Technical paper

Gear Tooth Flank Flaking Associated with White Etching Area

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Cases of rapid tooth flank damage have recently been sporadically appearing in assembly tests of gears (cylindrical gears and bevel gears) used in construction machinery powertrains. The damage to the tooth flanks has started to be recognized as a new failure mode (called gear flaking with white etching area) in which internal cracks form that are associated with white structure (white etching area). Since gear flaking with white etching area has not been reported in gears operating normally in the market, it is considered to be a phenomenon unique to assembly testing. Its cause has not been explicated. However, it is frequently reported in cases of bearing rolling contact fatigue, which are considered a similar phenomenon. So using the flaking with white etching area found in bearings as a reference, we have aimed to find a solution to the flaking with white etching area found in gears by examining white etching area, studying the generation mechanism and studying the effects of causes in gears.

***Key Words**: Gears, Tooth flank damage, Rolling contact fatigue, White etching area, White structure, Hydrogen embrittlement*

1. Introduction

A large number of gears are used in construction machinery powertrains, and their durability is evaluated by carrying out acceleration tests that operate the equipment continuously and increase the load in states of components such as final drives and axles. Sporadic cases of damage to cylindrical gears and bevel gears subjected to these assembly tests have recently been appearing. The damage consists of rapid and extreme flaking in gear tooth flanks. The designs meet the conventional strength standards and no manufacturing changes have been made, so the reason the damage is occurring so rapidly has not been found, and the reason for its occurrence has not been identifiable.

However, flaking associated with white etching area has frequently been reported in cases of bearing rolling contact fatigue [1] [2], and the failure mode of the recent gear damage has many features in common with the flaking with white etching area found in bearings. The hydrogen embrittlement theory [3] [4] is considered a plausible explanation for the flaking with white etching area of bearing; oil breakdown in sliding surfaces generates hydrogen that penetrates the steel and causes hydrogen embrittlement, resulting in white etching area and internal cracks. So to understand the phenomenon of the flaking with white etching area and study solutions to it, we have examined white etching area, studied the generation mechanism and used basic testing to evaluate the effects of causes thought to affect sliding and hydrogen embrittlement in gears. This paper reports our findings.

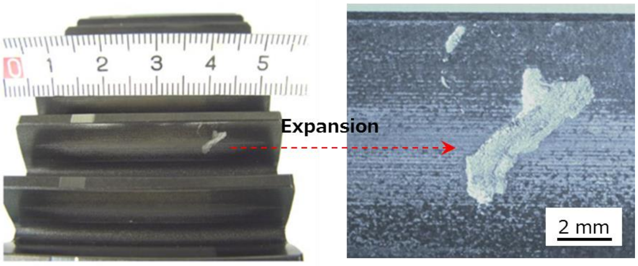
2. Characteristics and Mechanism of Flaking with White Etching Area

2.1. Characteristics of Flaking with White Etching area

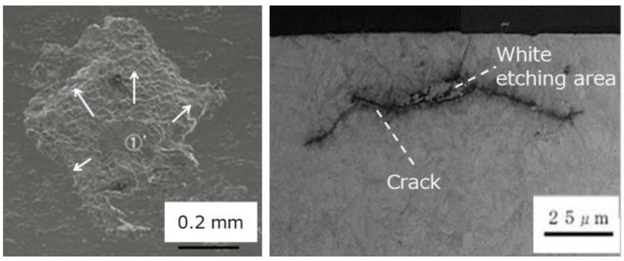
Fig. 1 shows an example of tooth flank flaking associated with white etching area generated during assembly testing. The common type of gear tooth flank damage is pitting failure originating from the surface, but as shown in **Fig. 1** (a), flaking associated with white etching area is a failure mode that is difficult to clearly differentiate from pitting failure by sight. We examined locations of minute flake generation in the same gear to find out where flaking originates from. As shown in **Fig. 1** (b), we found that cracks grew and developed into flaking from disk-shaped surfaces near the centers of fractures. We also examined tooth cross-sections and found multiple white etching areas and cracks generated inside as shown in **Fig. 1** (c). This finding indicates that the flaking originated from white etching area generated inside (tooth flank flaking associated with white etching area). Similarly, we examined white etching areas and cracks in multiple gears, and found the following characteristics:

- Many of the gear white etching area were generated near surface layers with depths of 40 µm or less. These depths were shallower than the depths at which the structures are generated in bearings (100 to 300 µm).
- Some white etching areas in gears were generated with nonmetallic inclusions as their origin.

