STUDY AND ANALYSIS OF FRACTURES IN GEARS FROM AUTOMOTIVE TRANSMISSIONS

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Abstract

Premature wear and fractures in automotive transmissions represent considerable negative costs for automakers, as they cause the vehicle to be disabled and its repair is usually costly and time consuming. Thus, understanding the source of these defects could permit us to more reliably propose alternatives, making this a valuable area of research. In this study, distinct defects in the helical gears of manual transmissions were selected and mechanical analysis was carried out focusing on the root cause of the failures. The study included hardness tests, liquid penetrate inspection (LPI) and visual inspection. In the Rockwell hardness test, values were obtained for the steel pieces which had been thermally treated by carbonitriding. In the liquid penetrate inspection, cracks were found present inside the teeth of the evaluated gears. The results obtained are consistent with the literature. It is noteworthy that the gears analyzed already had explicit defects, which prevented their reuse. We conclude that the failures in automotive transmission gears are related to various factors, usually related to torques above the design limit or lack of lubrication and maintenance, which implies premature failures and consequently a shorter than expected service life.

Keywords: Fractures, Automotive Transmissions, Gears, Hardness.

1. Introduction

According to the studies of Junior (2018), the automotive transmission system is the component responsible for transmitting force, rotation and torque from the engine to the wheels, this process is only possible through several components that together perform a mechanical transmission process.

According to the studies of Dias (2011), if the automotive transmission system were not used, the vehicle would be limited in terms of speed and strength. It is usually a system composed of the same elements that obey the physical principles that react in the vehicle dynamics. This system is divided into three categories, mechanical transmission, automated transmission and automatic transmission.

Such transmissions are made up of components, such as a clutch, gearbox, articulated axle, differential, semi-tree, clutch disc and plateau, and in particular the automotive transmission gears, which are used in some of the components described above, are the object of study and analysis in this article.

The automotive industry is among the largest users of gears, thus constantly creating and developing new specific tooth shapes, always wishing for the best geometry so that the gears are quiet and have good mechanical resistance. However, in order to guarantee the silent operation, it is necessary to build boxes and shafts with the maximum possible rigidity so that the areas of contact with the teeth are not affected by variations in transmitted power. Usually helical gears are used, since their tooth shape allows partial face engagement, unlike other types of gears that have full face engagement, this partiality leads to a quieter energy transfer. They are also able to handle larger loads; this is due to the size of the teeth that are effectively larger due to their diagonal positioning. Consequently, they are the most suitable for mechanical systems with high power and speed.

As for example, the differential gear, where the torques are not constant, and the teeth are not homogeneously requested, but with significant overloads during abrupt starts, which can lead to an elastic stress on the foot of the tooth of 1000 MPa and Hertz pressure up to 3,000 MPa. The ideal is to limit the Hertz pressure to 2,000 MPa and the tension at the foot of the tooth to 600 MPa.

According to the studies of Cunha et al., (2020) and Cunha & Santos (2020), in the industrial revolutions, as they are called, do not happen very often. Since the beginning of mankind, there have been four industrial revolutions. The other three were identified only after they had occurred, while the fourth is still underway. It is essential for everyone who works in any line of activity to know about this process and to prepare for the future that has already started.

2. Literature Review

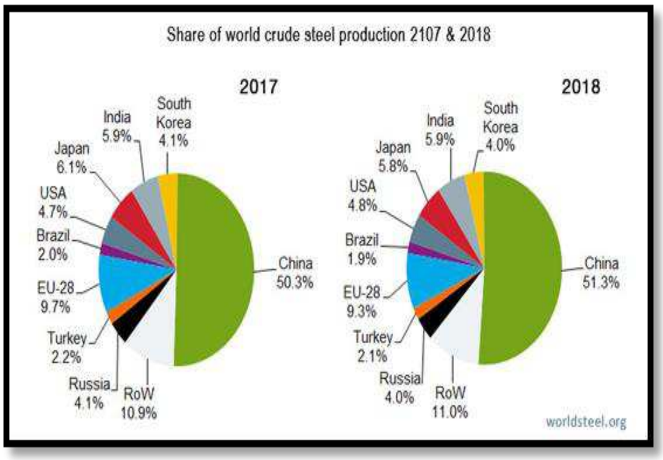
It is estimated that iron was discovered in 1200 BC, which is considered the last technological and cultural stage of prehistory. Its discovery generated, and has been generating, great changes and revolutions throughout society.

