new single helical gear sets were installed as part of a new mill system at a mine site. The pinion and gear sets are used to drive essentially identical ball mills used for processing ore from the mine.

After some relatively minor start-up problems, the gear sets were placed into normal service and performed without significant incident until some pitting was discovered during a visual examination conducted late in 1994. At that time, we noted only very minor surface distress, as Figures 1 and 2 show. The distress was located at about the middle of the face width and had been slightly ground out at the time of my November 1994 visit.

The pinion shown in Figures 1 and 2 was in service until its removal in August 1995 because of severe surface damage. It was reinstalled in mid-1998 and failed catastrophically in 1998, approximately three working years after start-up. The number of cycles accumulated by the pinion at the time of failure was lower than 3×10^8. This, therefore, was certainly not a low cycle failure, but it was only one-third of the total design life.

The failed pinion was replaced and the mill restarted. During a visual inspection conducted in early 1999, the new replacement pinion was found to be exhibiting pitting very similar in both extent and location to the pitting in the original pinion. This pitting was hand dressed out and was found to have not progressed significantly during a visual inspection, which was conducted during April 1999, as Figure 3 shows.

During an inspection in April 1999, we did not observe any cracks on this pinion (we were unable to dye check it). However, the pinion was reported to have some cracks in the pitted region which were discovered during a previous dye check inspection. The cracks were ground out and the pinion was returned to service. At the time of our inspection, it appeared that only minor progression of the pitting was occurring.

The Second Helical Gear Set

As noted above, there are two identical mill gear systems on line at this site. The second mill was running at the time of our visit and we were unable to shut it down for a good look at the teeth. We examined the teeth through the inspection port with the aid of a strobe, which allowed the pinion and gear rotation to be "stopped" artificially. As Figure 4 shows, this pinion exhibited moderate surface distress in the form of pitting.

We could not detect any cracks on the surface of this pinion; however, it would be almost impossible to do so under the conditions of this inspection. The regions of pitting observed were similar in size to those observed on the first (failed) mill pinion, but they were in a somewhat different location along the face width. In the profile direction, the pitting was located near the pitch line on both mill pinions.

Lubricant distribution on both gear sets appeared to be adequate and uniform across the face width. There was no indication of any lubrication-related distress on any of the pinions or gears examined.

The distress is located about 2/3 of the face width from the motor end of the face width. While Figure 4 shows typical distress, it is important to note that not all pinion teeth exhibit this distress. Figure 5 shows another group of pinion teeth on

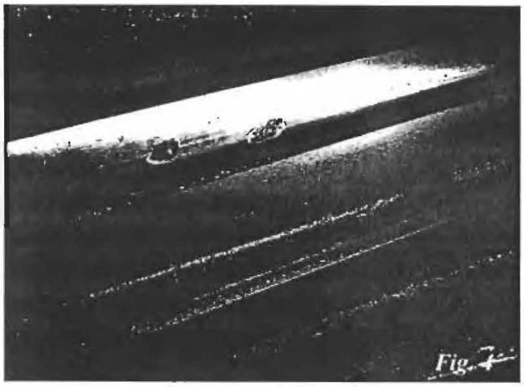

Fig. 4—Pitting distress on second mill pinion teeth.

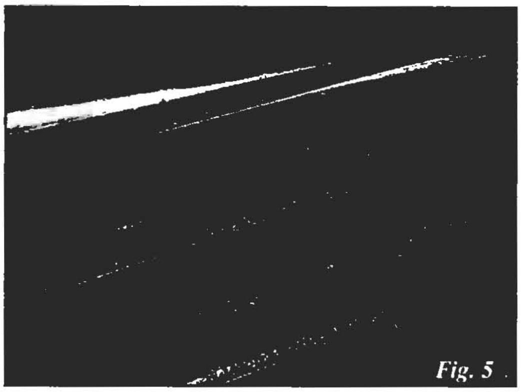

Fig. 5—Ball mill pinion #1 teeth, which exhibit no surface distress.

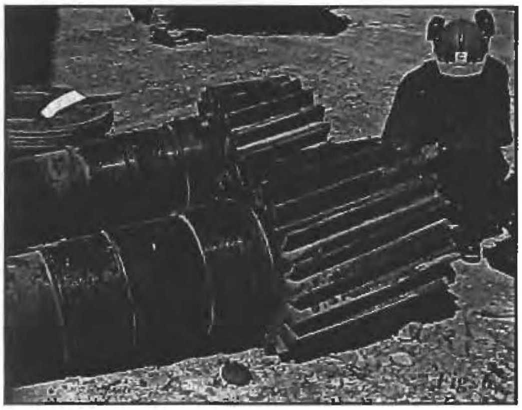

Fig. 6—Failed pinion removed from #2 ball mill in August 1998.

