Failure Analysis for Angle Head Spiral Gears

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Abstract: In this paper, a failure analysis for angle head spiral gears of CNC milling machines is investigated for discovering the failure reasons and so overcoming them in the future. Two spiral mating gears' set is of identical dimensions and its role is to convert the vertical motion to horizontal motion for a certain machining operations is studied in this research work. The gears are manufactured from carburized steel (18CrNiMo7-6), DIN standard No.1.6587. The gear module is 4 mm and number of teeth is 22 teeth. The gears have been failed after 2 weeks of operation. A visual investigation has been carried out and a set of photos were taken. The visual investigation showed that the gears have undergone some broken teeth. The operating conditions have been revised during consecutive intervals of operation. The design data has been reviewed according to standard gear design recommendations followed by a check for the manufactured gear data according to that design data. Material analysis and micro hardness measurements followed by a microstructure have been also investigated. Heat treatment faults were found.

The micro hardness survey through the teeth tips and roots were not correct because there was a decarburization at the manufactured gear up to 1 mm case depth and the carburizing depth at the teeth tip 2-2.2 mm is not suitable and more than the standards recommendations to the gears of module 4 mm.

The micro hardness measurements and micro structure revealed that the case hardness at gear tips was less than at its roots. This refers to an excessive retained austenite due to the slow rate of cooling in the quenching operation which did not avoid the CC curve nose and the gear temperature was less than 700 Co before quenching. In addition, the thick layer of the carburized case may lead to more probable to retained austenite formation. The thick carburized layer at teeth tip leads to brittle teeth at their tip, which leads to their failure due to sudden or impact loads. Therefore, it is recommended to select the carburizing parameters matching with standards recommendations of the carburizing layer with maintaining its thickness difference at both the teeth tips and roots.

Keywords: Gear failure, Angle head, Spiral gears, Carburizing, Decarburization, Case depth, Hardness, 18CrNiMo7-6.

I. INTRODUCTION

CNC machines used in rail way maintenance departments must be accurate and always ready for solving any urgent problems. So the machine components must be ready and trustable at any time to do its job. One important part of the machine is the angle head which used in special operations in the maintenance and repair. So any failure of the angle head components results problems in the urgent repairs. The main components of the angle head are the spiral gears which must be durable, accurate and have minimum backlash and wear. Therefor those gears must have long life and high wear resistance. Usually those gears have about 20 years' life but the manufactured set was failed within 3 weeks and that not logically so the failure reasons must be investigated to overcome in the future. Visual inspection had carried out and set of photos were taken for recording the conditions of the gears as shown in figures (1, 2, 3, 4, 5) for the original and manufactured gears. Micro hardness survey was done and microstructure investigation was applied. The pervious steps were applied to the original and manufactured gears to make a comparison between the failure reasons and detect the difference between the two cases failure and why the manufactured gears failed within 3 weeks and not had a life like the original gears. Investigation included the heat treatment procedures and its faults. The results of the investigation were compared to the recommended design data which revealed a difference between the standard design recommendations and the manufacturing results while the original was satisfied the standards recommendations.

II. LITERATURE SURVEY

Gear failure may occur due to many reasons as: heat treatment errors which can lead to gear failure. This failure can be summarized as: grain growth, inadequate phase transformation, un-tempered martensite, decarburization quench cracks, embrittlement, and retained austenite.

Pantazopoulos [1] observed that the low surface hardness and low core hardness at the root of the teeth makes it weak to withstand the bending and contact stresses loads. Therefore, he had recommended that appropriate carburizing case with hardness in the range of 700–900 HV enables the teeth to have a significant increase in the wear and fatigue resistance and give the surface a protection against micro-crack initiation.

Rossino et al [2] found that the surface contact fatigue failure was revealed that the excessive carburizing case depth led to an intergranular excessive thread like carbon-rich brittle cementite. This causes a crack initiation when contact stress is applied with cyclic load followed by crack propagation until intergranular fracture occurred.

Wanget al [3] stated that the failure may take place in gears due to the low hardness value of the surface which was 55 HRC and the standards (ISO 6336-5) [4] recommendation must be 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.

Vinokurov et al [5] concluded that the failure of gears 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 of 56–63 HRC.

