Metallurgical Investigation of "Tiger Stripes" on a Carburized High Speed Pinion

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"Tiger stripes" on a high-speed pinion made of a carburized SAE 9310 steel were investigated. The morphology of the damage was typical of electric discharge damage. The cause of the stripes and potential damage to the gear tooth were analyzed and are presented in this report.

Introduction

There are many gear failure modes, depending on the material and related strengthening and/or hardening processing, working condition (power, speed and load) and environment (temperature, lubrication, corrosion, etc.). It is important to identify the failure mode in order to take necessary measures to mitigate it or to prevent it from occurring.

Among the various failure modes, electric discharge is a common one. It is caused by electric arc discharge across the oil film between mating gear teeth. This discharge may produce temperature high enough to locally melt the gear tooth surface (Ref. 1). Electric discharge also causes bearing failures. It has been reported (Ref. 2) that electric discharge pits initiated spalling on a bearing, which in turn created vibration and overheating, which ultimately led to fatigue failure of the bearing.

The electric current typically originates from electric motors — especially variable frequency drives (VFDs) — sources of rapidly switching electric currents such as electric clutches, or accumulation of static charge and subsequent discharge. Accordingly, this can be prevented by providing adequate electrical insulation or grounding.

To the unaided eye, a surface damaged by electric discharge appears as an arc burn, i.e., similar to a spot weld. The density of the spots on the affected surface increases with the increase of the electric current intensity. On a microscopic level, small hemispherical craters can be observed. The edges of the crater are smooth, and they may be surrounded by burned or fused metal in the form of rounded particles that were once molten.

ANSI/AGMA 1010-E95 includes some macro- and micrographs showing the morphology of this failure mode. However, it does not mention any other surface appearance or property change. This paper introduces a specific appearance of electric discharge — tiger stripes — on a high-speed pinion made of carburized SAE 9310 steel. Morphology characterization was performed by means of scanning electron microscopy (SEM). The hardness profile across the carburized case depth was measured with a microhardness tester to reveal the damage due to electric discharge.

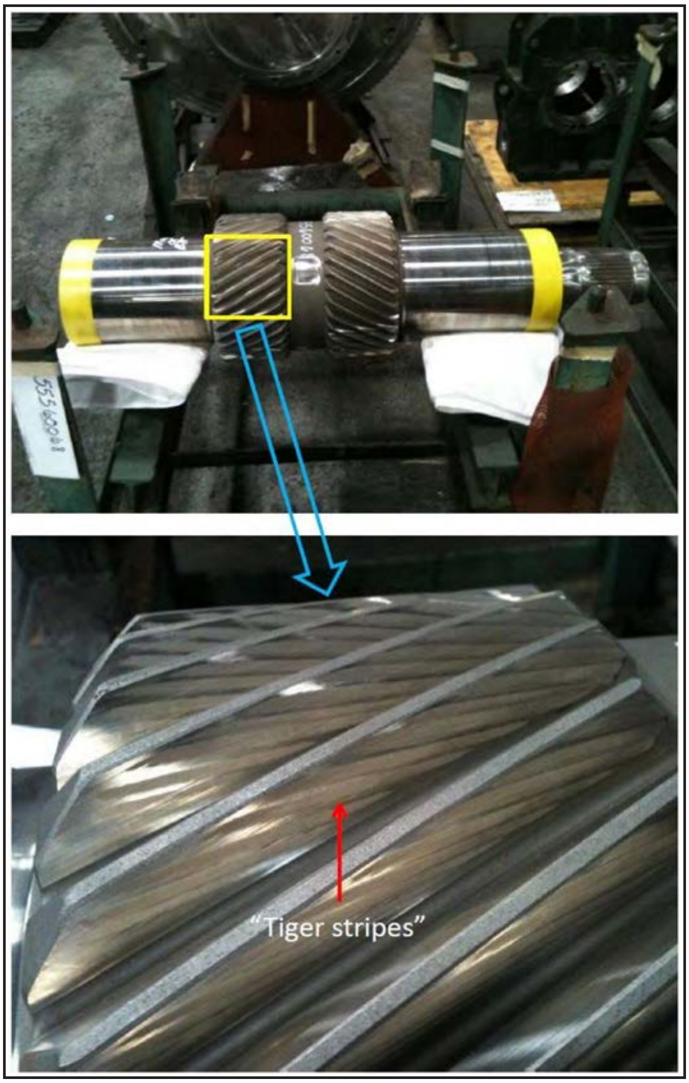

Figure 1 Tiger stripes on the pinion.