Fig. 7—Pinion fracture face. The light area at the top of the pinion is the crack propagation area. The dark area at the bottom of the pinion is the area that was cut after the failure.

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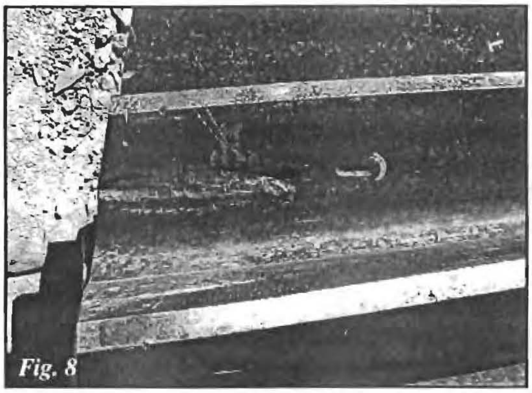
Fig. 8—Pitting observed on fractured pinion. Note the ground out condition of the pitted area and the lack of new progression.

9—Fractured tooth surface, suggestive of a subsurface flaw.

Fig. 10—Cracks progressed from the tooth roots.



the same pinion which exhibit virtually no distress at all.

The Failed Mill Pinion

The pinion, which failed in August 1998, was available for our visual examination; however, as Figure 6 shows, it was quite rusted. Still, our visual evaluation provided valuable clues regarding the cause of the failure.

It was apparent that a crack propagated through the pinion. The crack was on the divided face width at about the 2/3–1/3 point. The crack propagated through about 75% of the shaft thickness (Figure 7) but did not completely sever the pinion.

This failure was discovered during normal maintenance and no problem had previously been noted during operation. At shut down, maintenance personnel found a piece missing from one tooth and noted the crack extending about 75% around the circumference of the pinion.

It was reported that this pinion had been run in both directions and that the contact apparent on the tooth flanks confirms this. It was also reported to me that this pinion had been running in one direction only for "...many years...." The pitting observed was reported to have occurred generally at four locations, positioned about 90 degrees apart. The pitting which I observed on this pinion (Figure 8) was not sufficient, of and by itself, to account for this massive crack propagation failure. Note also that this level of pitting is not very different from that which I observed on this same pinion when I last visually evaluated it during my November 1994 visit (see Figures 6 and 7 above). Close examination of Figure 8 clearly shows that there was no real progression of the pitting distress and that the fracture does not appear to originate in the pitted region.

The surface characteristics of the failure, as shown in Figure 9, suggest the presence of a subsurface defect, which initiated the crack that propagated to failure. Despite the rusted nature of the fracture face, it is still relatively smooth in appearance. It is clear that multiple crack branches have propagated in the region of the fracture. This topography is suggestive of a fatigue crack propagation mechanism. Scanning electron microscopy of this region showed crack growth rates of 10^{-4} mm/cycle, that is, 80 mm in 3 days of operation.

Based on the view of the fracture face shown in Figure 10, it appears that the original failure had multiple origins and that it spread from the tooth root area down into the shaft section.

Current Pinion Condition

The conditions of the pinions and gears currently installed in both mills are very similar to each other. At this time neither pinion exhibits any critical problems; however, the overall condition of the pinions are very similar to the condition of the fractured pinion which failed in 1998. This is, of and by itself, some cause for concern.

The pitting which is apparent on these pinions is somewhat unusual in both its location and its appearance. The fact that the pitting is largely mid-face indicates that it will not be practical to realign the gear sets to favor the undamaged tooth surfaces. The appearance of the pitting suggests an over crowned condition on either the pinions or their mating gears or, perhaps, both. I have no indication of the actual geometry of these pinion and gear sets (i.e., lead and profile inspection charts or other similar measurements) which might identify the specific cause. Considering the experience of the failed pinion, however, and the similarity of the appearance of the pitting on all three pinions, it is quite possible that the two currently installed pinions also exhibit some of the material anomalies which affected the failed pinion and, as described below, ultimately led to its fracture.

If this pitting is the result of material anomalies as was the fractured mill pinion described below, dressing the pitted area will lower the stress level in the region where the inclusions appear to be prevalent, thus reducing the possibility that they will cause a crack initiation and progression mechanism similar to that which led to the failure.

