15th International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2011, Prague, Czech Republic, 12-18 September 2011

# ANALYSIS OF GEAR DAMAGE CAUSES USING MICROHARDNESS AND METALLOGRAPHIC TESTING

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## ABSTRACT
*Different types of damage can occur on the coupled teeth of gears. This paper presents the procedure for testing and analysis of the causes of hip gear teeth from a crane gearbox. The goal of this research was aimed to examine and to analyze the faults that occurred in the damaged teeth of gears made of steel E335 by BAS EN 10027-1 (Č.0645) and to determine what led to the formation of these defects. Experimental part of this research was performed by sampling from three selected gear tooth samples. Two teeth were damaged and there was one undamaged gear tooth. Metallographic and mechanical tests were carried out in order to resolve the respective issues, which occurred at the gear teeth sides. The results of metallographic and mechanical tests indicate that the damaged gear teeth were heavily loaded, and they were improperly welded afterwards, which led to the progressive formation of cracks around the side of the tooth.*
**Keywords:** Gears, Gear damage causes, Micro hardness testing, Metallographic testing

## 1. INTRODUCTION
Gear transmissions are vital parts of machines, and their reliable operation is required in order to prevent machine damage and fracture. However, different kinds of failures of gear teeth occur in service, altering the operating characteristics of transmission, eventually leading to failure of whole mechanical assembly with built-in gear. Great care is paid to analysis of different tooth failure types in order to prevent or at least to prolong the process of their initiation and development.
Depending on loading type and operating conditions, more than 20 different types of damage can occur on the coupled teeth of gears. According to the definitions of teeth damages given in standard ISO 10825, basic types of gear teeth damages include: surface deterioration, scuffing, permanent deformation, surface fatigue phenomena, cracks, and gear tooth fracture.
Parientea and Guagliano in [1] used X-ray diffraction to measure the residual stress state in metal gears and to evidence the evolution of the residual stress state and of the grain distortion due to damage development.
Starzhinskii et al. in [2] presented a draft of the interstate standard on classification and description of gear damage on the basis of analysis of the information from international (ISO) and national (ANSI/AGMA, DIN) standards. They discussed the causes of origination and development of characteristic types of damage illustrated by micro-images of individual examples of damage.
Nigarura et al. in [3] tested Surface densified powder metal gears and conventional wrought steel gears using a pulsator and a back-to-back gear tester. Based on the analysis of damage initiation and fracture mode, the densification depth is shown to be critical on bending fatigue life. They showed that through

deep densification in the root area, densified sintered gears can match the strength of wrought steel gears.
Kladarić et al. in [4] experimentally investigated the effect of normalization temperature, duration of the heating on the normalization temperature and cooling type on the hypo-eutectoid steel grain size changes.
Atanasovska and Momčilović in [5] presented testing and analysis procedures for some types and levels of teeth damage. They analysed different types of gear teeth damage, fracture and affecting conditions of environment, service and maintenance.
Kosec et al. in [6] have found that the failure to the pinion is a direct consequence of the incorrect geometry of the surface hardened layer. The lifespan of the pinion could have been extended if the whole surface of the faces and roots of the teeth had been hardened and if the hardening had been deeper.
Marković in [7] presented basic approach to repairing by surfacing of damaged gears and developed technological procedure by use of electric arc. They presented the results of repaired gears testing.

## 2. MICROHARDNESS TESTING

In order to determine mechanical properties, a micro hardness testing was performed. The following laboratory equipment was used:

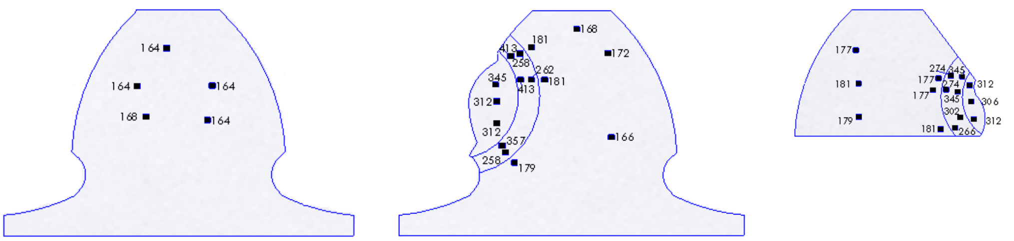
- Vickers Micro hardness testing device Zwick 3212 (measurement uncertainty ≤ ±0.5%)
- Optical microscope Olympus PMG3 (20 to 2000x enlargement ratio)

