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Failure Analysis for High Speed Gears

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Abstract: ***In this paper, the failure analysis of high speed gears driving air blowers in starch manufacturing processes was investigated in order to find the failure reasons and so over coming them in the future. The gear velocity was 21000 rpm and manufactured from carburized steel (18CrNiMo7-6) DIN No. (1.6587).The gear module was 2 mm and number of teeth was 23 teeth. The gear has failed within 3 weeks of first time operation. Visual investigation has carried out and a set of photos was taken. The teeth of the gear have undergone a bending deflection accompanied with surface wear. The operating conditions (environmental effects, lubrication, loads, assembly and alignment) were revised. The design data was reviewed according to the standard gear design recommendations and also the manufacturing data were checked according to the design data. Additionally, the material analysis; micro hardness measurements and micro structure were investigated. A set of errors were found. The analysis showed that the gear material selection was wrong because the carburization is not suitable for small gear modules. Also, the carburizing depth is not suitable to the gear of module 2 mm. Moreover, the heat treatment process has a set of faults. The micro hardness measurements and micro structure revealed that there was decarburization at surface with depth of 50 to 70 microns due to the presence of decarburization elements such as hydrogen and oxygen from the moisture inside the furnace. Also, there is an excessive retained austenite due to the slow cooling rate in the quenching operation which did not avoid the CC curve nose. The quenching temperature of the gear was less than 700 C^0. There was also an existence of bainite, which reduces the fatigue strength. Although, the recommended values of surface hardness of gear teeth must be more than 56 HRC, the hardness was about 52 HRC at surface of teeth and 42 HRC between teeth at roots, which may reduced the Hertzian contact stress resistance of teeth. Therefore, as a recommendation, the nitriding as a case hardening material must be selected with at least 0.5 mm thickness and of hardness more than 60 HRC for better wear resistance and contact strength for modules of less than or equal 2 mm.***

Keywords: Gear Failure, High speed gear, Carburizing, Hardness,18CrNiMo7-6

1. Introduction

Failure is a fetal point disturbs the researchers, designers, manufacturers and users of gears system. They have to face it and find reasons of failure to introduce solutions to them. So, a lot of efforts are done to avoid, eliminate or reduce the failure occurrence starting from design until the operation and maintenance.

Failure may be caused due to design faults, material defects, manufacturing defects, assembly errors, overloads, vibrations or random effects. Also, gears failures have many other reasons during the production operations such as machining, cleaning, heat treatment even painting.

The present case failure had not complete fracture of the gear teeth a deflection occurred at the pinion gear which resulted from the applied stress producing a deflection shape of teeth as shown in figures (1, 2). It was observed that the teeth had a high deflection at the most of teeth and along their width. The investigation procedure were surveying the assembly, operation and maintenance of the gearbox. Also the environment was surveyed looking for dust, heat or corrosion sources. The operating conditions also reviewed for finding any overloads or back pressure loads to the impeller back to the gearbox. Material selection was considered and heat treatment specifications of the design were reviewed. The heat treatment cycle parameters were checked. The micro hardness measurements survey for the teeth section and also at the teeth root at the area between teeth was surveyed. The microstructure investigations were applied to the teeth and the area between teeth. The results of the previous steps were discussed and a conclusion was drawn

2. Failure Reasons Survey

Errichello [1] had stated that most gear failures come due to overload, bending fatigue, Hertizian fatigue, wear, scuffing, cracking or heat treatment errors. Bouchireb and Sari [2] found that the presence of solid parts in between mating gears teeth is an essential cause severe abrasive wear of teeth; finally it leads to teeth failure. So the contamination must be removed from the gearboxes.

Blake et al [3] observed that the gear grinding process can cause micro cracks due to the abusive cutting conditions selection which burn the gear teeth flank. When the gear is loaded the crack propagation occurs and leads to failure. Xu and Yu [4] concluded that improper grinding operation, thick carburizing depth and weak intergranular strength assist to initiate the cracks and crack propagation.

Pantazopoulos [5] noticed that the low surface hardness and low core hardness at the root of the teeth makes it very weak to withstand the bending and contact stresses loads so he recommended that appropriate carburizing case with hardness in the range of HV = 700 – 900 enable the teeth to have significantly increase in wear and fatigue resistance and give the surface a protection against micro-crack initiation. Gao et al [6] concluded that the chemical reaction of the gas mixture produces of hydrogen which is dissolved in the steel causing hydrogen embrittlement. This leads to the intergranular fracture micro-mechanism at the carburizing layer.

