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Causal Analysis of the Pinion Teeth Failure in a Limestone Reclaimer

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Abstract. This paper presents a causal analysis of an unexpected failure of the pinion teeth of a large reducer installed in a limestone reclaimer which is part of a raw material transportation system of a cement factory. The Montano methodology is applied. It includes a collection of documentation, evidences, evaluation of failure mechanism by visual inspection and some hypothesis and their validation based on the analysis of the material resistance. It is demonstrated that although the teeth of the pinion were made of a suitable material and cemented correctly, they worked overloaded due to the presence of large rocks in the raw material. A resulting increase of contact tensions in the teeth over the allowed limits led to a fatigue failure process which is described in this work. The results of the analysis can be of great interest in order to develop preventive measures and avoid future undesired plant stoppages and economic losses.

1. Introduction

Mechanical elements are designed and manufactured for a specific purpose taking into account the loads, mode of loads application, planned operational conditions and environmental factors in order to guarantee a long useful life. However, mechanical failures during service are relatively frequent. When a failure occurs, a thorough analysis is necessary to establish its causes and then avoid its repetition [1].

Gears are the most widely used mechanical transmissions in the industry and to the study of their failures have been dedicated numerous research which had classified and characterized the failures according to its characteristics and causes in order to facilitate their study [2][3], also a methodology to gear failures study have been stablished [4] although each gear failure case have own particularities and need specifically analysis [5].

In the cement industry, gearboxes drives are massively used to drive most material handling and transportation equipment, working in hard conditions usually 24 hours by 7 days, inside a high powder content environment and usually with significant dynamics loads [6].

The significant economic losses as a result of mechanical failures in the cement industry are highlighted by Mayer [7], also Yanusa et al. [8] point the importance of analyzing each one in order to solve it correctly avoiding its repetition.

This paper is focused on the analysis of a gears critical failure in the gearbox drive of limestone rocks reclaimer in a Colombian cement factory, identifying the kind of failure, its causes and solutions to avoid repetition.

2. Limestone reclaimer

The limestone reclaimer has two main functions: drag the raw material from the pile where it is stored to the push system by using the rake arms showed in figure 1. The second function is to push continuously the material to a conveyor by means of an endless rolling mechanism with steel tablets as seen in figure. 2. Finally, the limestone is transported by a conveyor to the crude mill.

Figure 1. Drag system in the limestone reclaimer

Figure 2 shows the steel tablets that push the limestone through a bottom path of the pusher. These tablets return from the upper part doing a cycling process. A chain-driven mechanism connected with a gear reducer is used for the mechanical power transmission. This work is motivated by an unexpected failure of the pinion teeth of this reducer.

Figure 2. Push device in the limestone reclaimer.

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3. Failure Analysis

The methodology used in this work is based on the applied by Montano [9] and proposed by Errichelo [4]. The steps are shown next

1. Collection of documentary evidence.
2. Analysis of service conditions.
3. Visual inspection and evaluation of the failure mechanism
4. Preliminary hypothesis.
5. Material evaluation
6. Mechanical resistance assessment.

3.1 Collection of documentary evidence.

At this stage, data about gearbox X4FH210/T model was collected. Although in the cement factory there are other seven similar reducers operating different equipment, there are no records about failures or incidents in their use. The gearbox has two steps, the failure occurred in the output gear. The nominals data of gearbox are shown in table 1.

Table 1. Drag arm´s gearbox operational data

Nominal motor power	93 kW
Motor speed	1750 rpm
Output speed of gearbox	15,53 rpm
Input speed to the output gear pair	372,7 rpm
Total transmission ratio	112,6
Nominal gearbox power	80 kW

Since there is no available data about the dimensions of the gears, a methodology to geometric decryption of damaged cylindrical gears [10] in order to get the geometrical parameters of the faulted gear pair was used. The results are shown in Table 2.

Table 2. Geometric parameters of damaged gear pair.

Number of teeth of the pinion	19
Number of teeth of the crown	63
Transmission ratio	3,31
Module	9,5 mm
Distance between centres	400 mm
Helix angle	13,15 o

3.2 Analysis of service conditions.

The service regime of the push mechanism is very hard because of frequently big rocks in the limestone as can be seen in figure 3 (a) provoking dynamics loads which deform tablets and structure of the rake arm as are shown in figure 3 (b) and (c). Also the chain wear increases the dynamic loads.

