White Etching Areas on Case-Hardened Gears

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Abstract:

The phenomenon of white layers, which arises from high stress, can be observed under a microscope after the white layers have been treated with a weak nitric acid solution. Their occurrences in zones of high shear stress can provide qualitatively valuable indications of the size and direction of the stress, and they can point out possible starting points for flank damage. An investigation of this phenomenon is described.

Introduction

It is known that on the surface and just under the surface of rolling elements of hardened steels, so called "white layers" can be observed. This phenomenon, also called "white etching areas (WEA)," arises from high stress. These white etching areas are structured zones which are affected when etched with diluted nitric acid and which then form a light contrast with the matrix when observed with a microscope.

In References 1, 2, 6, 7, 10, 12 and 13, the different forms of appearances have been described and their appearances in connection with the actual stress have been analyzed. In the same way, the structure of these structured zones can be regarded as known to a large degree. The conditions for the appearance of WEA on the surface are high friction and/or impact stress; whereas, WEA were observed beneath the functioning surface only in elements which were at the same time exposed to strong hydrostatic pressure and a shear stress.[10] In the cited reference, the origin of WEA beneath the surface resulted because the presence of a mechanical thermodynamic state induced such high tensions, that in the areas, the shear resistance of the material had been exceeded. The flanks of the crack which run in the direction of the greatest shear stress are heated to the melting temperature in an extremely short time because of the plastic deformation of the structure. In this process the carbides dissolve and the carbon enters the gamma-matrix. After self-cooling, because of the surrounding structures with considerably lower termperatures, we get a highly over-saturated martensite.

Until now the investigations of WEA phenomena have been carried out largely with rolling element bearings. It is known that rolling element bearings are exposed to substantially higher Hertzian pressure than gears under similar conditions. This is probably why the occurrence of white etching areas on gears has so far been noticed in only a few cases, and it is still not clear whether WEA can be regarded as a cause of flank damage. This article will describe further some forms of occurrences of WEA on the highly stressed flanks of case-hardened gears. In addition, we will discuss whether there is a connection with fatigue failures.

This research is based on a number of operating tests with case-hardened gears for the investigations of pitting resistance, which have also been subsequently analyzed through metallographic investigations*. It is, therefore, not the purpose of this article to analyze the microstructure and triggering mechanism of WEA (We refer here rather to the abundance of existing literature), but we will investigate the occurrence of WEA in connection with the stress of the tooth flanks and the consequences of it.

*All operating tests and metallographic investigations were performed at the Gear Research Laboratory (FZG) of the Technical University of Munich, West Germany.

White Etching Areas in the Area of the Tooth Flank. Material Fatigue on Non-metallic Inclusions Beneath the Surface

The sliding-rolling motion under high Hertzian stress in the contact of two mating tooth flanks leads to a three-axis-pressure-stress state, which is superimposed by a shear stress resulting from the friction load. The main shear stress, which can be regarded as the cause of the crack[6,11] has, with ideal geometrical bodies, a path to the depth, as shown in Fig. 1.

According to investigations of References 4 and 5, micro-Hertzian fields of tension are formed on machined surfaces due to previous damage as well as scratches and roughness. These fields of tension lead to paths of tension that are different from those that should be taken in an ideal geometrical body. In Fig. 1, the path of the main shear tension for a rectangular notch with a depth of 0.1 b_H and a length of 0.2 b_H has been added. According to this, the main shear stress directly beneath the surface is considerably greater than the maximum, which follows the current hypothesis about the endurance. When reaching a depth of 0.5 b_H the influence of the surface roughness has decreased. After that depth, the path of the tension follows the pattern of the Hertzian pressure distribution on the ideally smooth surface. In this area the main shear stress is directed against the surface just under 45°. In addition to this, in the area of non-metallic inclusions peaks of tension occur, as pointed out in Fig. 2, which can lead to localized exceeding of the allowable shear. (See References 3 and 4.)

The calculation derived from Fig. 2 is confirmed by Fig. 3. An oxidation inclusion, whose E-modulus is about two times as large as for steel, lies in the area of the inner point of single contact, about 0.14 mm below the surface of the flank in the area of high main shear stress. (See Fig. 1.) In an undisturbed structure, the main shear tension did not reach a value which would be critical for a case-hardened steel. However, the approximate 2.5-fold increase in tension due to the inclusion (compare Fig. 2) led to the occurrence of cracks and WEA, which, in accordance with the path of main shear stress, are approximately 45° with respect to the surface. The gear data and the operating conditions for this experiment are listed in Table 1.

