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# Determination on Damage Mechanism of the Planet Gear of Heavy Vehicle Final Drive

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**Abstract**. The works focus on the investigation of damage mechanism of fractured in the form of spalling of the planet gears from the final drive assembly of 160-ton heavy vehicles. The objective of this work is to clearly understand the mechanism of damage. The work is the first stage of the on-going research on the remaining life estimation of such gears. The understanding of the damage mechanism is critical in order to provide accurate estimate of the gear's remaining life with observed initial damage. The analysis was performed based on the metallurgy laboratory works, including visual observation, macro-micro fractography by optical stereo and optical microscope and micro-vickers hardness test. From visual observation it was observed pitting that form lining defect at common position, which is at gear flank position. From spalling sample it was observed ratchet mark at the boundary between macro pitting and the edge of fractured parts. Further observation on the cross-section of the samples by optical microscope confirm that initial micro pitting occur without spalling of the case hardened surface. Spalling occur when pitting achieve certain critical size, and occur at multiple initiation site of crack propagation. From the present research it was concluded that pitting was resulted due to repeated contact fatigue. In addition, development of micro to macro pitting as well as spalling occur at certain direction towards the top of the gear teeth.

## 1. Introduction

Spalling is a type of damage, which involving detachment of small to medium parts of component. This type of damage is predicted related with common damage mechanism of gear component that works as mating parts and susceptible to various fatigue failure [1-3]. This type of failure can be the extension of other premature surface defect, namely pitting [4], and can also be accompanied and become worst with the presence of corrosion [5]. Gear component commonly manufactured in the form of case-hardened part [ 6-9], that offer high hardness at the surface and toughness at the inner parts. The first condition is required since gear is commonly used as mating parts where contact fatigue cannot be avoided. In addition the inner parts of the gear should has sufficient toughness in order to avoid brittle fractures once crack present in the component. Regarding this requirement gear component is preferably made from low carbon steel that having sufficient toughness. On the other hand, carburizing, which is thermo-chemical treatment is normally applied on the low carbon steel gear, in order to diffuse carbon element into the steel surface and forming harder phase in the surface.

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Investigation on this type of damage is important, and at least there are three points can be the objective of such investigation. The first is to understand the mechanism of the damage, second is to avoid the similar failure in the future and to estimate the remaining life of gears with pitting defect before finally spalling occur on the component. By understanding the mechanism of damage it can be followed with appropriate treatment on the manufacturing of the component therefore similar failure can be avoided in the future. On the other hand, by the ability to estimate the life of gear component with pitting defect, it will significantly help in making appropriate preventive maintenance. All of these benefits will also directly contribute in the cost saving of vehicle maintenance and services.

One method of works that has been widely implemented as well as developed is failure analysis works that commonly used to investigate various failures in the various industries. Different with root cause analysis that considers the human error as the probable cause of failure, failure analysis is merely count on the physical aspect of failure. It can be due to the quality of material [10], inappropriate services or manufacturing. The investigation was carried out based on metallurgical failure analysis works, as will be explained subsequently.

## 2. Results and Discussion

*There are several works have been done in order to obtain the objective of the present research. The first step is macrofractography by using DLSR camera with macro lense, in order to obtain the area where pitting as well as spalling defects occur. Further detail on macrofractography was performed by optical stereo microscope. In addition, in order to obtain cross-section data especially the case hardening profile of the gears, macro-structure characterization were performed by optical stereo microscope characterization. This characterization was performed both on the spalling section and the normal section. In order to support this characterization, micro-hardness test was also performed on the cros-section parts of the gears samples and the description of the data is supported with microstructure data of the corresponding section by optical microscope characaterization. Cross-section observation was also performed by optical stereo microscope in order to obtain the size and morphology of the pitting. By evaluating all of these data, damage mechanism that causing spalling on the gears samples can be determined.*

## 3. Research Methodology

The Figure 1 shows two gear samples with initial pitting and spalling defect respectively. It can be seen from Figure 1(a) that commonly initial pitting exists at certain position on the gears and forming line pattern. It should be noted that pitting terminology here is not representing pitting defect resulted from corrosion process. However it is resulted from mechanical works between two mating parts. From observation of various gears sample with pitting defects, it was observed that typical position of the defect mainly occur at 1/3 distance from the lower section of the tooth (gear flank position). On the other hand Figure 1(b) shows uncommon failure of the gear that experience spalling due to uncommon incident as well.

Figure 2 shows one closer view of figure 1(b) which showing the boundary between the spalling parts and the pitting parts. It can be observed that ratchet marks appear at the boundary of the spalling parts. These marks appears near big pitting (resulted from coalescence of several smaller pitting) and indicates that spalling initiate from multiple site close to big pitting. The edge of pitting is having high stress concentration due to sharp edges and it is predicted that there is critical size of pitting that finally induce in the bigger fracture of the parts (spalling case). Other interesting features are fine and coarse ridges on the crack surface. It can be seen from Fig. 3 that rupture crack propagated by forming fine ridges before coarse ridges occurs at the final stage of fracture. On the further observation, the ridges texture is found to be appeared on both macro pitting and rupture surface which is the characteristic of fatigue fracture (Fig.4).