The uses of metals have always been constant in the man's life, since prehistory. The first records were the use of bronze and copper in the production combat tools and hunting tools, needing resistant utensils in combat and production of rigid instruments for everyday use of the time. After the iron age around 1200 BC, many studies were carried out until the discovery of steel after the application of carbon in iron, it was noted that the material resulting from this binary alloy, had characteristics mechanics other than conventional iron. And they could be applied in different segments of that time (SANTOS et al., 2020).

Over time, new techniques and methods were developed which improved the characteristics of the iron and consequently amplified the number of applications, such as: making the iron harder and more resistant, working with the already cast iron, making it possible to obtain iron in a liquid state, etc. However, the most important milestone did not occur until 1856, when a way of producing steel was discovered.

In Brazil according to Bradesco (2017), currently 96% of steel production is located in the Southeast Region, with 14.3% of the production located in the state of Espírito Santo. Figure 1 and table 1, show steel production in the world and how Brazil fits into this scenario.

Figure 1 - Steel Production in the World between 2017 and 2018.



Source: Worldsteel Association (2018).

Table 1 – Largest Steel Producing Countries

Rank	Country	2018 (Mt)	2017 (Mt)	%2018/2017
1	China	928,3	870,9	6,6
2	India	106,5	101,5	4,9
3	Japan	104,3	104,7	-0,3
4	United States	86,7	81,6	6,2

5	South Korea	72,5	71,0	2,0
6	Russia	71,7	71,5	0,3
7	Germany	42,4	43,3	-2,0
8	Turkey	37,3	37,5	-0,6
9	Brazil	34,7	34,4	1,1
10	Iran	25,0	21,2	17,7

Source: Adapted of Worldsteel Association (2018)

Steel is found in several areas, such as: transport, structures, houses, buildings, agricultural tools, technological equipment, pipes, and machinery in general. With such a wide range of use, it becomes impossible to visualize a world without steel, since we are so dependent on this material which has made many technological developments possible over the years (CUNHA, 2017).

Steel alloys are basically Iron-carbon alloys containing up to 2.11% carbon, in addition to certain residual elements of the manufacturing processes. It is certainly the material most abundantly used in the manufacture of consumer goods and capital goods; in industries, in the manufacture of machinery and equipment, in motor vehicles, in civil construction. Particularly in automotive transmissions, the object of study and analysis of this paper, which are components of paramount importance for the proper dynamics of vehicles.

The steel alloys used in the gears of automotive transmissions, exchange and differential, are of low or medium carbon (0.14% to 0.23%). To guarantee the toughness, good mechanical resistance and superficial hardening on the face of the teeth the steal is treated with carbonitriding and tempered in an oil or salt bath.

The industries determine the choice of steel alloy according to the characteristics desired and suitable for the intended application, but mostly of similar composition, with some of the most commonly used being AFNOR low alloy 27 CD4, 27 MC5 and 16 NCD, DIN 16MnCrS5, 20MnCr5 and SAE 5120, among others.

3. Methodology

Gear systems are designed around the maximum and average torque, however there may be times when the applied torque exceeds the maximum torque foreseen, causing overloads that may lead to failures during its life cycle.

Failures and fractures in power transmission systems can occur due to flexion fatigue, contact fatigue or “pitting”, spalling, scoring, tooth wear, gear failure, among other less frequent reasons. The main causes of gear failures or fractures under normal conditions of use are flexion fatigue and contact fatigue or “pitting”, with disagreement among authors as to which is the most frequent.