In different publications, for example, References 6 and 10, an increase of WEA in connection with a greater number of revolutions has been noticed. This leads to the conclusion that also with non-metallic inclusions, WEA do not appear immediately after the first stress cycle. They only occur after a certain period of stress due to plastic deformation which causes change in the state of the residual stress. Possibly the crack expands very quickly once a critical state of deformation is reached, and the crack travels in its environment to temperature regions which are above melting temperature. (See Reference 10.) The high impact stress that occurs with roller element bearings can apparently also be reached locally with gears. In Reference 6, it is noted that a minimum impact stress of $\tau_{45} = 725$ n/mm² (105,200lb/in²), at the inner ring of a roller element bearing, leads to the occurrence of WEA. Also, with case-hardened gears, the main impact stress of this dimension can occur in the area of inclusions.

The cracks which occur on non-metallic inclusions below the surface of case-hardened gear flanks generally extend very little. So far, it has not been proven whether they extend to the surface and cause damage at the flank.

The strictly local limitation of WEA to non-metallic inclusions and the connection with the relation (E inclusion/E steel) become apparent in the example of sulfur content in case-hardened gears made of *(continued on page 22)*

Table 1
Gear Data and Operating Conditions

Module (Diametral Pitch)
m = 5mm (5.08/in.)
Number of teeth (1 = Pinion/ 2 = gear)
$z_1/z_2 = 17/18$
Face width
b = 16mm (0.63 in.)
Center distance
a = 91.5mm (3.60 in.)
Torque
M = 360Nm (265 ft-lb)
K − factor
K = 12.1 N/mm² (1650 psi)
Hertzian Pressure at rolling point C
Pc = 1440 N/mm
Revolutions of the driving pinion
$n = 3000\ min^{-1}$

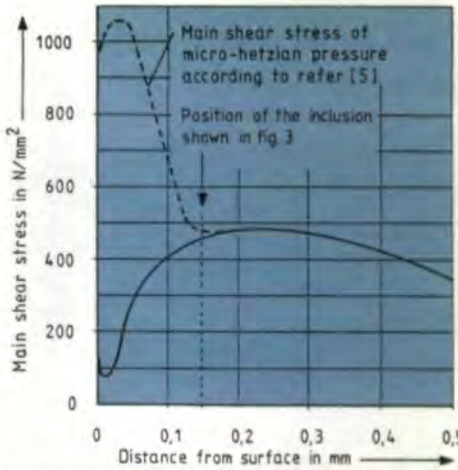

Fig. 1 – The path of the main shear stress into the depth with over laying of the Hertzian pressure and friction stress on a tooth flank. (See Table 1.)

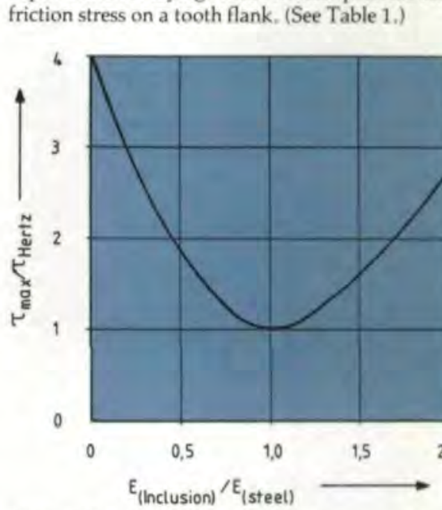

Fig. 2 – The increase in tension in the surroundings of non-metallic inclusions in the process of overrunning bearing steel 100 Cr 6. Reference 3: Findings from optical tension model tests in simulating the stress distribution on a contact line of a ball bearing inner ring 6309 for F_r = 19200 N radial load.

Fig. 3 – WEA starting from an oxide inclusion beneath the flank surface of a case-hardened gear of 16 Mn Cr 5.