The three samples were prepared, as shown in Fig. 1. Sample (a) is undamaged; sample (b) has a crack along whole length of a gear tooth and tooth side is damaged; sample (c) also has side defects, progressive pitting and remnants of a weld.

*a) Undamaged gear tooth* *b) Damaged gear tooth 1* *c) Damaged gear tooth 2*

*Figure 1. Samples for micro hardness testing*

Figure 2 shows locations of micro hardness tests. All gear teeth were tested on locations referred to as a basic material, and damaged teeth (b, c) were tested inside a weld and inside the heat-affected zone. Measurement results, shown in Table 1, show that hardness of undamaged gear tooth is uniform and has value of 164 HV10 across whole cross-section.




*a) Undamaged gear tooth* *b) Damaged gear tooth 1* *c) Damaged gear tooth 2*

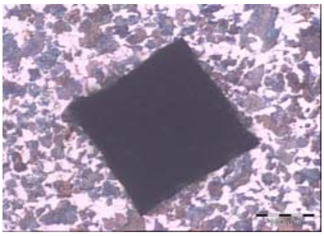
*Figure 2. Locations of micro hardness tests*

Sample (b) was tested in 15 different locations. Basic material has hardness between 166 and 181 (average 17.5 HV10). Lowest hardness 166 HV10 is registered in the middle of the sample, and hardness in heat-affected zone increases. The highest value in heat-affected zone is 357 HV10, while average hardness is 326.8 HV10. Within the weld, hardness is between 312 and 345 HV10, and average is 323 HV10.

Sample (c) was measured at 15 locations. Basic material hardness is between 177 and 266 (average 192.8 HV10). Lowest value 177 HV10 is measured in the middle, increasing towards heat-affected zone. Lowest value in heat-affected zone is 274 HV10, and the highest value is 345 HV10, both in gear tooth side. Welded part had uniform hardness with average value 310 HV10.

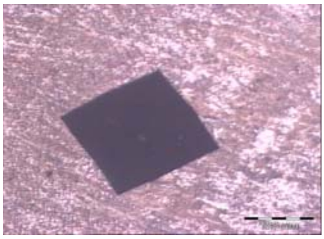
*Table 1. Micro hardness testing results*

| E 335 | Basic material | | | | | | Heat affected zone | | | | | | Weld | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Sample | Hardness HV10 | | | | | | | | | | | | | | |
| a | 164 | 164 | 164 | 168 | 164 | | | | | | | | | | |
| b | 166 | 172 | 168 | 181 | 181 | 179 | 262 | 413 | 258 | 258 | 413 | 357 | 312 | 312 | 345 |
| c | 177 | 179 | 181 | 177 | 177 | 266 | 274 | 302 | 274 | 345 | 345 | 302 | 312 | 312 | 306 |



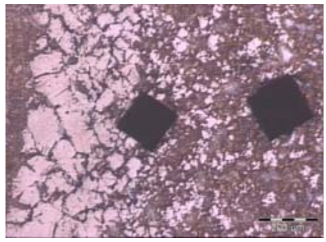
*2% $HNO_3$ x145*

*a) Middle of tooth, ferrite-pearlite structure, Hardness HV10:164*



*2% $HNO_3$ x145*

*b) Weld, Hardness HV10:345*



*2% $HNO_3$ x72*

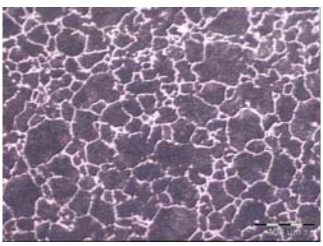
*c) Heat-affected zone, Hardness HV10:357*