According to Alban (1988), apud Castro (2005), points out the most frequent failure as flexion fatigue in the foot of the tooth, whereas Dudley says that research indicates that contact fatigue or “pitting” is largely responsible for fractures in automotive and industrial gears.

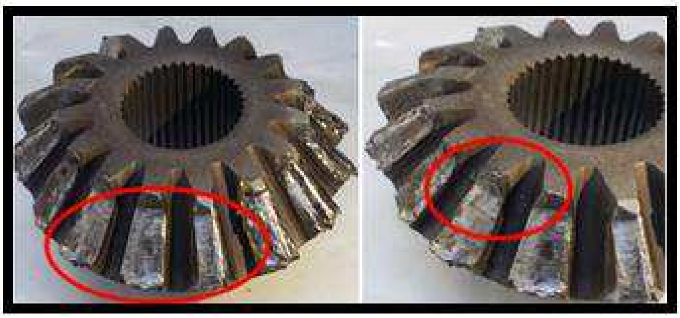
3.1 Bending Fatigue

The fracture of a gear tooth due to flexion fatigue has a surface as shown in figure 2, and some specific characteristics such as:

- Origin of crack in the tooth’s root is on the side where the loading occurs;
- The crack appears first in the middle of the tooth’s loading face;
- The material does not have any metallurgical flaws present, being in accordance with the specifications.

Breaks occur due to the growth of these cracks, being more frequent when the focal point, where the crack originates, coincides with a stress concentrator of edge that is present in the rounding radius of the tooth’s root. After a rupture due to flexion fatigue, there is another rupture due to an overload in the teeth next to the broken tooth, this happens because, even with one or two broken teeth, the gear remains in operation increasing the shock between the teeth. As we can see in the figure 2 below.

Figure 2 - Gear teeth Breakage Because to Flexing Fatigue.



Source: Authors (2020)

3.2 Contact Fatigue or “Pitting”

The breakage due to contact fatigue is related to the criterion adopted to define production and quality standards. This type of failure occurs after a number of cycles, and is characterized by abrasions on the surface of the teeth classified as: macro-pitting, micro-pitting or destructive pitting, as shown in figure 3.

Figure 3 - Destructive Micro-Pitting.

Source: Authors (2020)

Contact fatigue occurs more frequently in pinions, which, because they are motor gears, are subject to greater numbers of cycles, so fatigue occurs before the crown. On the other hand, pinions with low or medium hardening can minimize the problem of “pitting” due to the wear and tear caused by the sliding of the pinion teeth in contact with the crown teeth. In figure 4, you can see a pinion showing wear and the crown showing “micro-pitting” (CASTRO, 2005). Lack of lubrication is also a cause of contact fatigue.

Figure 4 - Gears Crown and Pinion.

Source: Authors (2020)

3.3 Spalling

Spalling is a failure caused by the spread of pitting, and is characterized by a crack formed on the surface and then propagated by the gear tooth, which can occur on the top of the surface and not only in the region of the primitive line.

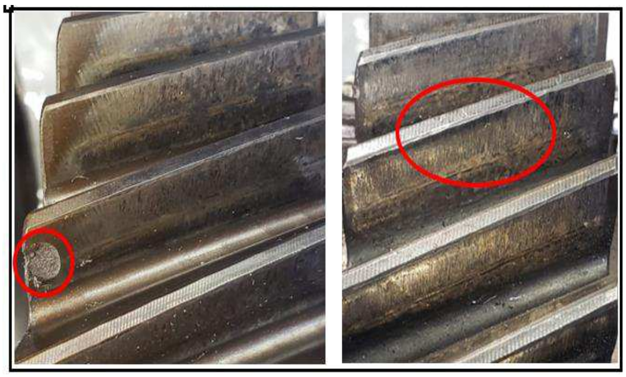
3.4 Scoring

This failure, unlike fatigue, can occur with low loading cycles, often associated with lubrication problems, such as: absence of oil film on the tooth surface, low viscosity, etc.