16MnCr5 (See Table 2), with globularly formed sulfide inclusions in which a great number of very small WEA can be noticed in the area of high impact stress. These WEA result exclusively from inclusions; whereas, such occurrences cannot be found with long strips of manganese sulfide. Globular sulfides are harder than manganese sulfides due to combination with the sulfide influencing elements. The cracks that have been examined are never longer than some μ m and never have connection to the surface. (See Fig. 4.) The inclusions themselves are spread out very finely.

The Stress of the Gear Flank at the Beginning of Contact

It is a fact that WEA frequently occur in surface areas which are exposed to strong shock stress. In highly stressed gear pairs, the gear teeth that are in contact are deformed, so that the following gear tooth tip strikes against the flank of the driving pinion in the area of the gear tooth root too early. (See Reference 8.) This leads to an impact shock. Shown in Fig. 5 is the tooth stretching signal of the driving pinion under the conditions described in Table 1, which shows a very steep increase at the beginning of contact which points out a very high shock-type stress at the beginning of contact.

Metallographical examinations show that the greatest number of and the most prominent WEA could be found in this area. (See Fig. 6.)

Fig. 7 shows WEA at the surface which have occurred due to high stress caused by the impact shock. Their extension in depth is between 30 and 50μm. Beneath the surface, the WEA are limited by a crack which runs almost parallel to the surface. Due to the contact shock, there occurs locally high pressure as well as strong friction forces, because of which the flank surface is exposed to an extreme shear stress in this area. Shown in Fig. 8 is the path and the direction of the main shear stress relative to the local pressure on the flank for two friction values as a function of depth from the surface.

Only with increasing depth does the direction of the main shear stress come closer to an angle of 45° relative to the sur-

Table 2
Material and Heat Treatment

Chemical Composition

C: 0.16%
Si: 0.29%
Mn: 1.12%
P: 0.015%
S: 0.015%
Cr: 0.92%
Al: 0.026%

Heat Treatment

Carbonizing
940° C/3 hours/Carbon-Level 1.1
940° C/3 hours/Carbon-Level 0.8
830° C/1 hour/Carbon-Level 0.8

Hardened: Oil 60° C

Tempered: 180° for 3 hours

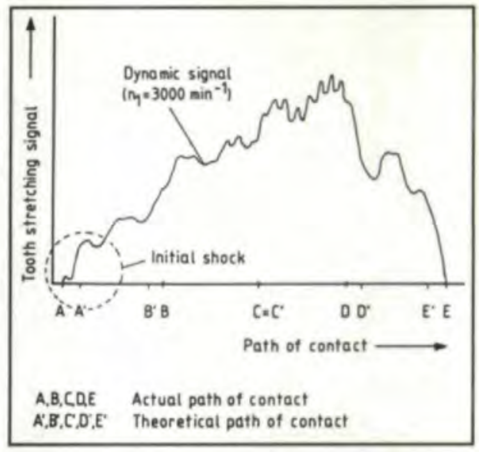

Fig. 5 – Tooth stretching signal in root of the pinion over the length of gear contact. (See Table 1.)

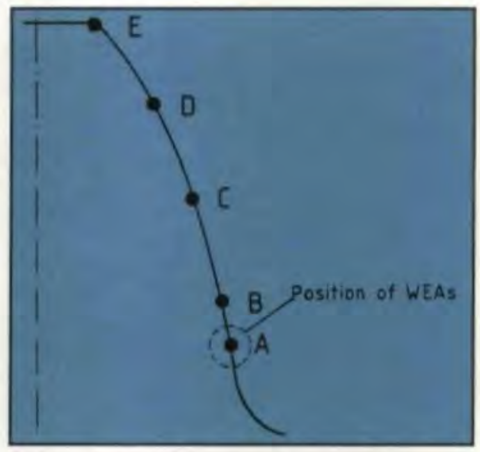

Fig. 6 – Position of the white etching areas in the area of the beginning of contact on the flank of the driving pinion.

Fig. 4 – White etching areas at globular form sulfide inclusions beneath the flank surface.