(a) (b) (c)

Figure 3. Operational conditions of push device

3.3 Visual inspection and evaluation of the failure mechanism

In visual inspection, the damaged gears were carefully examined in order to identify the failure mechanism. Large stones are observed in the raw material and plastic deformation in the steel structure and tablets

In figure 4 some pictures of the failure in the pinion are shown, the failure of the gears pair is mainly in the pinion. In figure 4 (a) the circle marked teeth surfaces show pitting and micro-pitting failure mode with scales removed, on teeth surfaces mark by box, which are on the teeth back, some fragile fractures are observed through the surface. In figure 4 (b) the highly destructive character of the failure is shown and two teeth fully removed from the pinion are shown, evidenced the effects of the high overload level produced by the progressive spoilage the teeth profile and also by the external dynamic load action. The tooth before the completely removed teeth has a large significant loss of material. Figure 4 (c) show a best picture of the mass loss in the work tooth flanks are shown. No significant evidence of wear or plastic deformation was found on any affected teeth.

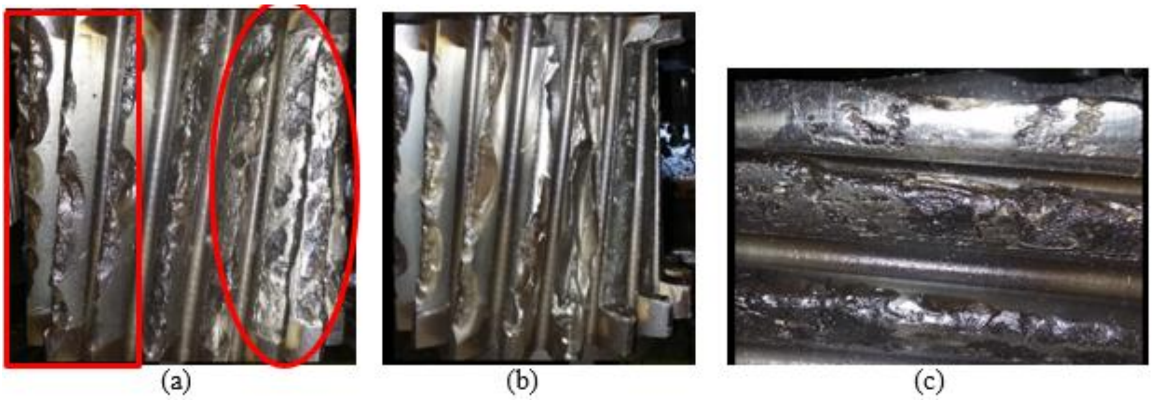


Figure 4. Visual inspection of the pinion teeth.

The fractographic study was carried out on both sides of the tooth as are shown in figure 5 (a). The behaviour is typical of this kind of failure with micropitting at the beginning and progressive pitting and lost large part of the surface with the consequent increase of surfacing stress and removing scales from the surface until its destruction. In figure 5 (b) a fractographic study of the tooth back surface is shown, the high level of destruction of work surface and the dynamics loads cause the extension of fragile fracture to this surface destructing.

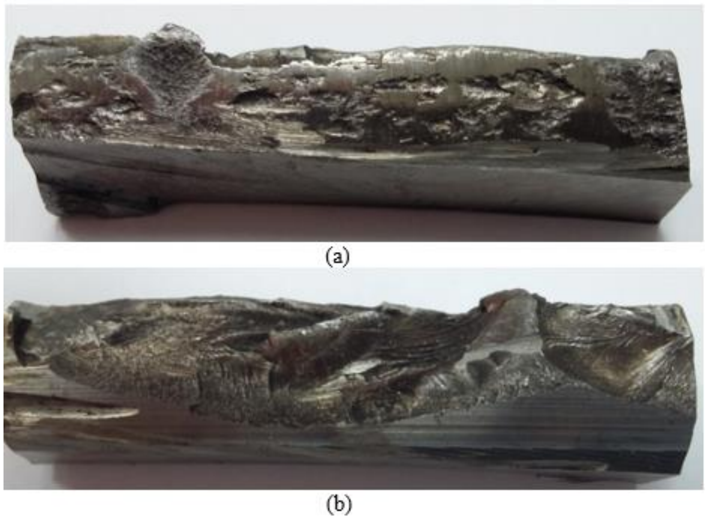


Figure 5. Macrographic study (25 X) on the tooth surface, (a) work surface y (b) back surface

Surface fatigue in the closed gears is not easily detected and have a trend to worse because of the growth of contact stresses and the presence of metal´s fragments detached from teeth surfaced which introduce additional loads which contribute to fracture by the base of other teeth. When a tooth is broken by a sudden shock or an overload, the fracture usually has a fibrous appearance, even when the tooth is fully hardened, the fracture will look like the fibers of a plastic material that has been twisted [4]. When consecutive teeth are broken, it usually happens that one or two are broken by fatigue; As the gear continues to rotate under torque, the hit of the wheel that meshes when jumping into the gap left by the fatigued tooth will break other additional teeth. Looking at several fractured teeth, one can define which one failed due to fatigue (it will present a smooth appearance) and which failed later due to overload (fibrous appearance). This phenomenon is manifested in figure 6 where a detail of removed teeth are shown, in which the tooth-marked No 1 was fractured by fatigue and those on the right of this failed due to overload, in the absence of tooth No 1.