Slager [7] studied a helicopter gear failure and also stated the failure reason was the intergranular embrittlement, but due to the bad grinding conditions during the gear finishing operation. Rossino et al [8] investigated a case hardened driver pinion and they found that the surface contact fatigue failure was revealed that the excessive carburizing case depth led to intergranular excessive threadlike carbon-rich brittle cementite. This cause crack initiation when contact stress is applied and with cyclic load the crack propagation is happening until intergranular fracture occurred.

Wanget al [9] studied a 1.5 MW Wind turbine gear failure and was looking for the failure reasons. It was found that the failure took place due to the incorrect hardness value of the surface which was 55 HRC and the standards (ISO 6336-5) [10] recommendation is more than 58 HRC. This deviation leads pitting at surface through 5 years followed by fracture of the teeth. It can be noticed that just a small deviation from the standard hardness value causes a reduction of the gear life from 20 years to 5 years only.

A study was carried out by Vinokurov et al [11] for tractor gear failure and after investigation, it was found that the failure was occurred due to the insufficient hardness of the case because it was varying between 53 to 58 HRC and this value is not satisfying the Standard GOST 21354–87 established the hardness of surface hardened teeth within the range 56–63 HRC.

Netpu and Srichandr [12] investigated a helicopter gear failure case and they found that the gear teeth stress was more than the strength of the gear materials 3.2 times, so the contact stress started pitting on the surface, which developed to fatigue cracks which was propagated till failure occurrence. The pitting was starting according to the excessive stress due to driver power was changed from 300 kW to 600 kW.

Dhanasekaranet al [13] examined a planetary gearbox sun gear failure for the failure reasons and they found that pitting occurred at the surface due to fatigue load and may be a retained austenite at the surface which followed by micro cracks propagated until failure occurred. Saber [14] investigated an oil pump gear failure reasons. The results detected that the material and the heat treatment have satisfied but it was noticed that the pinion had case hardness less than the gear which subjected to more cyclic loads. So, the hardness selection may be done for safety or for replacing the smaller one at failure but under fatigue, the pinion tooth was failed and the broken fragments start to initiate pitting and cracks at both pinion and gear teeth.

Also, heat treatment errors can lead to failure and is summarized as: grain growth, inadequate phase transformation, un-tempered martensite, decarburization quench cracks, embrittlement, and retained austenite. Scutti and McBrine [15] had stated that there are many other errors during cleaning, inspection and assembly leads to create faults which initiate failure.

3. The Research Methodology

The procedures followed in this paper for analyzing the present case failure can be summarized in a set of steps such as:

- Observe visually the failure gear
- Review the design data
- Assembly procedure check
- Working conditions review Maintenance history review - Investigate the hardness and the case depth
- Investigate the gear microstructure
- Compare the results with the standards specs. Then the failure causes can be carefully identified and recommendations can be given to avoid the future failures.

Gear Design Data

The design was carried out by reverse engineering with the following data:
Speed = 21000 rpm
Working hours/day = 24
Module = 2 mm
Pressure angle = 20^{o}
Helix angle = 15^{o} Left
Width = 80 mm
Backlash = 0.05 … 0.1 mm
Max permissible concentricity = 0.005 mm
Material: Carburizing Steel (18CrNiMo 7-6).

Case hardening

Case Depth = 0.6 - 0.8 mm
Case Hardness HV = 670 - 730 kg_f/mm^2
Core Hardness HV = 380 - 420 kg_f/mm^2
Tempered at low temperature.
Balancing according to ISO 1940, G2.5
General tolerance: DIN 7168 - fine class

4. Observations and Reviews

When the gear was put in operation, a severe deformation in the gear teeth was observed during the first 15 days of starting up the gear box unit as shown in figures (1), (2).

The gearbox was cleaned and no impurities were found inside it or in the lubrication system. The gear dimensional, geometrical and tolerances data adapted the design data. The material analysis and heat treatment are also investigated.

Figure 1: The gear after failure

Figure 2: The gear after cut off for investigation

The gearbox was assembled correctly and no errors in alignment or geometrical errors outside the recommended values. It was filled with the correct quantity and type of oil which was forced lubrication system under proper pressure and flow rate pump. The gear box was started idle and the vibration and heat were measured. They were in the normal values then gearbox was started under load for three days under observation and everything was normal i.e. no vibration, no heat and no noise up normal then the gearbox was under routine operation and maintenance checks. There was no overload sources or back pressure to the impeller.