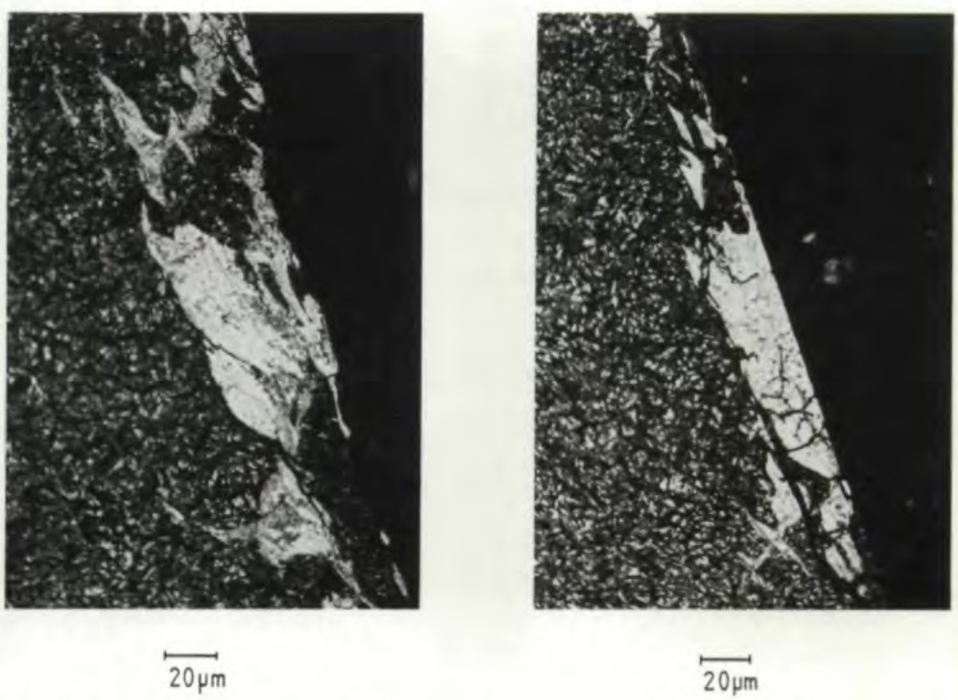

Fig. 7 – White etching areas in the area of the beginning of contact on the surface of a case-hardened pinion made of 16 Mn Cr 5.

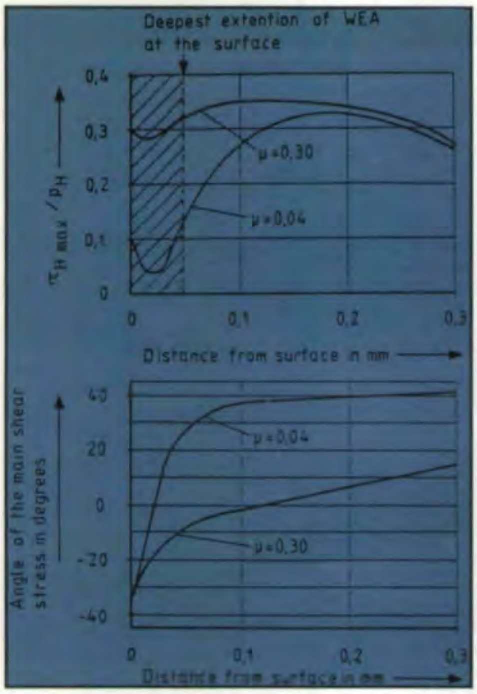

Fig. 8 – The path and the direction of the main impact stress for two different friction values.

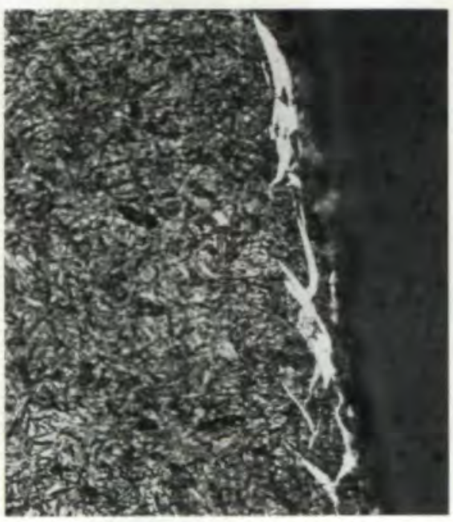

Fig. 9 – White etching area in the area of the surface in the direction of the main shear stress.