Figure 6. Removed teeth

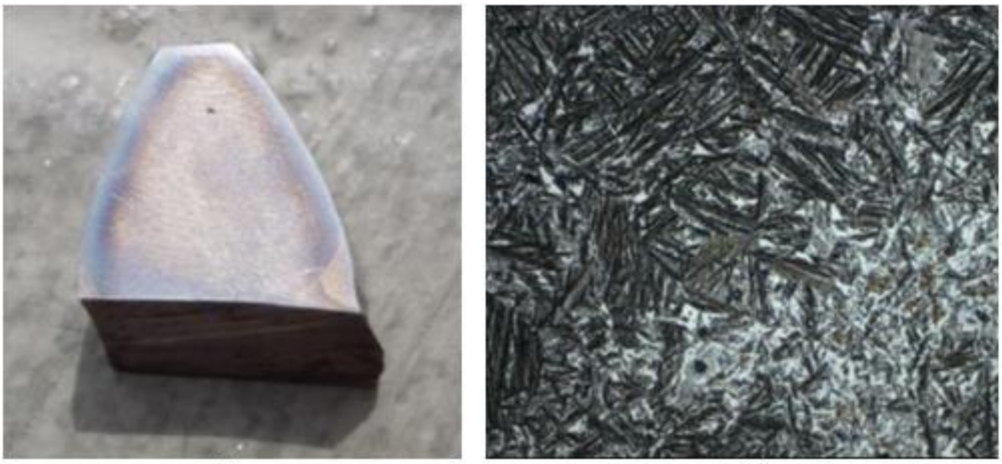
3.4 Preliminary hypothesis.
There are six generic causes for gear failure: wrong design, inadequate material selection, faulty thermal treatment, defective manufacture, faulty assembly, operation and poor maintenance [9]. Since the gearbox is a successful commercial product and there are in the factory several of the same kind without technical problems the hypothesis associated with design, manufacturing or materials are refuse. The preliminary hypothesis is that the dynamics load and overloads provoked by operational conditions with the usual presence of oversized stones y in limestone pile and the push chain wear are the main cause of the gear failure and if these conditions are corrected the gearbox could work reliability.

3.5 Material evaluation
Since the material and thermal treatment of the gears were not known several tests were carried out in order to identify the material and its characteristics. The results of the chemical analysis indicate that the steel is slightly alloyed to the chromium - nickel, with very low percentage of carbon and without the presence of grain refiners. Steel corresponds to an 18NiCrMo 7 steel, by German and European standard. In table 3 the results of chemical analysis are shown.

Table 3. Chemical analysis

Element	C	Si	Mn	P	S	Cr	Mo
%p/p	0.159	0.313	0.609	0.023	0.025	1.560	0.264
Element	Ni	Cu	Al	As	B	Co	Nb
%p/p	1.513	0.211	0.019	0.013	0.00055	0.017	0.0051
Element	Pb	Sb	Sn	Ta	Ti	V	W
%p/p	0.0002	0.0033	0.017	0.005	0.0025	0.0071	0.001
Element	Zr	Ca	-	-	-	-	-
%p/p	0.0005	0.003	-	-	-	-	-

In figure 7 (a), a specimen from a pinion tooth taken from lateral side which not contact con crown tooth is shown, used for macrographic analysis, hardness measurement and micrographic analysis. The macrographic analysis of polished area evidenced two zones, one peripheral, around 1,3 to 1,6 mm, where the surface is darker as a result of the chemical attack with Nital at 3 % and other inside the tooth clearest. The structure is typical of cemented steel which is corresponding with hardness measures the 60 HRC in surface and 45 HRC below the cemented layer. Additionally, the micrograph of the surface layer in figure 7 (b) shows martensite with low tempering, typical of the cemented and tempered. It should be noted that the steel is of very good quality due to the degree of cleaning, there is a low level of non-metallic inclusions, in the form of oxides.



(a) (b)

Figure. 7. Tooth section (a) macro structural analysis and (b) microstructure showing martensite

The results let concluded that that the Pinion was cemented, with posterior tempering, with a core (inside the tooth), for its chromium and nickel levels the inside of the tooth hardens enough (45 HRC), limited by the Low carbon inside (0.16 % C), giving rise to a tempered martensitic of medium hardness. In contrast, the surface has high hardness (60 HRC) due to the martensitic rich in carbon and chromium. In addition, small grain size is evident, which is desirable.