Scoring is characterized by scratches and scrapes, and the greatest occurrence is in contact between the top of the crown and the nose of the pinion, the lower region of the pinion, the upper region of the crown and counting the top of the pinion with the crown root.

It occurs mainly in gears that operate at high speeds like automotive ones, and is influenced by the materials used and their tempera. Affinity materials can fuse in contact teeth and pinions with surface hardness higher than crowns increase the resistance to this type of failure in the figure 5 illustrates an initial scoring.

Figure 5 - “Scoring” Destructive Initial.



Source: Authors (2020)

3.5. Tooth Wear

Wear occurs mainly on low speed gears, in which the lubricating oil does not form the film on the tooth surface with sufficient thickness to reduce friction. It can also occur on gears that work at high speeds, where although the lubrication is good, the temperature can be high by shearing the oil and causing "scoring" and wear.

The weakening of the material due to wear, reduces the resistance to fatigue of bending the teeth of the gears in the figure 6 shows the wear on the teeth of a gear.

Figure 6 - Gear tooth wear.

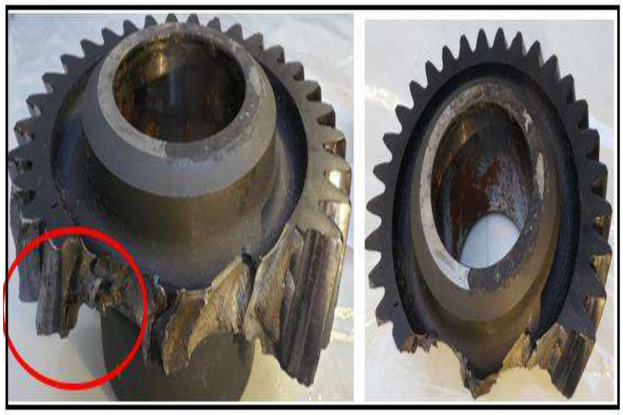
Source: Authors (2020)

3.6 Impact Gear Failures

The fractures in the teeth of the gears usually occur from the rounding radius at the root of the tooth where it is most fragile, also due to contact fatigue from the primitive line and in the middle of the root between 2 teeth, these fractures being due to failures in the process of heat treatment causing high residual stresses and hardening, weakening the region.

Impact failures occur without the parts showing high cycling, being caused by overloads, for which the teeth were not designed or because the material showed some fragility in the figure 7 shows the characterization of an impact fracture.

Figure 7 - Impact Break at the Tooth Root.



Source: Authors (2020)

4. Results

In this stage of the work, penetrating liquid inspection and hardness tests were carried out to check if there were flaws that were not as apparent as those previously presented and also for the evaluation of the cementation layer of these gears after being used.

4.1 Tooth Wear Testing of Penetrating Liquids Inspecion

The test with penetrating liquids inspecion is indicated for parts in which they undergo traction, compression, flexion and cyclical stresses, as is the case of automotive transmission gears. This method consists of the application of a penetrating liquid inspecion, which can be visible or flourished, and a developer, the purpose of the test is to detect very small surface discontinuities, such as: cracks, pores, folds, among others. Two cracks in the helical gear can be seen in figure 8.

Figure 8 - Test of Penetrate Liquid Inspecion (LPI).

Source: Authors (2020)