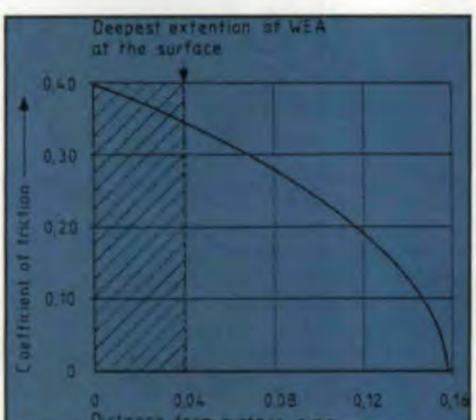

Fig. 10 – Location of the maximum impact stress with $P_H = 1440\ N/mm^2$ $b_H = 0.20mm$ in relation to the friction value.

face. Correspondingly, the angles of the WEA change as is pointed out in Fig. 9.

The position of the main shear stress minimum depends on the magnitude of the coefficient of friction. As shown in Fig. 10 from $\mu = 0.40$ onwards, the maximum main shear stress lies at the surface. As friction stress increases, the point at which the direction of the main shear stress reaches the 45° limit can be found as it travels deeper.

This connection, again, is valid only for ideal geometrical bodies. Since tooth flanks can be considered as technical surfaces, we have to take also into account the tension-increasing effect of the notches directly in the area of the impact shock beneath the surface according to Reference 5. (See Fig. 1.) Also favoring the formation of WEA is the local flash temperature, which again is largely dependent on friction value.

Caused by the effects of running-in, the

(continued on page 36)

stress in the area of the beginning of contact decreases with an increasing number of stress cycles. It can therefore be expected that the WEA would occur at this spot following a comparatively short amount of time.

Specific Characteristics of the Examined White Etching Areas

Structure and the composition of WEA have been metallographically examined on a broad basis in various research tests. The findings with case-hardened gears are largely in agreement with the aforementioned research. According to our measurements on our sample, the microhardness of the WEA at the surface is based on an average of 1200 HV_1, clearly higher than that of the surrounding matrix with about 850HV_1.

The WEA at the surface examined on the light electron microscope show a partly porous structure which points to a tempering process. (See Fig. 11.) Also, with the light microscope, regions of a darker color can be seen within the WEA. It is still unclear whether within the surface near the WEA, as shown in Fig. 12, such high temperatures can occur that can temper the

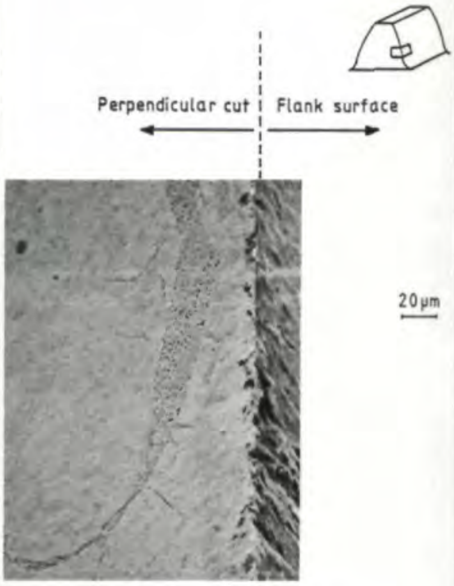

Fig. 11 – Porous structure in the surface area of a gear flank.

Fig. 12 – Partly tempered WEA at the flank surface.

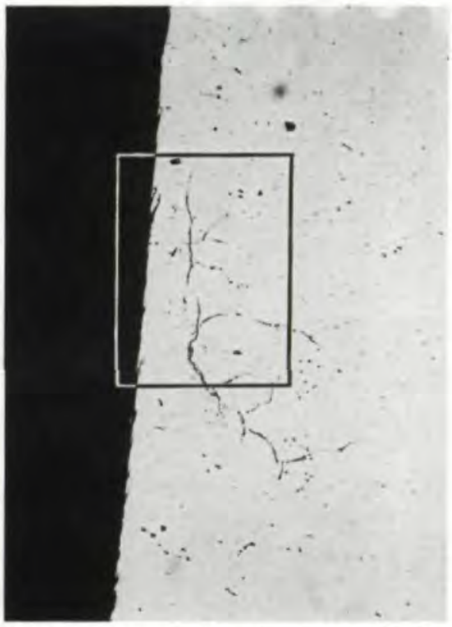

Fig. 13a – Crack near the surface (unetched slide).