Failed Pinion Shaft Analysis

The fracture failure of this pinion shaft is an extreme example of the highly deleterious effects of material anomalies on the load capacity, reliability and life expectancy of large gears. The specific mode of failure experienced was via initiation of cracks near the top of one tooth with propagation occurring across approximately 75% to 85% of the shaft cross section, as Figures 11 and 12 clearly indicate. The cross hatched areas in these figures show the region which was cut to expose the fracture faces while the unhatched regions show the region over which the cracks progressed. Note especially the origin of the failure in the tooth top at the top of both figures and the extensive, branched crack network below the origin.

Despite this extensive propagation, no indication of the failure of the shaft was observed during normal operation of the mill. The fracture was only noted during a maintenance check. This crack propagation took place in less than three months of operation.

The condition of the tooth flanks and location of the fracture (almost mid-face) also indicated that the problem was not related to alignment. Further, the nature of the crack initiation and early progression indicates that the failure was not due to an overload condition, either one time or repeated. These factors point to problems with the material or manufacture of the pinion.

Based on the appearance of the fracture surface, a material anomaly is the primary suspect. In order to investigate this possibility, a detailed metallurgical evaluation was required.

The relatively good condition of the teeth over most of the face width combined with the large piece which was fractured away from one tooth near the middle of the face from just below the pitch diameter of the tooth tip very strongly suggests a localized anomaly. Pitting failures due to overloading or overall material insufficiency (e.g., low hardness, etc.) will manifest themselves relatively uniformly on all or most teeth while pitting failures due to misalignment-induced overloading will occur in a localized region of the face width, biased to the more highly loaded end but also uniformly dispersed on most or all teeth. The surface failures observed on this pinion were highly localized, as Figure 13 shows.

The pinion was cut through the remaining shaft section to render the fracture faces visible. Figures 14 and 15 show the fracture faces after shaft sectioning. In Figure 14, the darker region in the upper right of the photograph is the section that was cut through to reveal the fracture face, which

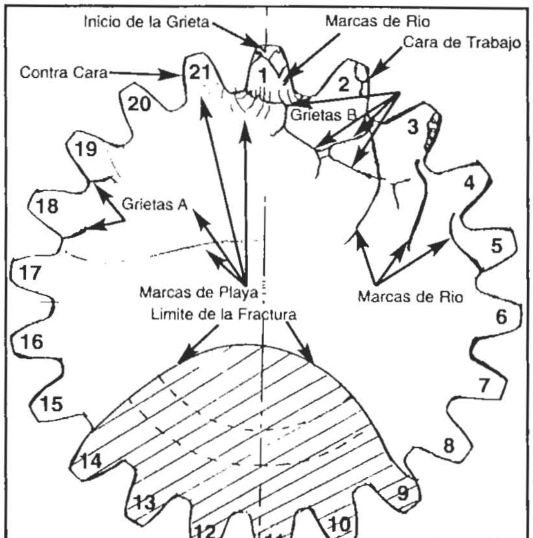


Fig. 11

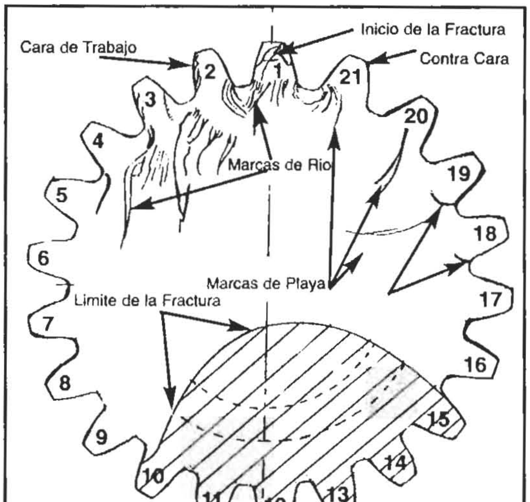


Fig. 12

Fig. 13

Fig. 11—Pinion fracture face. Mating surface shown in Figure 12.

Fig. 12—Pinion fracture face. Mating surface shown in Figure 11.

Fig. 13—Fractured pinion after removal. Note the large piece fractured from one tooth.

Fig. 14—Pinion fracture face corresponding to Figure 12.