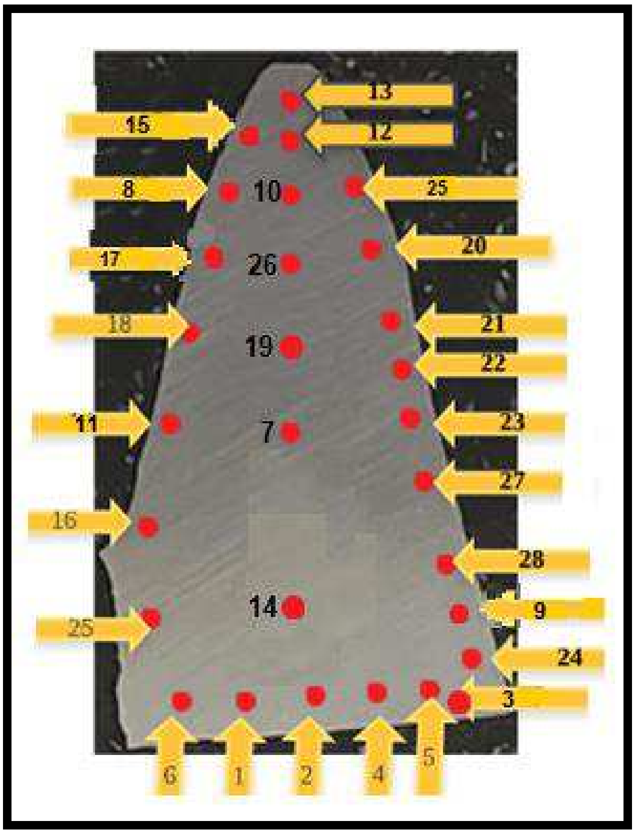
4.2 Hardness Test

Hardness can be measured by the penetration of a material into another material in standard tests, and is a measure of the resistance offered by the material to plastic or permanent deformation. It can be used to determine uniformity of metal samples or the results of heat treatments. It is a mechanical property widely used in the comparison and specification of materials.

Methods for measuring hardness have been developed, the first being the Mohs Scale method. But it is not suitable for metals, and other methods have been developed, such as Vickers, Brinell and Rockwell, which are suitable.

For this project the Rockwell test was used in a Panambra, equipped with a conical diamond penetrator and a load of 150 kgf, to test a gear tooth of the 4th gear of a Mercedes Bens that had fractured losing 6 teeth. The test was performed with 28 measurements on the contour, on the root and also from the upper end of the tooth to the root through the center of the tooth. The average of the measurements was 55 HRC, the lowest reading being 30 HRC on one side of the tooth root and the highest reading was 62 HRC at two points on the same edge of the tooth in the carbonitriding region, one being close to the root and the other close to the center of the tooth. In table 2 and in the figure 9 we can see some points where the hardness test was performed and the values obtained in the test.

Figure 9 - Representation of Rockwell Hardness Test Points (HRC).



Source: Authors (2020)

Table 2 - Results Points of the Hardness HRC Test of the figure 9

Results of Hardness Test HRc			
1.) 46 HRc	2.) 56 HRc	3.) 58 HRc	4.) 59 HRc
5.) 55 HRc	6.) 42 HRc	7.) 42 HRc	8.) 53 HRc
9.) 56 HRc	10.) 49 HRc	11.) 57 HRc	12.) 47 HRc
13.) 56 HRc	14.) 20 HRc	15.) 51 HRc	16.) 54 HRc

17.) 62 HRc	18.) 62 HRc	19.) 41 HRc	20.) 51 HRc
21.) 59 HRc	22.) 60 HRc	23.) 61 HRc	24.) 57 HRc
25.) 57 HRc	26.) 49 HRc	27.) 51 HRc	28.) 58 HRc

Source: Authors (2020)

According to the studies of Castro (2005), The surface hardness of automotive gears is around 60 HRC and the core hardness is 30 HRC. Values very close to those found in our measurements, and also corroborated by the characteristics of SAE 5120 steel.

5. Conclusions

Based on all the research carried out, we conclude that the failures in automotive gears are related to several factors, some of which are more common than others. However, it is worth noting that many of these failures occur due to torques above the design limit, use cycles greater than those anticipated, lack of lubrication, and maintenance issues, among others.