Application, Chemistry and Material Tensile Properties

The application is a speed increaser gearbox with a 4.735:1 ratio driven by an 1,800 rpm VFD electric motor and driving a centrifugal compressor. The

Table 1 Chemistry of the sample, wt. %

Chemistry	C	Si	Mn	Cr	Mo	Ni	S	P
Sample	0.14	0.26	0.66	1.32	0.12	3.28	0.011	0.007
SAE 9310	0.07 0.13	0.15 0.35	0.40 0.70	1.00 1.45	0.08 0.15	2.95 3.55	0.040 max	0.030 max

Table 2 Mechanical properties of the samples

	Ultimate tensile strength, psi	Yield strength, psi	Elongation, %	Area reduction, %
Sample 1	148,300	107,500	17.7	58.1
Sample 2	148,700	110,700	16.8	58.3

high-speed pinion has 34 teeth and a normal diametral pitch of four.

A sample of material was cut from the pinion shaft and analyzed using a mass spectrometer. The results of the analysis are shown (Table 1) along with ranges specified for SAE 9310 steel. It shows that the carbon content is a little high, but all other elements are within specification.

Two tensile test specimens were prepared from the pinion shaft, and the measured mechanical properties are shown (Table 2).

The manufacturing records show that the surface hardness of the pinion teeth is 59-60 HRC, with 10% retained austenite and dispersed carbides.

Visual Examination

Figure 1 shows the tiger stripes on the pinion. These stripes appeared to be along lines of contact of one (load) side of the pinion teeth and distributed at different rotational positions of the pinion. Also, it was noted that the tiger stripes occurred on the pinion only; the mating gear didn't show any stripes.

Microstructure Investigation

One pinion tooth was cut for morphological characterization by scanning electron microscopy (SEM) (Fig. 2).

The SEM showed clearly that each stripe was composed of a high density of craters (Fig. 2c). Under higher magnification it revealed these craters were caused by electric discharge, indicated by the typical fused metal particles and gas pockets (Figs. 2d and 2e). The particles were about 1-3 micron in diameter. For comparison, Figure 3f is cited from ANSI/AGMA 1010-E95