We then examined white etching areas in gears using a Transmission Electron Microscope (TEM). We examined their crystal structure and found that it exhibits the halo pattern shown in **Fig. 2** (a), and may be an ultramicroscopic crystal with a bcc crystal structure (ferrite structure) periodicity. The white etching areas we found in bearings are also shown for comparison. We found they exhibit the same crystal structure. **Fig. 2** (c) is a photograph of the structure, which are equiaxed crystals of between 10 and 20 nm. We measured their hardness with a Vickers microhardness tester. We found the white etching area had a hardness of about 1,230 HV, while carburized martensite had a value of about 830 HV. This large difference in hardness could have been responsible for generating fatigue cracks at boundaries of white etching area.

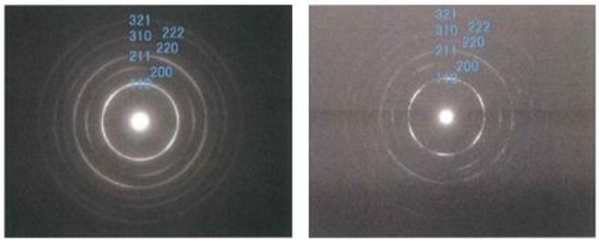


(a) Tooth flank damage (flaking with white etching area)

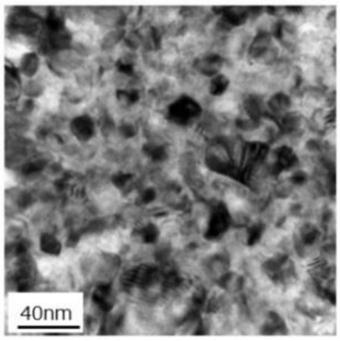


(b) Fractures with minute flaking (c) Internal white etching area and cracks

Fig. 1 Gear flaking with white etching area example



(a) Electron diffraction image of gear white etching area (b) Electron diffraction image of bearing white etching area



(c) Photograph of white etching area

Fig. 2 TEM observations of gear white etching area

2.2. Mechanism of Flaking with White Etching Area

Since we found that white etching areas in gears are the same as the structure found in bearings and are the same rolling contact fatigue phenomenon, the flaking with white etching area found in gears may essentially be the same as the hydrogen embrittlement-based rolling contact fatigue [3] [4] found in bearings. However, white etching areas have been found to have different occurrence depths and modes in gears from those in bearings. This finding may be due to the effects of the different materials, sliding states and stress fields in gears and bearings. Gears are generally used at higher pressures than bearings, and have higher slip factors. Gears also generate friction as they engage. These factors may affect white etching area generation by affecting sliding surface states and the diffusible hydrogen that penetrates the steel. **Fig. 3** illustrates the mechanism thought to be responsible for flaking with white etching area in gears.

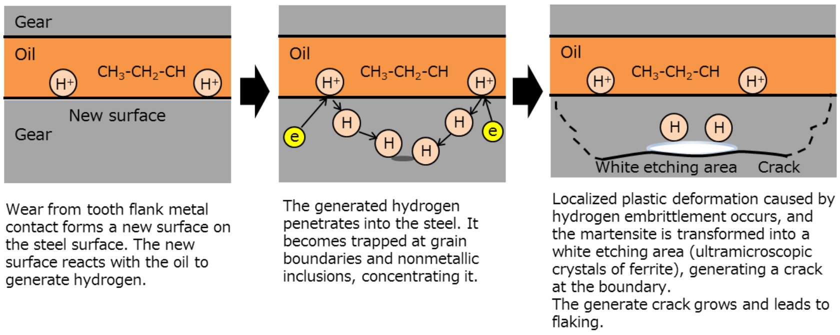


Fig. 3 Mechanism of gear flaking with white etching area

3. Causes Affecting Flaking Associated with White Etching Area

3.1. Causes Existing when Gears Engage

The inferred mechanism for flaking with white etching area indicates that surface pressure, slip factor and vibrations affect generation of white etching area, so we evaluated the effects of these factors on white etching area generation by carrying out power recirculating gear tests and roller pitting tests. Each test was continued until a set number of gear engagements was reached. After testing, the gear and a cylindrical test specimen were cut, and their internal structures were observed to assess whether white etching areas were present.