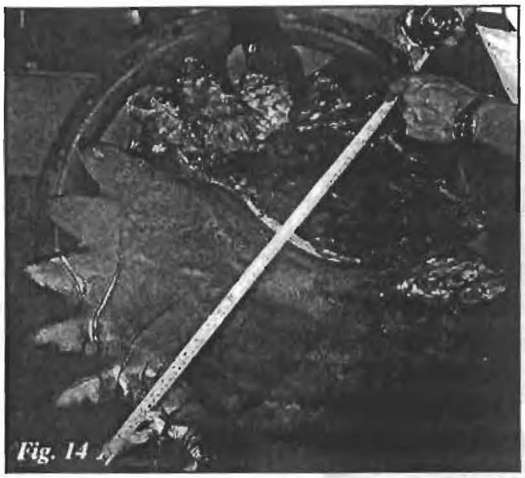


Fig. 15—Pinion fracture face corresponding to Figure 11.

Fig. 16—Inclusions that were found in the fracture origin region.

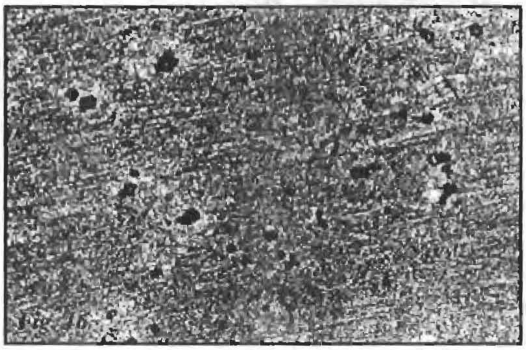
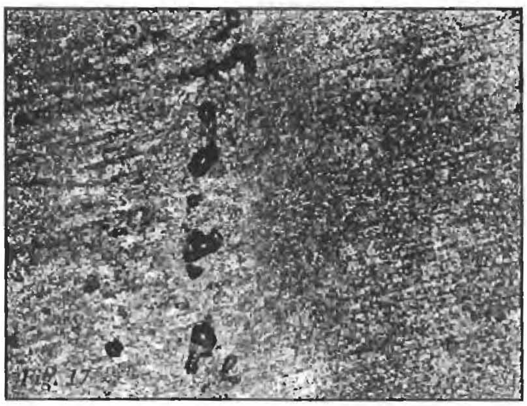


Fig. 17—Inclusions clustered in a longitudinal pattern.



is the smoother surface at the lower left of this photograph. It is clear from these figures that the origin of the crack network is in the tooth region identified by the arrows shown in Figure 15.

Metallurgical Evaluation

In order to better understand the nature of the fracture, metallurgical samples were obtained from the origin region and subjected to detailed analysis. Based on this evaluation, the specific mechanism of crack initiation became quite clear.

Once polished and etched, these sections revealed the presence of large concentrations of inclusions, as Figure 16 shows. These inclusions were widely distributed in the region where the cracks originated. Such inclusions are, of course, impurities in the basic steel forging. The effect of inclusions on the capacity of the gear depends very much on their location.

Inclusions act as stress concentration factors which effectively increase the nominal, load induced stress level. Depending on their location on the tooth and the stress field which exists at that point, such inclusions may prove harmless or they may cause substantial localized stress concentrations, which can result in crack initiation. The length of time required for crack initiation and progression depends on many factors including the magnitude of the basic applied stresses. If the basic applied stresses are very high and concentrated in a single region, such as tooth root bending stresses, the crack may initiate and propagate quickly. Conversely, if the basic applied stresses are more diffuse, such as they are in the contact region, cracks may not initiate for a very long time and, once initiated, may also have long propagation times. The latter appears to be the case here.

Inclusions were found throughout the origin region, but the ones which most directly influenced this failure are those which were found close to the surface of the tooth. If the inclusions are well below the tooth surface and widely dispersed, their effect may be small. When close to the surface or in the tooth fillet region, however, they can be quite significant. Concentrations of inclusions can also pose a very great problem for carburized pinions when they are heat treated. This pinion was through hardened, thus this aspect was not observed.

Of even greater significance is the situation which occurs when inclusions occur in clusters, as Figure 17 shows. These clustered inclusions form a very large stress concentration and can adversely affect both the surface load capacity and bending fatigue strength of the teeth. When clustered, the negative effect of an inclusion is magnified many times over.

It was a group of inclusions, such as the ones shown in Figure 17, which caused the failure of this pinion. Specifically, the clustered inclusions were located below the surface but within the high stress region. As Figure 18 shows, the fracture passed through the pitted region. The pitted