3.6 Mechanical resistance assessment

In order to verify the results of the visual inspections, which evidenced the occurrence of destructive pitting destructing the surface and the profile of the tooth increasing the dynamic loads until the full fracture of the teeth in its base is also appreciated; a verification of the surface resistance and breakage by bending of the teeth for different levels of dynamic loading is carried out using the software KISSOFT (http://www.kisssoft.ch/castellano/home/index.php) applying the calculation methodology established by ISO 6336: 2006 [11]

The input data for the calculation are taken from tables 1 and 2 and material analysis. In order to take into account dynamics loads, the recommended values for the load application coefficient of ISO 6336:2006 [11] shown in Table 4 are used.

Table 4. Regimen of work machine driven

	Steady	Light shock	Medium shock	Heavy shock	Very shock	heavy
Steady	1	1.25	1.5	1.5		2
Light shock	1.1	1.35	1.6	2.5		3.5
Medium shock	1.25	1.5	1.8	2.8		4
Heavy shock	1.5	1.75	2.5	3.5		4.5
Very heavy shock	2	2.5	3.7	4		5

As the operating regime of the chain and the push plates driven by the reducer is heavy collisions, the verification calculation consisted in calculating the contact and bending stresses at the foot of the tooth and the admissible tensions for values of the Load application coefficient between 1.5 and 5.5. The results are shown in figure 8.

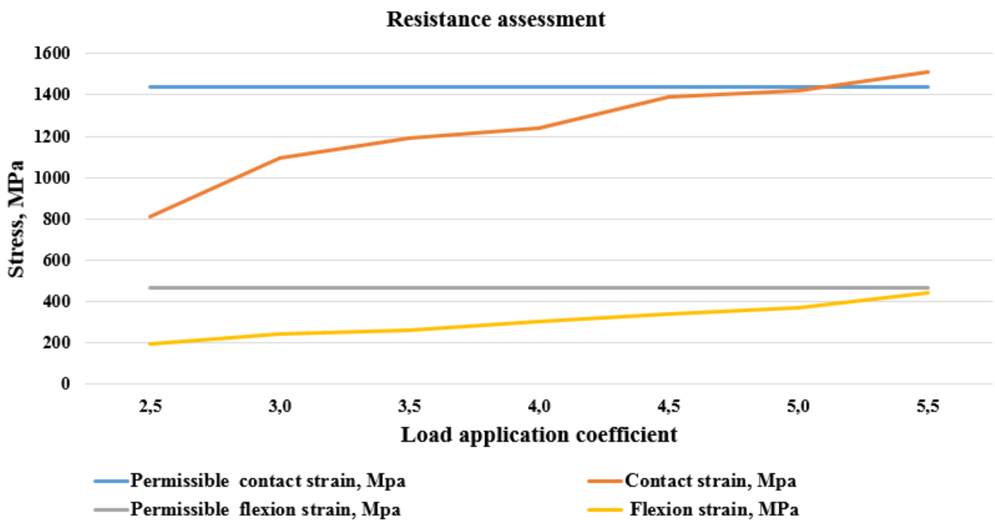


Figure 8. Mechanical resistance assessment results

In figure 8 can be seen that values of the load application coefficient below 3, the safety coefficient to the pitting is greater than 1.5; nevertheless, with values close to 5 the superficial stress exceeds the admissible stress of the material and the useful life of the gears must be shortened significantly. The bending stresses at these coefficient levels are remarkably close to the allowable stresses even without taking into account the effects of the destructive pitting on the profile of the teeth.

From the analysis, is possible concluded that the pair of gears is well designed and can have a useful life of the order of 20 000 hours considered in the verification calculations, the cause of the failure is the conditions of severe dynamic loads to which is subjected to the operating conditions of the mechanism that triggers.

4. Conclusions

The pinion steel of the gears is well selected and corresponds to the group of the best steels for cementing, slightly alloyed chromium, nickel and molybdenum, type 17CrNiMo-7 by European standard. The mechanical properties and the microstructures indicate that it was correctly treated with cementation, more tempering and tempering, presenting very few impurities in the form of oxides.

The gearbox is well designed for normal working conditions according to the resistance calculations. The verification of the contact and bending stresses in the tooth and the admissible stresses for values of the Coefficient of Application of the Load of between 1.5 and 5.5 show that up to values of the Coefficient of Application of the Load of 3, the safety coefficient at the pit is greater than 1.5; nevertheless, already with values close to 5 the acting superficial stress exceeds the admissible stress of the material and the useful life of the gears must be shortened significantly.

The more probable cause of failure in the pinion is the overloads and high contact stresses, which increase significantly with the degree of deterioration. The failure begins with superficial fatigue, progressive pitting and scaled; then the volumetric fatigue fracture is caused in the base of one or two teeth and the lack of these, the inertia and the torque of the motor cause the fracture by the base of several contiguous by overload and impact.

It is concluded that the working conditions of the reducer are extremely severe, with shocks and strong dynamic loads resulting from the oversized stones in the limestone pile and push chain wear.

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