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A PHENOMENOLOGICAL APPROACH TO WEAR DEBRIS ANALYSIS

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Abstract: In wear debris analysis, phenomenological observation and characterization of wear debris can be systematically exercised to offer clues about the underlying wearing conditions. While there is terminology which describes phenomena occurring in worn surfaces and subsurfaces, phenomenological observations of wear debris have not been coined in technical terms. In this paper, the concept of wear debris phenomena is proposed to ascertain the phenomenological aspect of wear debris analysis. Two terms are defined to describe phenomena which can occur in relation to wear debris: cutting and severe sliding. An extended classification of wear is made to accommodate wear debris phenomena.

Key Words: Ferrography; oil analysis; wear debris analysis

Introduction: Wear debris analysis is an important subject in maintenance, especially condition based maintenance. It represents one of the very limited ways by which the wear life of mechanical components can be predicted without significant interference with machinery operation. In wear debris analysis, a broad spectrum of techniques is applied to extract information. Among these, optical examination of wear debris has long been used as an effective method to find clues to the progress of wear that occurs in machinery. Its origin as a diagnostic tool can be traced to Ferrography developed in the early 1970's. Westcott and Seifert [1] state the heart and soul of Ferrography, or optical debris monitoring, as follows.

> *The key to Ferrography or optical examination of wear debris is to find marks or features on wear debris which suggest likely wearing conditions from which they were generated. When changes in wear rates are detected, it is important to predict whether equipment will go back to a normal condition or get worse and fail. Since most equipment is designed for normal wear, abnormal wear may quickly lead to catastrophic failure. Therefore, it is essential to detect machine faults, even though it is hard to predict the exact time of failure.*

Wear processes produce an amazingly complex array of types of wear debris from surfaces. The interpretation of the appearance of the wear debris is subject to the individual judgment and optical means employed. However, human expertise is not usually discussed in the open literature nor is it readily available in the present tribology community.

Since the advent of Ferrography, much effort has been devoted to correlating the visual assessment of wear debris with the relevant wear modes. There exists internationally understood knowledge [2] which bridges the gap between wear debris and its origin. However,

phenomenological observation of wear debris has not been solidified in technical terms. The lack of terminology describing wear debris might be one of the reasons why wear debris analysis is not usually recognized in the conventional framework of wear. In this paper, the phenomenological aspect of wear debris analysis is addressed. The concept of wear debris phenomena is proposed so that the outcome of phenomenological observation and characterization of wear debris is effectively accumulated in one domain. Terminology is coined to represent two significant phenomena, the effects of which can be visually observed on wear debris, namely cutting and severe sliding. An extended classification of wear is undertaken to accommodate wear debris phenomena, in addition to worn surface phenomena and wear processes.

Identification of wear modes based on wear debris: In maintenance, the motivation to investigate wear modes arises from the fact that the wear life of mechanical components can be predicted by the identification of wear modes occurring in a machine. The wear mode-the way surface damage proceeds or a manifestation of wear processes-can be studied by examining the evidence of wear, i.e. worn surfaces, wear debris and subsurface deformation (Figure 1). Of these three results of wear, visual assessment of worn surfaces and wear debris is adequate for routine maintenance practice. However, the examination of wear debris is more cost-effective.

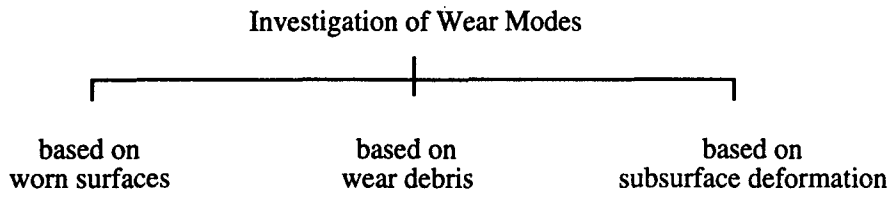

Figure 1. Investigation of wear modes.

In wear debris analysis, the wear mode is usually concluded by examination of wear debris using optical means. Before examination, wear debris are usually mounted on a glass slide or trapped in filter paper. It is not conceivable to rotate debris to see the exterior appearance all round [3]. Since observations are usually done from above, some shapes, e.g., concave shapes, are misleading and overall shape is hard to tell. Nevertheless, visual assessment of wear debris by light microscopy can be correlated to the wear mechanisms by which they were removed.

With technological advances in the field of computer vision, attention has focused on an automated means for wear debris analysis. To date, results have been limited by the 2-dimensional nature of conventional light microscopy [4]. Recently, it has been suggested that the high resolution 3-dimensional imaging capabilities of laser scanning confocal microscopy may provide a more complete analysis of wear debris [5].