Saber [6] observed that the material and the heat treatment have satisfied the recommended values but it was noticed that the pinion had case hardness less than the gear. Pinion is 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 teeth were failed and the broken fragments start to initiate pitting and cracks at both pinion and gear teeth.

Gao et al [7] noticed that the chemical reaction of the gas mixture produces hydrogen which is dissolved in the steel causing hydrogen embrittlement. This leads to the intergranular fracture micro mechanism at the carburizing layer.

Goher et al [8] had studied a high speed gear failure and they revealed that the failure was due to the occurrence of decarburization caused by the existence of O2, H2 or H2O at high temperature. Also, another reason of failure was the excessive retained austenite due to the slow rate of cooling through the quenching operation which caused ductile gear failure.

Dhanasekaran et al [9] examined a planetary gearbox sun gear failure searching 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.

Starzhinskii et al [10] stated that, to increase the gear the surface life, there are many parameters must be controlled such as: ensuring optimum martensite microstructure, carburizing depth, proper hardness and absence of micro-cracks, decarburization, corrosion, and machining defects.

Nordin et al [11] concluded that there was a certain proportional relation between carburizing depth with the wear rate and fatigue strength to a certain limit.

Tobie et al [12] had shown that the case hardness depth can Influences both bending and surface (contact) load capacity but in different manners. Maximum load capacity is achieved for an optimum value of case depth, but optimum values for maximum tooth root bending strength and pitting resistance of a gear need not necessarily be the same. An unfavorable case depth, smaller or larger than the optimum, leaded to a reduction of attainable load capacity.

III.PROBLEM DEFINITION

As known that machine components which have long cyclic life, can work in stable and accurate operations. Therefore, the components of the milling machines must be well-accurate designed to be durable and highly wear resistance, especially for the high precision CNC. Angle head is an attachment used to do special jobs in milling or boring operations so, it must be robust and accurate. Some of angle head spiral gears were failed after 20 years of operation. A new set was manufactured according to the original data using the reverse engineering technique of collecting the original data. The manufactured set was assembled and put on operation but it failed during four weeks of operation. The new manufactured set and the original set failure were studied to discover the failure reasons to avoid them in the future. Failure analysis for that failed gears showed that these failures may occurred due to: reverse engineering data faults, material defects, manufacturing defects, assembly errors, overloads, vibrations or random effects. Moreover, the analysis showed that the manufacturing process of these gears may cause failure during the production operations such as machining, cleaning, heat treatment even painting.

During the working period of the gears, the machine was used in boring operation of repairing engine blocks after welding. The engine block material was cast iron and the welding was hard and of irregular surface, so the gears' teeth were subjected to impact fluctuating loads until the machined surface became regular.

The original gears and the manufactured ones were visually investigated and the investigations showed different reasons of failures.

The investigation procedure was 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. Material selection was considered and heat treatment specifications were reviewed. The heat treatment cycle parameters were also checked. The micro-hardness measurements survey for the teeth sections and also at the teeth roots 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 conclusions are withdrawn.

IV. THE RESEARCH METHODOLOGY

The procedure followed in this paper for analyzing the present case failure can be summarized in a set of steps [13,
14, 15] such as:

- Observe visually the failure gears
- Review the gears' manufacturing data
- Check the assembly procedure
- Analyze the working conditions
- Investigate the hardness and the case depth
- Investigate the gears microstructure
- Compare the results of the original gear and the manufactured one
- Compare the results of both the original and manufactured gears with the standards specs.
- Then the failure causes can be carefully identified and recommendations can be given to avoid the future failures.

V. OBSERVATIONS AND REVIEW

The visual observation of the original gear after failure had shown complete teeth separation at the keyway from outside and inside, as shown in figures (1, 2) which occurred after operation of about 20 years. Almost, the teeth were in good conditions except around the key way area.

The manufactured gears had some broken teeth, but not at the key way and had not complete separation, as shown in figure (3). The gears' failure occurred within four weeks of operation.