*Figure 3. Microstructure of hardness tests*

## 3. METALOGRAPHIC TESTING

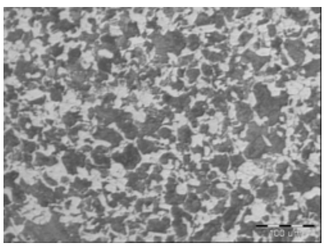
In order to determine microstructure, samples were subjected to metallographic analysis. The following laboratory equipment was used:

- CUT machine Buehler Abrasiment-2 (Type 95-C-1800)
- Press for impressing samples into plastics Simplimet 2 (Type 95-C-1800)
- Wet polishing machine
- Optical microscope Olympus PMG3 (20 to 2000x enlargement ratio)
- Stereo microscope Technival 2 (8 to 80 x enlargement ratio)



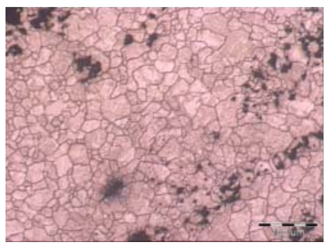
*2% $HNO_3$ x145*

*a) Undamaged gear tooth Secondary cementite, Austenitic grain size 5-6 (cementation method)*



*2% $HNO_3$ x145*

*b) Damaged gear tooth 1 Secondary grain size 5-6*



*Picric acid x145*

*c) Undamaged gear tooth Austenitic grain size 5-6 (oxidation method)*

*Figure 4. Metallographic test results*

Fig. 4 shows results of metallographic tests. Undamaged gear was tested by cementation method (Fig. 4.a). The carbon defunded by grain edges and formed mesh of secondary cementite ($Fe_3C$). Secondary grain size was tested by method ASTM E112 (Fig.4.b). Undamaged tooth was tested by oxidation

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method (Fig.4.c). The microstructure is inhomogeneous and the surface is oxidised. The grain size is 5-6. These tests showed lack of hardened surface and damaged gear teeth had heat-affected zones. Microstructure in all samples was ferrite-pearlite, with grain size 5-6, which provides good mechanical characteristics.

## 4. CONCLUSIONS

Metallographic tests were carried out according to test methods (ASTM E 407). The size of austenite grain size of the secondary grains was also tested (ASTM E 112), followed by mechanical testing-testing method for micro hardness BAS EN ISO 6507-1.

Metallographic examination revealed the absence of a hardened surface, and the two damaged gear teeth expressed existence of the heat effect zone and weld metal in the area on both tooth sides. These two damaged gear teeth also expressed dent in the side of the tooth that was filled with oxide. The microstructure of all three tested samples showed an uniform ferrite-pearlite structure. The secondary grain size on all three samples is between 5 and 6. To assess the size of austenite grains, detection of austenitic grain was performed using Mc Quaid – Ehn method of carburisation followed by etching with 2%$HNO_3$ solution and the oxidation method was performed with picric acid etching. Testing of austenitic grains of all three samples of gear teeth revealed medium grain size, between 5 and 6, which guarantees favourable mechanical properties.

The mechanical testing of two damaged tooth pinion and an intact gear tooth was done by testing micro hardness according to standard EN ISO 6507-1. We used the hardness HV10. On the intact tooth pinion average hardness amounted to 164.8. Hardness was uniform across the section of gear teeth. On the damaged tooth gear one hardness was uneven across the tooth cross-section. hardness in the impact zone and heat-affected area of weld was significantly higher than the base material, and hardness was significantly uneven in heat-affected area.

Weld damaged the macro-and micro-structure, resulting in uneven hardness across the side of the gear tooth. Fatigue damage in terms of initial and progressive pitting on the sides of individual teeth were formed as a result of uneven surfacing. Also on some adjacent teeth, initial signs of pitting were observed, but in a much smaller scale.

The working life of the this gear would be significantly extended if the gear teeth were surface-hardened or cemented.

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