(a) (b)

Figure 1. Two gear samples with initial pitting (a) andfractured failed (b)

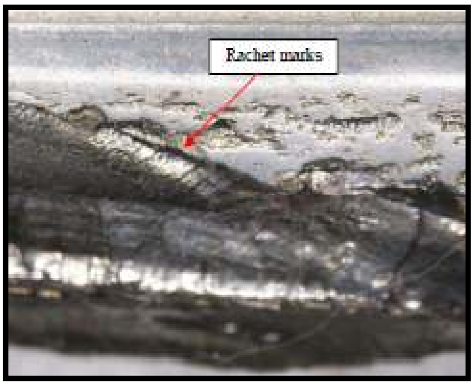


Figure 2.Rachet marks on fracture surface

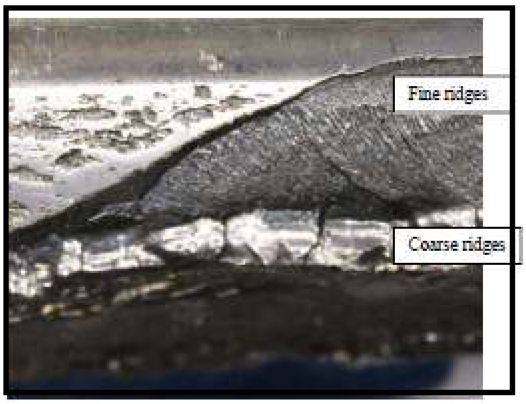


Figure3. Fine and coarse ridges on fracture surface

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Figure 4. Ridges pattern on macro pitting and rupture crack surface

In addition, samples inspection at cross section area were conducted in several processes which are macro case-hardened profile, micro-structure characterization and microhardness test. Case-hardened profile inspection was conducted in order to identify and compare the cross section between gear tooth which has micro pitting and another gear tooth that has been fractured. Figure 5 shows gear teeth that having micro pitting (left figure) and the fractured gear (right figure). From the left figure it can be seen that the gear teeth has homogeneous and compact case-hardened surface that indicate pitting does not preceded with the breaking of case-hardened surface. On the other hand, cross section figure of the fractured gear tooth, shows that the case-hardened surface has been degraded with rupture tend to proceed toward the top of the gear. Refer to the position of the initial pitting which is at the bottom of the gear (flank position), it is predicted that the crack propagation starting from this position up to the top of the gear teeth.

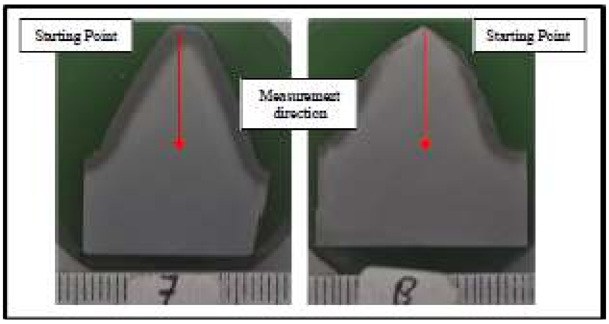


Figure 5. Cross section figure of initial pitting sample (left) and fractured sample (right)

Figure 6 shows cross section microstructure of initial pitting and fractured gear teeth shown in the Figure 5. This characterization was performed in order to observe any microstructure degradation after operation. From these figures it can be seen that both of gear tooth contains the same phase which is TemperedMartensite. However there is a distinct phase morphology between them. The left figure contains surface structure that finer than its core structure, while the right figure for the fractured gear, the case-hardened surface has been diminished and the surface structure become similar with its core.

In addition, micro-hardness profiles were evaluated in order to emphasize the distinction between two different cross section profile especially on its mechanical properties. The inspection was conducted by micro-vickers hardness test and 7 hardness (HV) values points starting from gear teeth's top edge into its core with distance 0.5 mm between every measurement point were performed. Table 1 shows micro-hardness test data, and it can be seen that surface hardness of initial pitting gear teeth is significantly higher than its core value. On the other hand, hardness value of fractured gear tooth is relatively similar between both surface and core area. This phenomenon confirms microstructure data in the Figure 6, and signify the differences between gear tooth that only contain micro pitting and spalling gear tooth. One point to be noted from the above data is the initiation of pitting is formed without the breaking of case hardened surface. Spalling or fracture of the gear surface initiate when

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pitting rearch certain critical size, and this crack propagation initiate from the multiple site of critical pitting.