5. Investigation

The investigation includes a material analysis, a micro hardness and a micro structure scan.

Material Analysis
Spectra and Chemical Analysis results ensured that the material is confirmed to the German Standard (18CrNiMo7-6) DIN No.(1.6587).

The Chemical analysis percentages were as follows:
C= 0.19, Si=0.25, Mn= 0.8, Cr=1.7, Mo=0.3,
Ni=1.6 and base Fe

Hardness Analysis
Micro hardness HV0.1 kg (kg_f/mm^2) inspection was carried out through the teeth section and the area between teeth at the root at which the maximum bending stress position. Then the results were tabulated and presented in table (1):

Table 1: Hardness through the gear tooth sections

On tooth surface		Between teeth roots	
Depth (µm)	HV0.1 kg (kg/mm^2)	Depth (µm)	HV0.1 kg (kg/mm^2)
20	547	20	408
100	566	100	473
200	582	200	579
300	598	300	585
400	567	400	556
500	547	500	536
600	524	600	513
700	497	700	477
Core hardness of the teeth Hv0.1 = 408 kg/mm^2			

The next data Hv0.1 (kg/mm^2) are extracted from the above table:
The surface hardness on the teeth = 547,
The surface hardness between the teeth = 408,
The surface hardness at the core of the teeth= 410,
The surface hardness at the core of the gear = 390. The effective carburizing depth is considered at HR_c=50 or HV = 513 (Kozlovskil et al [16]) = 0.6 mm.

The Microstructure
Three microstructure scans were implemented: first at the tooth carburizing case figure (3), second at the tooth core figure (4) and third at the area between teeth figure (5).

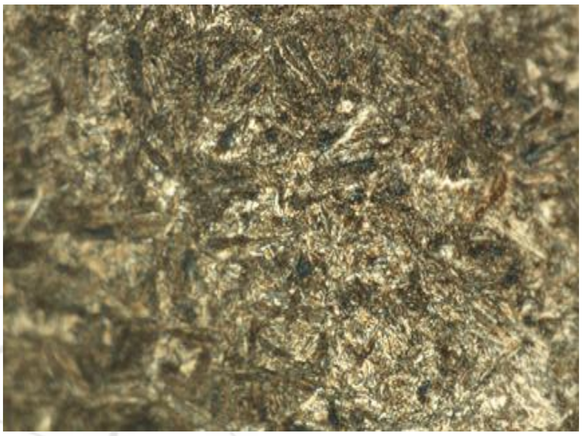

Figure 3: Carburizing case tooth microstructure (excessive retained austenite) Nital 5%, 1000X

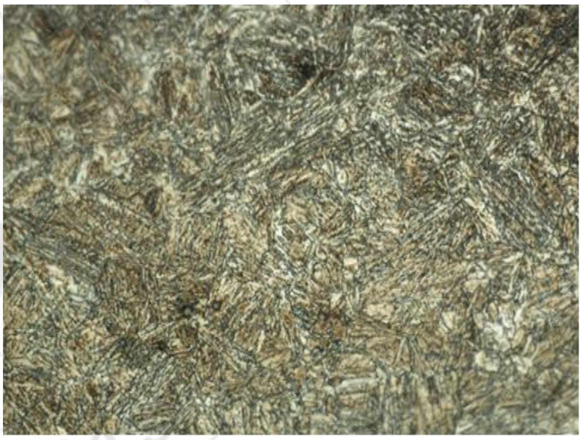

Figure 4: Tooth core micro-structure (excessive retained austenite) +coarse martensite Nital 5% , 1000X

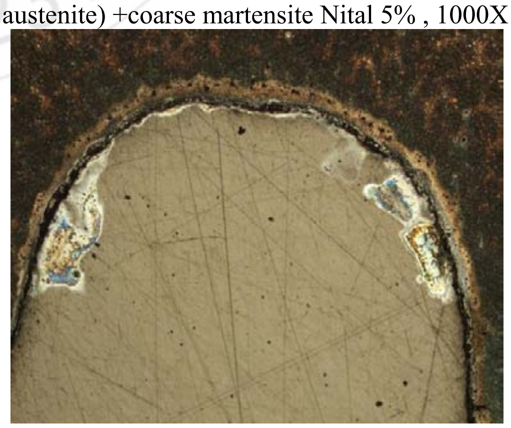

Figure 5: Decarburization depth (white area) between teeth

6. Discussion of Results

The main characteristics of the gear tooth are:
1) Outer hard layer with optimum thickness and hardness to reduce the wear and to overcome the contact stresses.