Fig. 13b – View magnification of the crack shown in Fig. 13a that is bordered with white etching area. (Etched with HNO_3.)

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WEA structure.[10]

As a condition for the formation of WEA under high stress, we must also consider the initial structure and the heat treatment of the steel which influences the distribution of the carbides.[11] The more even the carbides are spread out, the better conditions are for the formation of WEA. Table 2 lists the heat-treatment data for the examined gears.

Possible Connection Between White Etching Areas and Flank Damage

Fig. 13a shows a crack beneath the surface of a tooth flank on an unetched slide. Fig. 13b shows the crack at the HNO_3 – etched slide in an area magnification.

The fact that the crack is bounded with WEA, in accordance with the theory described in Reference 10, points to a very high crack propagation. The question whether the crack has a connection to the surface cannot be answered by just a single plane of a cut; however, we have to assume that such cracks can lead to pitting. Figs. 14 and 15 show slides of tooth flanks of a driving pinion with white etching areas near the beginning of contact and a frontal view of the damaged flank.

On both pictures, the lower part of the flank is characterized by strong fatigue scratches and pores due to the high stress of the impact shock. Starting in this zone, pitting stretches out in the negative slippage area which caused the failure of the pinion.

The WEA that are shown as a light electron microscopical picture lie directly on the surface. (See Fig. 16.) In the right half of the picture the strongly fatigued tooth flank around the WEA can be discerned.

Based on the theory in Reference 10 about the formation of WEA, there is the following connection between WEA and flank damage in case-hardened gears.

At hard, non-metallic inclusions, high shear stresses that lead to the formation of limited cracks can occur locally. If the inclusions lie deeply, the crack does not extend to the surface, but it can favor an outbreak of pitting by growing together with a crack originating at the surface. It cannot, however, be regarded as the cause of the pitting. Inclusions below the surface certainly do not primarily have an influence on flank damage.

In zones of high stress, for example at the beginning of contact, WEA occur at the surface due to strong friction and high flash temperature. Simultaneously, high shear stresses lead to the formation of cracks from which pores and, later on, pitting may arise. In this case WEA cannot definitely be seen as the cause of the large pittings. Rather, WEA are an indicator for the occurrence of high shear stress. Thus, as an example, they allow for the conclusion of high friction values at the beginning of contact.

Obviously, the material composition and the state of the structure are the criteria for the formation of WEA. A case-hardened outer layer with fine carbide distribution, as could be found in the examined gears, seems to favor the formation of white etching areas.

Conclusion

In this essay the phenomenon of white etching areas on the flanks of highly stressed case-hardened gears has been described. It can be assumed that WEA are not the cause of fatigue damage on tooth flanks. Their occurrences in zones of high shear stresses, however, can provide qualitatively valuable indications of the

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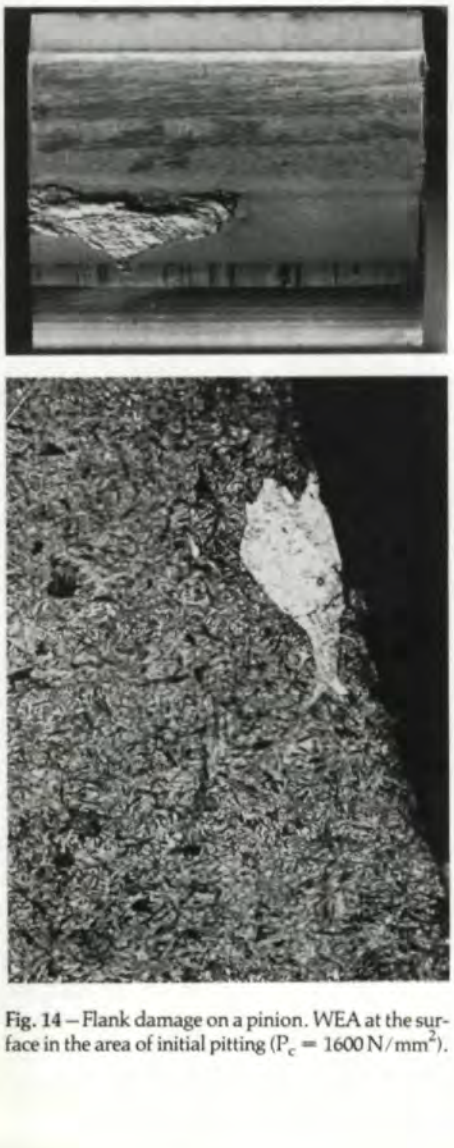

Fig. 14 – Flank damage on a pinion. WEA at the surface in the area of initial pitting (P_c = 1600 N/mm^2).