Fig. (1) Original gear teeth cracks

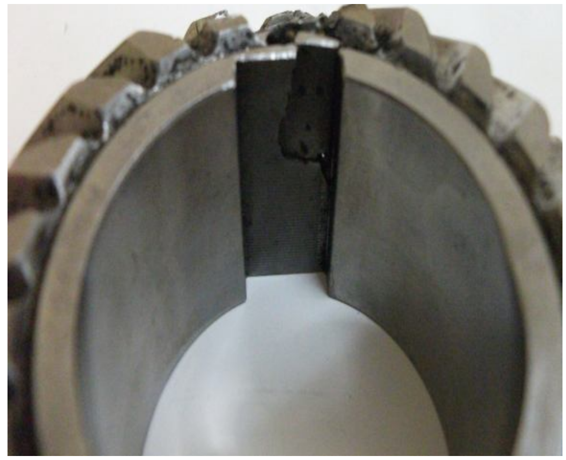

Fig. (2) Original gear keyway crack

Fig. (3) Manufactured gears after failure.

Fig. (4) Manufactured gear teeth breakage (1)

Gear (1) had some broken teeth and cracks at the keyway, as shown in figure (4) but not complete separation as the original gear, figure (2). Also, gear (2) had some broken teeth and cracks at the keyway, as shown in figure (5). Both manufactured gears had a severe pitting through the most of gears' teeth, as shown in figures (3, 4 and 5).

The two gears; original and manufactured, had the same design data which are derived by reverse engineering with almost same dimensions. Therefore, no visual difference between the original and manufactured was observed. Also, the head assembly and operation had no abnormal situation. No heat, no noise and no vibration were observed. Also, no foreign objects were found in the head housing. The applied load for both cases is normal and routine operation. The cutting tools were in good condition and did not cause any overloads. The workpieces' hardness was in the normal values as the work requirements. The operating and maintenance team had continuously observing the machine during operation and routine maintenance was carried out periodically according to the maintenance sequence.

Fig. (5) Manufactured gear teeth breakage (2)

VI. INVESTIGATION

The laboratory investigation included: material analysis and micro hardness followed by a microstructure scan as in the following subsections:

a. Material Analysis

The spectra and chemical analysis results ensured that the material was confirmed to the German Standard (DIN 1.6587)-(18CrNiMo7-6) for both original and manufactured gears.

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 the base was Fe.

b. **Hardness Analysis**

A micro hardness HV0.1 kg (kgf/mm2) inspection was carried out for both the original and manufactured gears through both the teeth section and the area between teeth at the root at which the maximum bending stress position. The results were then tabulated and presented in the following table (table 1) and figure (6) which show the measured data of the original gear.

Table (1) Hardness values through the gear tooth sections for the original gear

	On tooth surface	Between teeth roots
Depth (μm)	$HV_{0.1}$ (kg/mm^2)	$HV_{0.1}$ (kg/mm^2)
20	689	681
100	689	672
200	681	657
300	681	657
500	672	641
700	664	591
800	650	571
900	634	547
1000	611	530
1100	585	513
1200	576	507
1300	566	497
1500	524	460
1600	513	440
1700	497	430
Teeth core hardness $Hv_{0.1}$ = 430 kg/mm^2		

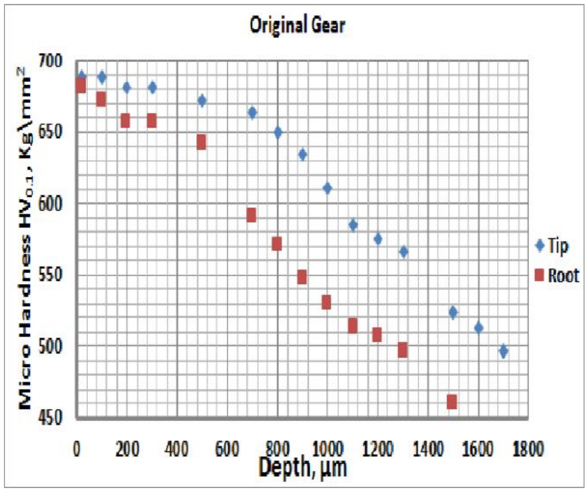

Fig. (6) Original gear micro-hardness

The surface hardness HV0.1 of the original gear = 670 – 690 Kg/mm², while the core hardness of the original gear = 430 Kg/mm².