In order to evaluate the performance of these gears, penetrating hardness and liquid tests were carried out in gears with existing and evident flaws. The Rockwell hardness test obtained values corresponding to the characteristics of steel with thermal carbonitriding treatment. In the penetrating liquid test, new cracks appeared inside the gears which had been expected due to the existing fractures in the gear teeth

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REFERENCES

BRADESCO. Steel. Sectorial Information. Economy in Day. Osasco, SP: Department of Economic Research and Studies / BRADESCO. Available at: < https://www.economiaemdia.com.br/BradescoEconomiaEmDia/static_files/pdf/pt/monitores/setorial/infset_mineracao_siderurgia.pdf >. Accessed on: 04 jun. 2017.

CASTRO, R. M. Design Criteria for Helical Gears Applied in Vehicle Mechanical Transmissions. São Paulo: Polytechnic School of the University of São Paulo, 2005.

CUNHA, C. E. Design, Construction and Validation of Jominy Apparatus, According to ASTM A255-02 Standard. 2017. 70f. Course Conclusion Paper (Graduation in Mechanical Engineering) - Federal Technological University of Paraná. Ponta Grossa, 2017.

CUNHA, Kathleen Cristina Silveira; SANTOS, Ramon Oliveira Borges dos. The Reliability of Data from Metrologia 4.0. **International Journal on Data Science and Technology**, v. 6, n. 4, p. 66-69, 30 nov. 2020. Science Publishing Group. Doi: http://dx.doi.org/10.11648/j.ijdst.20200604.11. Available at: http://www.sciencepublishinggroup.com/journal/paperinfo?journalid=390&doi=10.11648/j.ijdst.20200604.11. Accessed on: 12 jan. 2021.

CUNHA, Kathleen Cristina Silveira; SANTOS, Ramon Oliveira Borges dos; D'AVILA, Larissa Silva; CABETTE, Regina Elaine Santos; MUNIZ, Wilson de Freitas; PRADO, Pedro Henrique Colman; HONORATO, Luiz Felipe Freire; MOTTA, Mariana Ferreira Benessiuti; JAEGER, Carlos Dolberth; CHAGAS, Joselito Moreira. The Reliability of Metrologia 4.0 Data in the Industrial Technological Scenario: how this can impact the forms of dimensional control in the industry. **International Journal of Engineering And Applied Sciences (Ijeas)**, v. 7, n. 4, p. 34-38, 30 abr. 2020. Engineering Research Publication ERP. Doi: http://dx.doi.org/10.31873/ijeas.7.04.05. Available at: https://www.ijeas.org/download_data/IJEAS0704005.pdf. Accessed on: 12 jan. 2021.

DIAS, J. Specialization course in Automotive Engineering - Module: Transmissions, Federal Technological University of Paraná, 2011.

JUNIOR, A. C. S. S; Technical and comparative analysis of manual and automatic gearbox, Federal University of Santa Catarina, Joinville 2018.

NEVES, Roberta Braga; PEREIRA, Valdecy and COSTA, Helder Gomes. Auxílio multicritério à decisão aplicado ao planejamento e gestão na indústria de petróleo e gás. **Produção**. 2015, vol.25, n.1, pp.43-53. Epub Sep 03, 2013.

SANTOS, Ramon Oliveira Borges dos; PRADO, Pedro Henrique Colman; OLIVEIRA, Livya Vitoriano Morando; GAMA, Renann Pereira. ANÁLISE METALOGRÁFICA DA FORMAÇÃO DE CAVACO DO AÇO SAE 1020 EM UM PROCESSO DE TORNEAMENTO POR COMANDO NUMÉRICO COMPUTADORIZADO. **Revista Sodebras**, v. 15, n. 175, p. 53-59, jul. 2020. Doi. http://dx.doi.org/10.29367/issn.1809-3957.15.2020.175.53. Available at: < http://sodebras.com.br/edicoes/N175.pdf>. Accessed on: 12 jan. 2021.

WORLDSTEEL ASSOCIATION. Global crude steel output increases by 4.6% in 2018. Available at: <https://www.worldsteel.org/media-centre/press-releases/2019/Global-crude-steel-output-increases-by-4.6--in-2018.html>. Accessed on: 10 May. 2020.