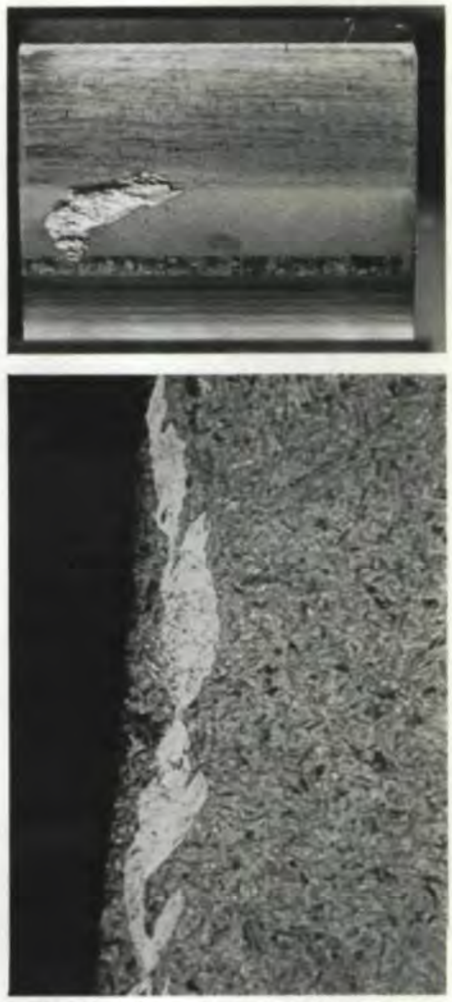

Fig. 15 – Flank damage on the pinion WEA at the surface in the area of initial pitting. (P_c = 1560 N/mm$_2$).

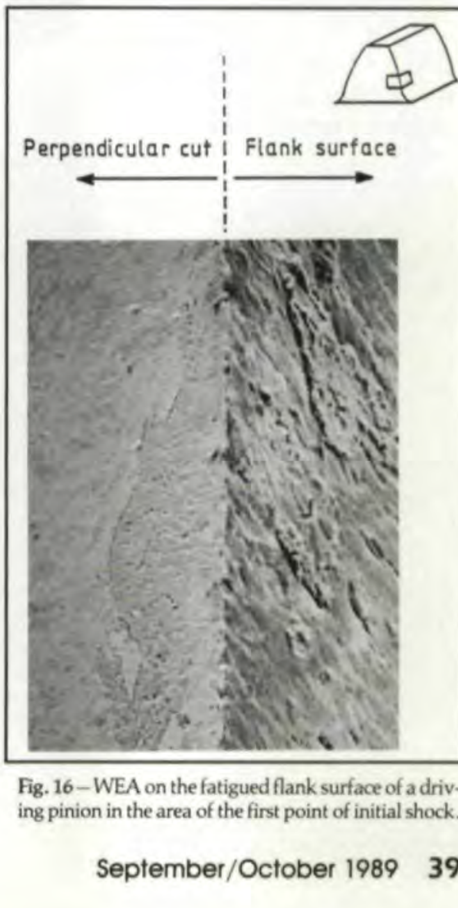

Fig. 16 – WEA on the fatigued flank surface of a driving pinion in the area of the first point of initial shock.

WHITE ETCHING AREAS . . .
(continued from page 39)

size and direction of the stress, and they can point out possible starting points for flank damage.

In order to come to a quantitative conclusion about the definite connection between calculated paths of tension and the formation and direction of WEA on the tooth flanks, a further analysis must examine the influence of residual stress, which, especially at the surface, must not be neglected.

It is also unclear whether the temperatures that locally occur at the flanks can cause a tempering process, and, thereby, the decay of the WEA structure over a longer time.

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