The case depth on the teeth tip of the original gear = 1.6 mm, while the case depth at the teeth root = 1.2 mm

The micro-hardness between the root and the teeth showed an excessive carburizing depth compared to the gear teeth thickness.

For the manufactured gear, the measured micro-hardness data are presented in table (2) and figure (7).

Table (2) Hardness values through the gear tooth sections for the manufactured gear

	On tooth surface	Between teeth roots
Depth (μm)	$HV_{0.1}$ kg (kg/mm^2)	$HV_{0.1}$ kg (kg/mm^2)
20	672	665
100	672	649
200	672	649
300	672	649
500	672	649
700	672	629
800	681	605
900	689	571
1000	674	533
1100	667	527
1200	657	519
1300	657	497
1500	619	
1700	578	
1900	530	
2100	508	
2300	473	
Teeth core hardness $Hv_{0.1}$=450 kg/mm^2		

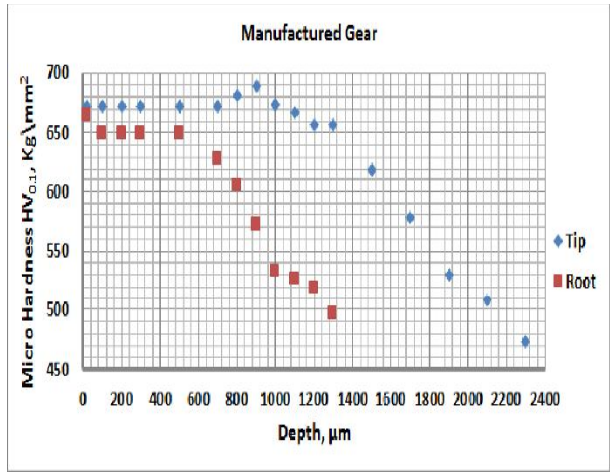

Fig. (7) Manufactured gear micro-hardness

The surface hardness HV0.1 of the two gears = 670 Kg/mm², while the core hardness of the two gears = 450 Kg/mm².
The case depth on the teeth tip of the two gears = 2.1 mm, while the case depth at the teeth root of the two gears = 1.2 mm.
The effective carburizing depth is considered at HRc=50 or HV= 513 (Kozlovskil et al [16]).

c. **The Microstructure**

Optical microscope with X1000 magnification power was used in investigating the microstructure; Nital Etching 2% of the specimen. The microstructure of the original gear at the surface and the core of the teeth are shown in figures (8, 9) respectively.

Figure (8) shows large martensite plates with small amount of retained austenite.

Whereas, figure (9) shows the teeth microstructure, which reveals small amount of martensite; black points in the microstructure.

The microstructure of the manufactured gears, as shown in figure (10) at teeth surface reveals an amount of martensite with large amount of retained austenite.