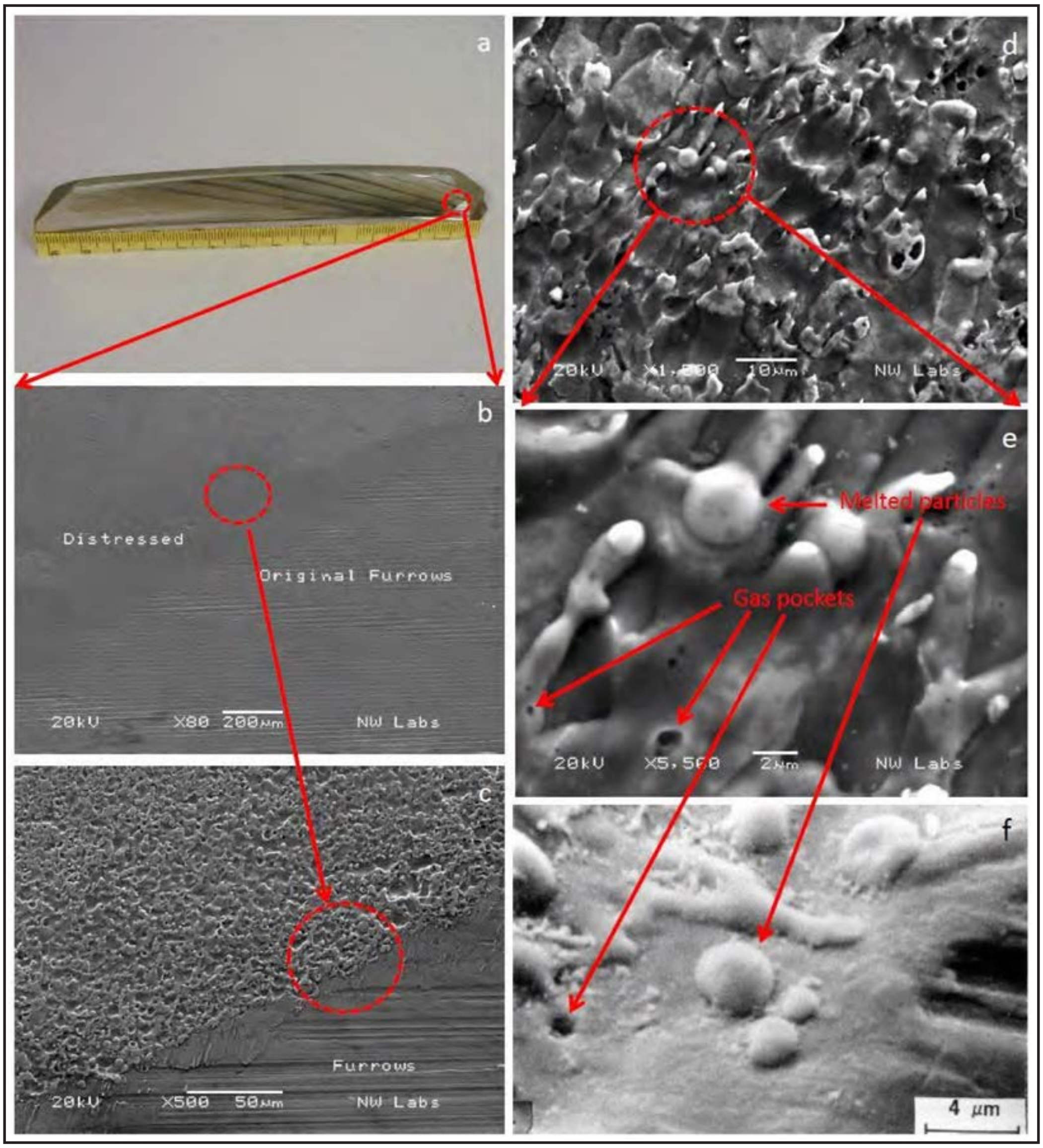

Figure 2 Morphology of tiger stripes revealing electric discharge: a – e were taken from the sample; f is cited from ANSI/AGMA 1010-E95. Note they are under different magnifications, as indicated by scale bars.

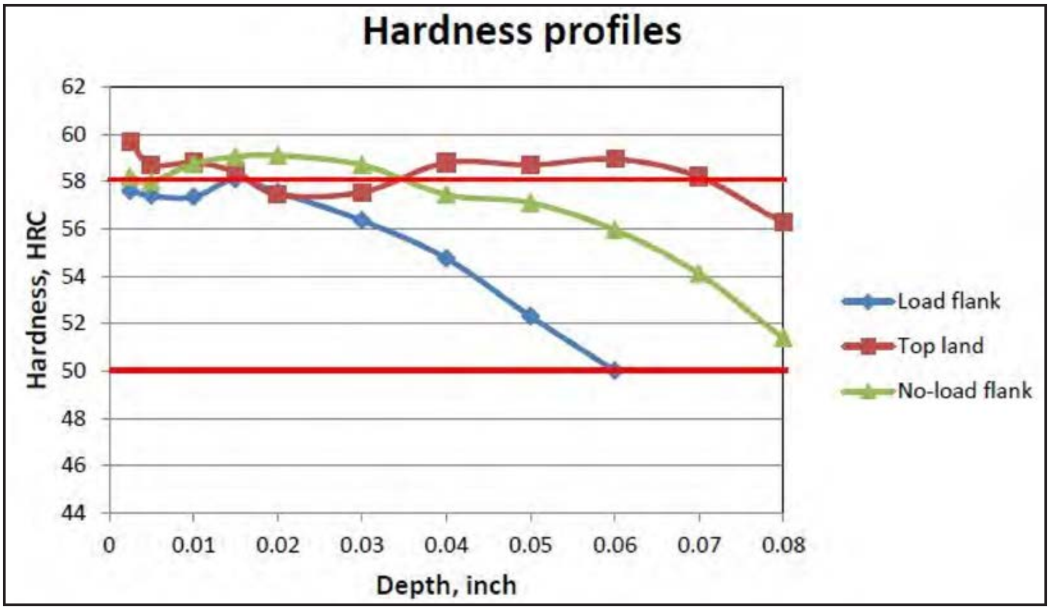

Figure 3 Case hardness profiles of the pinion tooth.

as an example of electric discharge. Figures 2b and 2c show the original machining marks outside of the tiger stripes.

Hardness Profile

In order to evaluate the extent of damage caused by electric discharge, one pinion tooth was sectioned for microhardness profile checks across the gear flanks (load and no-load sides), and the top land from the surface to the hardened case depth (Fig. 3).