Fig. 4 shows the results of surface pressure effect evaluated by a gear tester. The results indicate that low surface pressure does not result in white etching area, but white etching areas are generated near the surface as surface pressure increases. Further increasing the surface pressure starts to generate white etching area at deep locations. We also found these surface pressure effects in roller pitting tests done by maintaining a constant slip ratio and varying the surface pressure. Increasing the surface pressure creates a more severe sliding condition, promotes the formation of new surfaces, and promotes the entry of hydrogen into the steel. The penetrating hydrogen may also have been subjected to stress field effects, becoming more easily trapped by grain boundaries and nonmetallic inclusions.

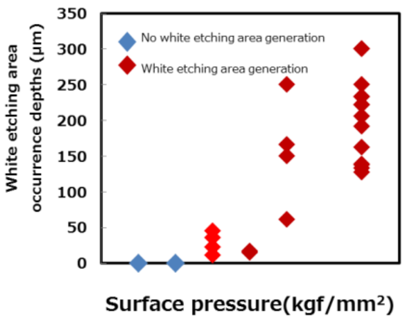


Fig. 4 Effect of surface pressure on white etching area

While bearings roll without slip, the meshing of gears generates a large amount of sliding. To evaluate the effects of this sliding, we conducted roller pitting tests that varied the rotary speed of two cylindrical test specimens to test with different slip factors. The tests used a constant surface pressure for generating white etching area, and varied the slip factor. As shown in **Fig. 5**, we found that increasing the slip factor tended to promote the generation of white etching area. This finding may indicate that increasing the slip factor promoted the formation of new surfaces from sliding, and promoted hydrogen generation.

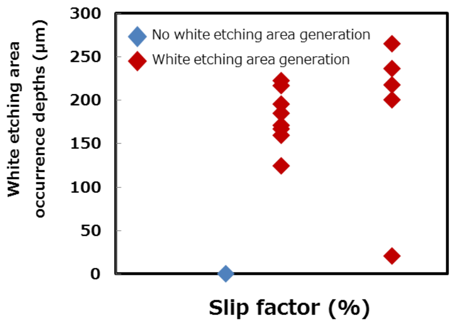


Fig. 5 Effect of slip factor on white etching area

Gear vibrations may affect the generation of white etching area since they change sliding and stress states. To enable changes in vibration magnitude, we used spur gears and helical gears in our gear tests. Acceleration sensors were attached to gear side surfaces to measure gear vibrations directly. Testing was done by measuring vibrations while varying the rotary speed initially, and then subsequently keeping the rotary speed constant. **Fig. 6** shows the test results. We found that helical gears with low vibrations did not generate white etching area, while spur gears with large vibrations were prone to generating white etching area. This finding may indicate that the combined effects of sliding and stress fields generated hydrogen and promoted its accumulation.

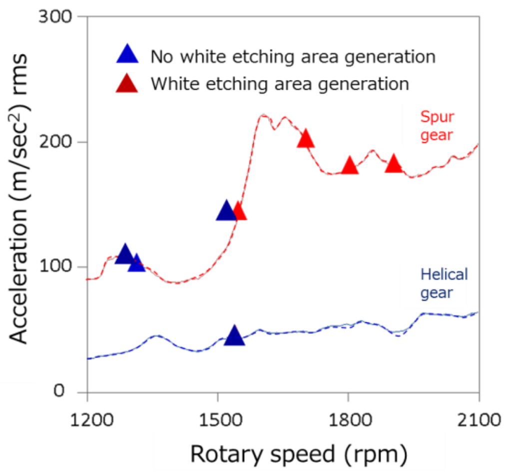


Fig. 6 Effect of vibrations on white etching area

3.2. Lubrication-Related Causes

Differences in oil have reportedly affected flaking with white etching area in bearings [5] [6], so oil components might similarly affect this flaking in gears. We therefore investigated the influence of oil components on the flaking with white etching area in roller pitting tests using two types of oil (Oil A and Oil B). These oils consisted of same type of base oil with a different additive. Slip factor and surface pressure were varied in the tests, and white etching areas were observed after testing. **Fig. 7** shows the white etching area observed. We found that Oil B inhibited the generation of white etching areas more than Oil A under the same test conditions. Since the Oil A and Oil B had equivalent kinematic viscosity, the change in lubrication states due to oil additives may have been the cause of white etching area.

To investigate the difference in lubrication states between Oil A and Oil B, we focused on the behavior of tribofilms generated on surfaces by reactions between oil additives and steel and measured film deposition rate in MTM (Mini Traction Machine). **Fig. 8** (a) shows the result of the Electrical Contact Resistance (ECR*) in each oil, and we can estimate the film deposition rate with ECR. Since metal contact is inhibited as a tribofilm is generated on a sliding surface, ECR changes. **Fig. 8** (b) shows the thickness of the generated tribofilm. As shown, Oil B resulted in faster tribofilm generation than Oil A. This faster tribofilm generation may have restrained hydrogen penetration from new surfaces, which causes white etching area.