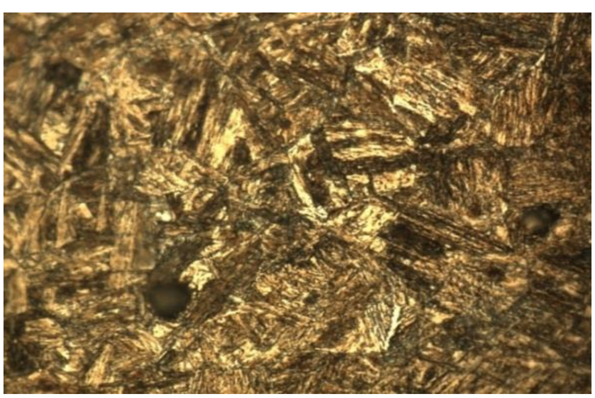

Fig. (8) Original gear teeth surface microstructure

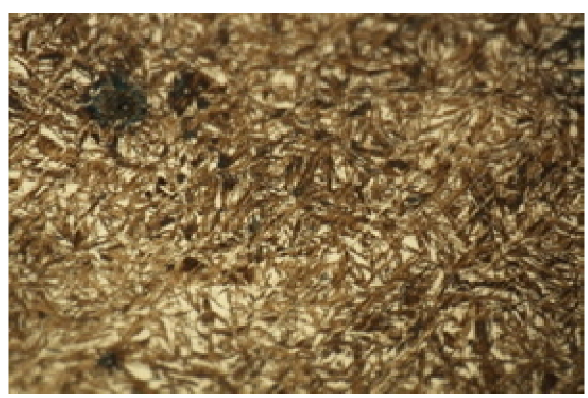

Fig. (9) Original gear teeth core microstructure

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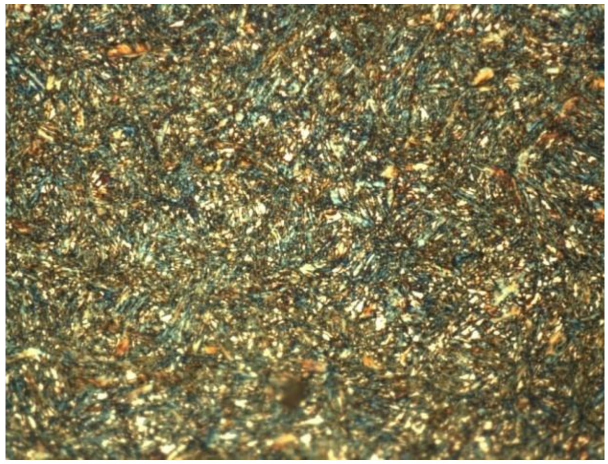

Fig. (10) Manufactured gear teeth surface shows excessive retained austenite.

VII. Discussion of Results

The original gear micro hardness is confirming the recommended values ISO 6336-5 [4] and reference [5], as shown in table (1) and figure (6).

In addition, its case depth of 1.2 mm satisfies the recommended values presented in reference [17] (the case depth to be within 0.3- 0.4 module) which proposed for avoiding the teeth failure.

Additionally, the martensite microstructure of the gear teeth with small amount of retained austenite is found to be adequate.

Since the gear teeth hardness, case depth and microstructure were proper, and then the failure of the original gear has been occurred due to the fatigue cycles time for operation about 20 years. The failure may started with cracks at the key way due to the stress concentration at the keyway accompanied with a crack at that end as shown in figure (2). After cracks initiated, the small separated fragments were found between teeth, which have accelerated the cracks propagation and failure occurrence. This type of failure is classified as tooth bending fatigue [18].

Regarding the manufactured gears as derived from table (2) and figure (7), the following aspects can be illustrated:

The failure has occurred, beside the stress concentration at the key way, due to the excessive retained austenite, which may help in initiating cracks at grinding operation after heat treatment, which propagates during operation.

Excessive retained austenite at the surface decreased the Hertzian strength of the surface, which may cause pitting. Also, retained austenite decreased the toughness strength and accelerated the failure [19].

The micro-hardness scan, the hardness at surface is less some points inside the case, shows that there a decarburization had occurred due to oxidation of carbons at temperature over 860 Co when transferring the gears from the carburization media to next heat treatment operation without cooling it in a reach carbon surrounding the gear to less than 860 Co [8, 20].

Case depth is more than the recommended value of 2.1 mm, which make a full-hardened portion at the tip of the teeth, which make this portion, lose its toughness and could not resist the impact loads due to the irregular machined surfaces of the welded work pieces. Too much case depth makes the gear teeth more brittle with the tendency to shatter off the top of teeth [17].

VIII. Conclusions

Besides, the material selection, the design analysis and the manufacturing accuracy, the heat treatment is considered as one of the most important operation for gears working success. The following points must be considered during the heat treatment process of gears:

- The hardness value, for improving the Hertzian strength of gear teeth.
- Optimum case depth value, for avoiding thinner case, which leads to an initiation of cracks, or deeper case, which leads to shatter of the teeth at top.
- Avoiding decarburizing which leads to a drop in gear teeth hardness and increasing the retained austenite causing a crack initiation in teeth.
- The time and conditions of work piece transfer from carburizing furnace to the cooling furnace must be in reach carbon environment to avoid the decarburization.
- The time of work piece transfer from the hardening furnace to the quenching media to suitable to avoid the TTT intersection.

REFERENCES

[1] A. George, Pantazopoulos, "Bending Fatigue Failure of a Helical Pinion Bevel Gear", Journal of Failure Analysis and Prevention", 2015, 15:219–226.