Figure 6. Cros section microstructure of initial pitting gear teeth and fractured gear teeth

Table 1 Micro-Hardness Value of initial pitting and Fractured Gear Tooth

| Sample | Hardness (HV) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Pitting sample | 727 | 673 | 524 | 475 | 475 | 460 | 407 |
| Spalling sample | 439 | 439 | 446 | 453 | 432 | 439 | 378 |

Figure 7 shows cross-section surface texture of initial pitting gears by optical microscope. It can be observed uneven texture with the appearance of sharp high peaks and valley texture. According to Moorthy [11] this peak and valley texture can be atrigger for the the initiation of micro-crack and micro-pitting. Therefore up to this point, we have obtain two condition for the initiation of pitting, occur at the gear plank position and preferably on the coarse surface with sharp peak and valley texture.

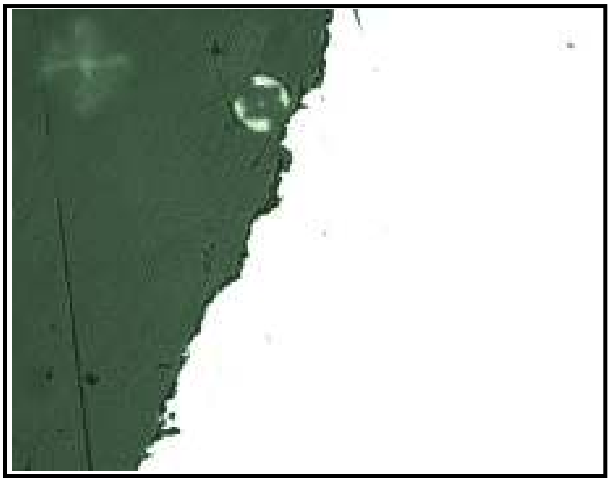

Figure 7. Surface Texture of Gear Teeth with initial pitting

In addition, Figure 8 shows the appearance of deep micro pitting and coarse crater defects. Both of these defects are predicted resulted from the different modes of pitting growth. The deep micro pitting is predicted resulted from single micro pitting that grows into sharp deep pitting. The other one is predicted resulted from the coalescence of more than one pitting and creating coarse crater. Furhermore, micro pitting will growinto its preferential direction which is against sliding direction (Moorthy, 2013) and for this case is toward the top of gear tooth.

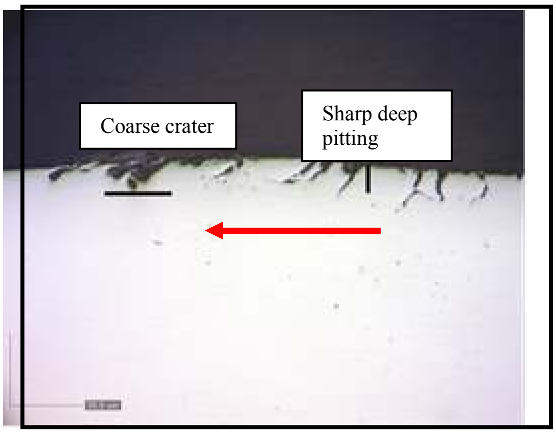


Fig. 8 Prediction of pitting growth direction

### *3.1. Damage Mechanism*

As previously said that the damage initiated due to peak and valley texture of gear tooth's surface which then become micro-crack or micro-pitting, and the mechanism of defect is repeated contact fatigue, as can be predicted from the position and morphology of the defects. Micro-pitting then will grow within two modes whether sharp deep pitting (single) or coarse crater. Furthermore, micro-pitting will continue grow by contact fatigue mechanism. The coalescence of multiple micro-pitting will produce macro-pitting. Macro-pitting then became initiation site of fatigue cracks. The cracks on the gears itself generated from multiple initiation site, based on observation of ratchet marks at fracture surface. Cracks then propagated towards gear's top section by forming fine ridges until certain cross-section area before cracks propagates into coarse ridges at the final stage of fracture. Figure 9 show the scheme of damage mechanism observed in the present research.

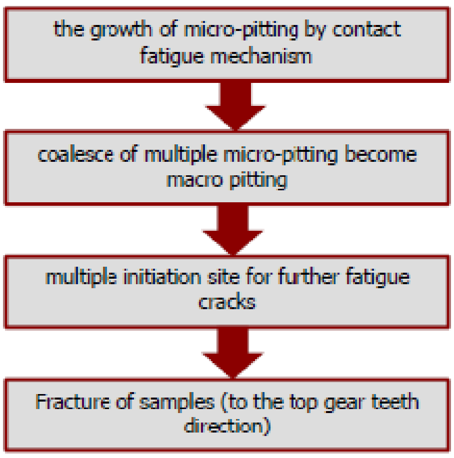


Fig. 9 Scheme of Damage Mechanism from Micro-Pitting to Rupture

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## 4. Conclusion

From the investigation, the following damage mechanism has been concluded.

a. It was observed gears samples with pitting and fractured/ spalling defects condition
b. Pitting was resulted from repeated contact fatigue of the mating gear
c. Progressive macropitting causing spalling (pits coalesce and form irregular craters over a large area)
d. Coalesce macro pittings can be the sites for multiple initiation sites for further fatigues

The result of this investigation is used to develop the in-situ methodology of the remaining life estimate of the gear, which will be reported elsewhere.

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