*ECR: Indicates the electrical contact resistance ratio. A value of 100% indicates that a tribofilm and oil film have been generated, and the metal surfaces are no longer in contact.

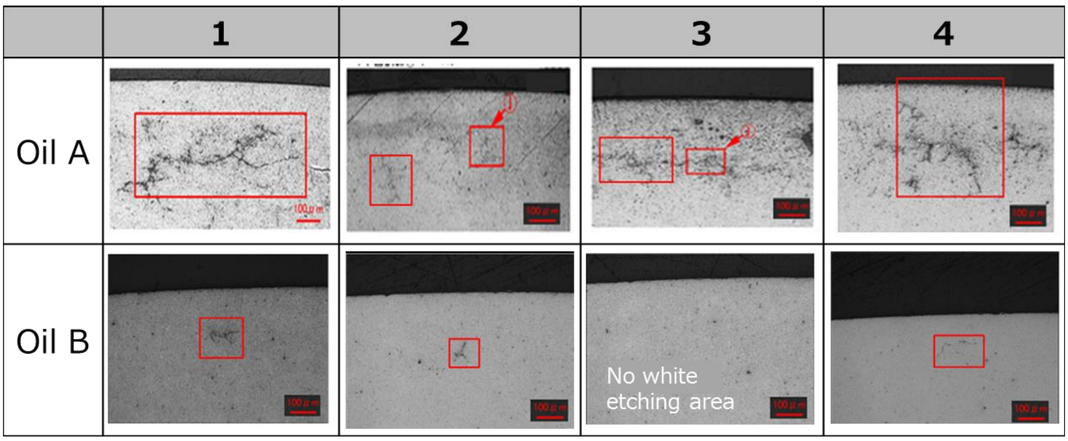
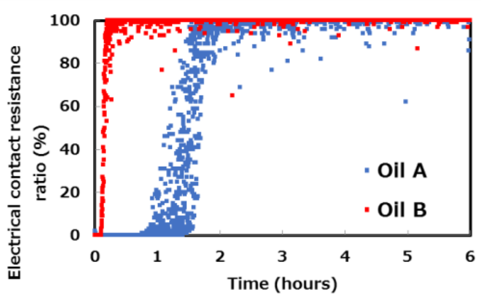
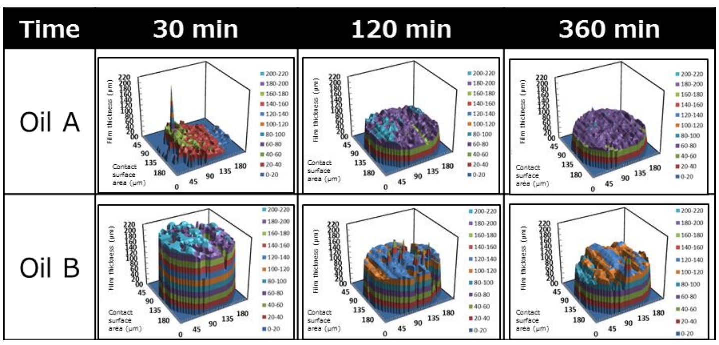


Figure 7 Differences in white etching area generation caused by different oil types



(a) Change in Electrical Contact Resistance (ECR*)



(b) Tribofilm thicknesses

Figure 8 Sliding state changes caused by different oil types

3.3. Operating Condition-Based Causes

If diffusible hydrogen is the cause that generates white etching area, hydrogen will be in a trapped state in stress fields. However, it will diffuse freely if stress is not present, so no further hydrogen embrittlement will occur. The generation of white etching area in bearings is reportedly dependent on hydrogen penetration speed [3], so hydrogen penetration and trapping may greatly affect white etching area. And since flaking with white etching area has not been reported in gears operating normally in the market, the phenomenon in gears may be affected by operating conditions. Construction machinery gears are not in constant operation since the machinery usually combines traveling and working operations, and operators change shifts. We therefore evaluated white etching area generation in FZG gear tests with operating conditions that included temporary shutdowns to simulate market conditions. The tests were conducted in two patterns of alternating operation and shutdown to simulate market operating states. In these tests, conditions other than the operation were made constant. Each test was continued until a set number of gear engagements was reached. **Fig. 9** shows the test results. White etching areas were not generated in any test with operating conditions of alternating operation and shutdown. This finding may indicate that hydrogen was diffused by the shutdowns before white etching area could be generated from the concentration of the hydrogen that had been generated and trapped in the steel as the result of operation [5]. White etching areas were therefore not generated.