2) Tough and high strength core to overcome the applied stresses and shocks and
3) Good surface roughness to reduce the probability of crack initiation.

Case surface hardness is the most important parameter which influence the quality and service performance of case carburized of gears which are required to sustain high surface stresses (contact and sliding), the hardness is normally specified > 56 HRC (HV=613) minimum [10,11] to overcome the applied loads but the surface hardness of the delivered gear = 547 HV maximum on the teeth and not homogeneous and this is the main problem, and 408 HV between teeth. The hardness is graphically represented in figure (6) which shows a decarburizing at the surface which reduces the resistance Hertzian stress.

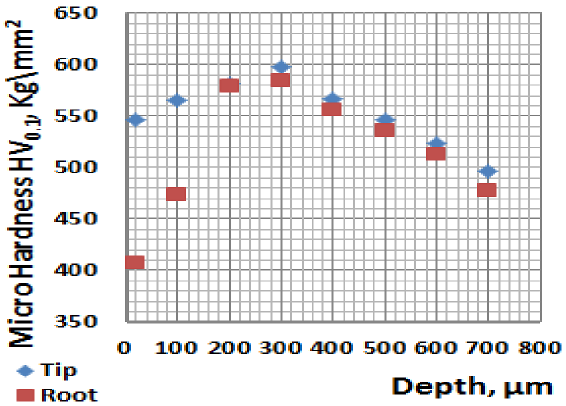

Figure 6: Micro-hardness against case depth

The micro hardness drop in the case which is an indirect means of the low quality of carburization process (it reveals partial decarburization 50-80 Micron, figures (5, 7).

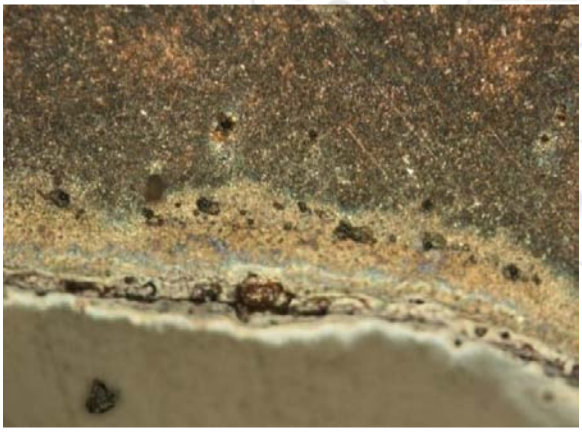

Figure 7: Decarburization at the tooth root Nital 5%, 200X

The presence of Bainite which decreases the fatigue strength, especially contact fatigue strength, where (the ideal structure of the case would be fine tempered martensite with very little or no presence of other transformation productions. The presence of the excessive retained austenite (figures 3, 4) due to incorrect quenching after the carburizing process, as shown in figure (8), where (retained austenite is more critical with steel containing increased Nickel and chromium).

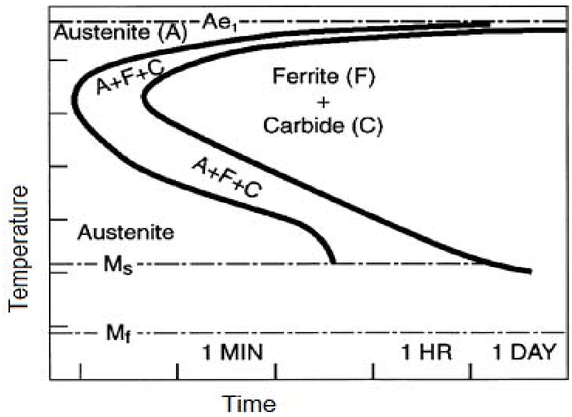

Figure 8: Time, Temperature, Transformation Curve

7. Conclusions

The carburizing case depth and hardness are very effective to the gear performance [17] and the values of them are recommended in reference [18].

The decarburization may be due the presence of O_2, H_2 or H_2o, excessive retained austenite due to incorrect quenching rate and low hardness due to, insufficient carbon in the case layer and incorrect quenching, are the reasons of gear ductile failure. Final recommendation for small gears modules, nitriding case must be used because its optimum effective layer (0.1 – 0.6 mm) is less than carburizing optimum effective layer [18].

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