[2] S. Luciana, D. B. Villarino de Castro, J. A. Moreto, "Cassius Olivio Figueiredo Terra Ruchert, Dirceu Spinelli, José Ricardo Tarpani "Surface Contact Fatigue Failure of a Case Hardened Pinion Shaft", Materials Research 2014; 17(3): 535-541.

[3] Q. Wang, Yankun Zhu, Zhefeng Zhang,Changming Fu, Chen Dong, Huihe Su, "Partial Load: A Key Factor Resulting in the Failure of Gear in the Wind Turbine Gearbox", Journal of Failure Analysis and Prevention, 2016, 16:109–122.

[4] ISO 6336 -2003- "Calculation of load capacity of spur and helical gears".

[5] G. Vinokurov, S. P. Yakovleva, M. I. Vasil'eva, S. N. Makharova "Operational Failure of Tractor Gears", Russian Engineering Research, 2012, Vol. 32, No. 3, pp. 220–224.

[6] Aabed Saud Saber "Failure of an Oil Pump Bevel Gear", Journal of Failure Analysis and Prevention (2008) 8:419–425.

[7] Yu-zhouGao , Xiao-lei Xu, Zhi-wei Yu "Brittle Cracking of a Cylindrical Spiral Gear of Axle Gearbox", Journal of Failure Analysis and Prevention (2014) 14:68–75.

[8] R. I. Goher, B. S. Azzam, M. M. Abdrabou "Failure Analysis for High Speed Gears" – International Journal for Science and Research (IJSR)-Volume 6 Issue 3, March 2017-ART20164083

[9] R. Dhanasekaran, P.Senthil Kumar, K.Santhi "Crack Failure of Planetary Gearbox Sun Gear"- International Journal of Recent Trends in Engineering and Technology, Vol. 3, No. 6, May 2010.

[10] V. E. Starzhinskii , Yu. L. Soliterman , A. M. Goman , and S. A. Osipenko "Forms of Damage to Gear Wheels: Typology and Recommendations on Prevention" - JOURNAL OF FRICTION AND WEAR Vol. 29 No. 5 – 2008

[11] Imaduddin Helmi bin Wan Nordin, Salmie SuhanabintiChe Abdullah, Mohd Afendi bin Rojan, MohdHafis bin Sulaiman " Bending Fatigue Strength of Case-Carburized Spur Gears with Boss " – International Conference on Applications and Design in Mechanical Engineering – 27-28 February 2012, Penang, Malaysia

[12] T. Tobie, Peter Oster,Bernd-Robert Höhn" Systematic Investigations on the Influence of Case Depth on the Pitting and Bending Strength of Case Carburized Gears" - Gear Technology – July/August 2005

[13] ROBERT L. ERRICHELLO and JANE MULLER "How to analyze gear failure" – POWER TRANSMISSION – MARCH 1994

[14] D. Hemanshu, Joshi1, K. D. Kothari "Mode and cause of failure of a Bevel gear-A review" - International Journal of Advance Engineering and Research Development (IJAERD) Volume 1 Issue 2, March 2014, e-ISSN: 2348 - 4470, print-ISSN: 2348-6406

[15] A. Yadav "Different types Failure in gears-A Review" - International Journal of Science, Engineering and Technology Research (IJSETR)- Volume 1, Issue 5, November 2012

[17] I, S. Kozlovskil, V. A. Olovyanishnikov, V. M. Zinehenko "Criteria for evaluating the quality and bases for rational selection, of carburized and nitrided steels, "Chemical-thermal Treatment - No. 3, pp. 2-9, March, 1981.

[18] ASM International " Heat Treatment of Gears: A Practical Guide for Engineers" -2000 - ISBN: 0-87170-694-6, SAN: 204-7586.

[19] ASM HANDBOOK – VOLUME 11 – Failure Analysis and Prevention- ASM International - 2002

[20] Shen-Chih Lee and Weio-Youe Ho "The Effects of Surface Hardening on Fracture Toughness of Carburized Steel" - Metallurgical Transactions A - Volume 20A- March 1989--519

[21] Zhi-wei Yu, Xiao-lei Xu "Failure Analysis of Cracked Gear Shafts" - Journal of Failure Analysis and Prevention. (2009) 9:43–48.