The load flank hardness profile revealed that although the depth between the surface and the location where the hardness number is 50 HRC reached 0.060" and is deeper than the specified minimum effective case depth (in this case 0.036"), both the load flank and top land lost some hardness below the surface due to the tiger stripes — especially on the load flank of the teeth. For example, the hardness was only 57.6 HRC on the load flank surface, which is lower than the required minimum 58 HRC. This made the pinion soft and lowered its contact fatigue resistance. As a matter of fact, except at 0.015", its hardness is lower than 58 HRC at any other depth. Even the top land showed some degree of hardness drop. The tiger stripes had the least negative influence on the no-load flank of the pinion teeth. Since the original manufacturing records show that the surface hardness on any flank of the pinion was 59 - 60 HRC, the hardness loss of the inspected pinion was due to the tiger stripes; i.e., electric discharge.

Discussion

The chemical analysis confirmed the material is SAE 9310 carburizing steel. Mechanical properties were in the normal range.

The hardness profiles exhibited hardness loss due to the tiger stripes. The load flank surface hardness was even lower than 58 HRC, the minimum hardness required by the AGMA standard. SEM analysis revealed that these stripes were electric discharge defects. The electric discharge generated very high local temperature and local melting of the pinion teeth. As a result, some areas of the pinion were re-tempered at high temperature. This gave rise to lowered hardness and jeopardized the contact fatigue resistance. Furthermore, as the surface hardness is lower than 58 HRC, the original gear rating is not valid. It is recommended that a new pinion should be manufactured to replace this damaged one if the user wants to keep the initial rating.

It should be noted that this tiger stripe pattern is different from normal electric discharge. While the latter shows random spots on the gear tooth, tiger stripe takes on regular patterns. Obviously, these stripes came from periodic discharge between the mating flanks. Although some composite bearings have been introduced to minimize this type of damage, proper operating grounding such as brushes is still considered to be the best solution to prevent this from happening (Ref. 3).

Conclusions

- The steel for this pinion was confirmed to be SAE 9310.
- Tensile test showed its mechanical properties met the requirements.
- SEM analysis confirmed the tiger stripes are electric discharge damage.
- It generated high temperature and locally melted the pinion surface, giving rise to low surface hardness.

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Rainer Eckert is a forensic engineer and director of the metallurgical services department for Northwest Laboratories in Seattle, WA. In that role he has conducted several thousand failure analyses of industrial components and has served as an expert witness in several hundred court cases. Eckert has also assisted manufacturers in basic research, design improvement, quality control, and root cause failure analysis. His expertise also extends to wind turbines, thus he serves as Northwest Labs' technical advisor to domestic and international wind turbine manufacturers. Eckert holds a BS in science and engineering (1983) from the Technical University of Berlin; a BS of science and engineering in welding engineering (1983) from the Welding Institute of Berlin; and a Masters of science and engineering in materials science (1985) from the University of Pennsylvania. As a graduate research assistant there, he studied monotonic and cyclic fracture (fatigue) behavior of various copper alloys by means of optical microscopy, scanning electron microscopy (SEM) and auger spectroscopy. He has authored a number of technical papers for various associations such as AGMA and STLE. And finally, and of equal importance, Eckert is one damned good auto mechanic.

Prior to his recent retirement, **Phil Terry** was chief metallurgist for Lufkin Industries, responsible for the direction of materials technology across the company, covering the Power Transmission and Oil Field Divisions in the U.S. and their various overseas facilities. He graduated with a degree in metallurgy from the University of Aston in Birmingham, England, and continued academic research in the field of fracture mechanics before receiving his Ph.D. in 1972. Terry worked for the United Kingdom Atomic Energy Authority (UKAEA) on the UK Prototype Fast Reactor program and the installation of the first UK Pressurized Water Reactor. He joined Houston-based oil company Cameron at their Leeds, UK facility and held several positions, including chief engineer R&D, technical manager, and director of central services. Terry has served as Chair of the Leeds Engineering Initiative NGO and continues to work with TWI and BSI standards development. Terry is also a member of the Institute of Minerals, Materials and Mining; a Fellow of the Institute of Mechanical Engineers; a Chartered Professional Engineer; and a member of the American Gear Manufacturers Association, serving in various capacities and on several committees. He has presented numerous technical papers and taught courses on metallurgy and material related subjects in Europe, the Middle East and U.S.

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