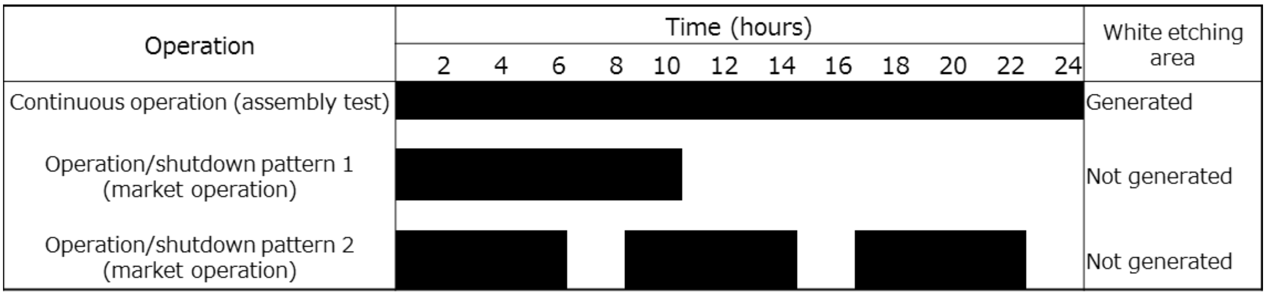


Fig. 9 Effect of operating conditions on white etching area

4. Conclusion

Tooth flank flaking with white etching area is a phenomenon that has been generated in gear assembly tests. We studied this phenomenon by evaluating white etching area composition and a mechanism specific to gear engagement using fatigue tests and sliding tests. The findings we obtained point to the rolling contact fatigue caused by hydrogen embrittlement that can be described by the behavior of hydrogen and is essentially the same as the white etching area reported in bearings. Flaking with white etching area in gears may be the result of tooth flank flaking caused by oil decomposition in sliding surfaces from gear engagement, penetration of hydrogen into the steel, trapping and concentrating of hydrogen at grain boundaries and nonmetallic inclusions, transformation of hydrogen into white etching area through hydrogen embrittlement, and crack formation and growth.

1. We found that many white etching areas in gear were generated in association with cracks near surface layers of no more than 40 μm in depth, and that some white etching areas were generated with nonmetallic inclusions as their origin. The white etching areas were ultramicroscopic ferrite structure of equiaxed crystals.
2. White etching area generation starts near the surface as the surface pressure increases and starts at deep locations when surface pressure is increased further, indicating that it is affected by stress fields.
3. We found that increasing the slip factor tends to promote white etching area generation. This finding may indicate that formation of new surfaces in sliding surfaces promoted hydrogen generation.
4. We found that large gear meshing vibrations tended to promote white etching area generation. This finding may indicate that both sliding and stress fields generated hydrogen and promoted its accumulation.
5. We found that different oil additives caused different white etching area generation states. This finding may indicate that the tribofilms generated by the oil additives were generated at different speeds, and affected the penetration of hydrogen into the steel.
6. Under conditions that generate white etching area in a state of continuous operation, white etching areas were less likely to be generated when operation and shutdown were alternated. This finding may indicate that hydrogen diffused during the shutdown periods, thereby inhibiting white etching area generation.

References

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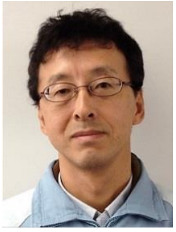
[All sources are in Japanese.]

Introduction of the authors



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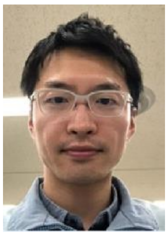

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[A comment from the authors]

While hydrogen embrittlement may be the cause of flaking on gear tooth flanks associated with white etching area, it is difficult to directly interpret the behavior of the diffusible hydrogen that causes hydrogen embrittlement, so this report has been limited to understanding the phenomena and evaluating the causes. In future we would like to work on solving this difficult damage issue by working in collaboration with related Komatsu departments and through joint research with outside research organizations to enable the explication of hydrogen behaviors and the creation of effective solutions.

This study received guidance from former Toyohashi University of Technology Professor Minoru Umemoto, and extensive assistance from Kazuhiko Hiraoka of Sanyo Special Steel Co. We would like to express our sincere appreciation here.