Wear debris phenomena: Whenever there is a tribological interaction, the surface is worn and deformed, the subsurface is deformed, and wear debris are generated. In the course of wear

processes, several phenomena occur in the surface, subsurface and wear debris. Phenomenological observations and characterizations of wear are attempts to pinpoint significant wear processes. There exists terminology which describes meaningful phenomena that occur on worn surface (pitting, scuffing, plowing, scoring, etc.) and subsurface deformation (microcracking and recrystallization, etc. [6]). However, phenomenological observations related to wear debris have not been coined into technical terms. The concept of wear debris phenomena is proposed with the hope of embracing the efforts of phenomenological observations and characterizations. The meaning of wear debris phenomena is self-explanatory. In the field of wear, terminology assessing the results of wear is highly descriptive of the appearance, and in a sense is indicative of possible wear mechanisms [7]. So terminology of wear debris phenomena should also be capable of such descriptions. Due to their small size, phenomenological observation of debris is highly subject to the use of optical means. For example, wear debris phenomena can be defined as follows.

Curling: A process by which overall shape of debris becomes like machining swarf (Figure 2, left). This phenomena can be observed when surface is cut either by a sharp projection or by an abrasive particle.

Scratching: Fine-scale deformation resulting in a multitude of lines which run parallel to the sliding direction [6] (Figure 2, right). Scratching results in striated surfaces on wear debris, which can be indicative of severe sliding.

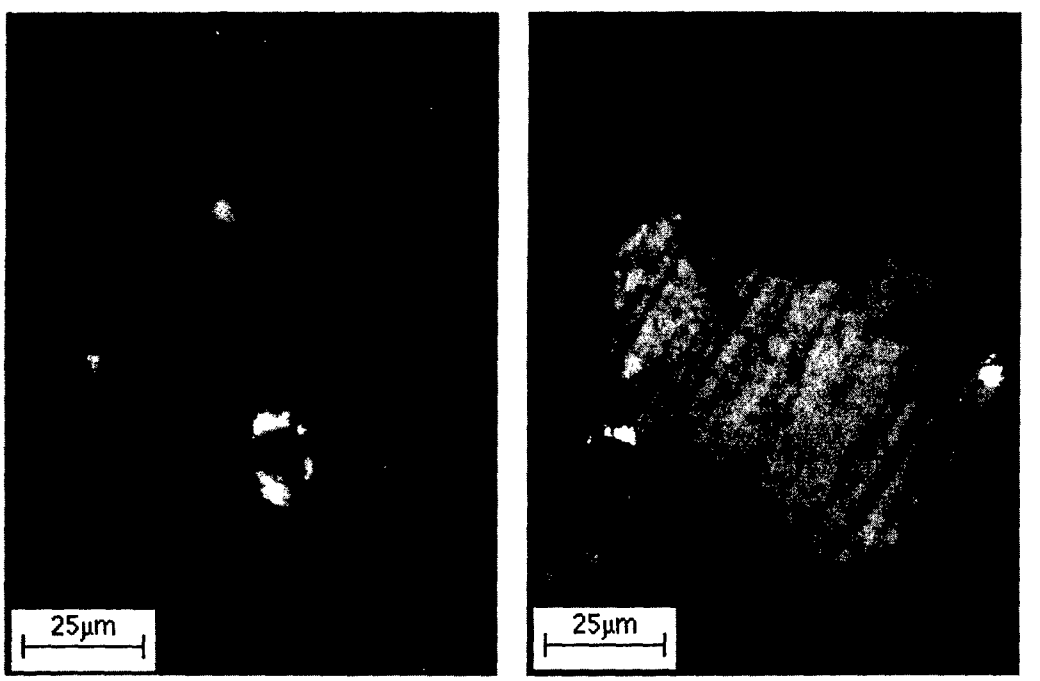

Figure 2. Wire-like aluminum debris cut by abrasive grains (left), aluminum debris with striated surface generated in a severe sliding condition (right).

An extended classification of wear: Wear is generally regarded as the "unwanted removal of material by chemical or mechanical action" [8]. Another definition [9] is the "progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface." Laws, mechanisms and theories have been developed to understand fundamentals of wear; and the accumulated knowledge of wear has been systematically arranged according to numerous classification schemes. In general, wear can be broadly classified based on the results of wear and the nature of the underlying processes [7, 10]. For example, in Dowson's classification [7], one category is highly descriptive of worn surfaces as well as somewhat indicative of the wear mechanisms. The other is based on the wear processes (Figure 3). However, the conventional classification of wear does not include any wear debris phenomena.

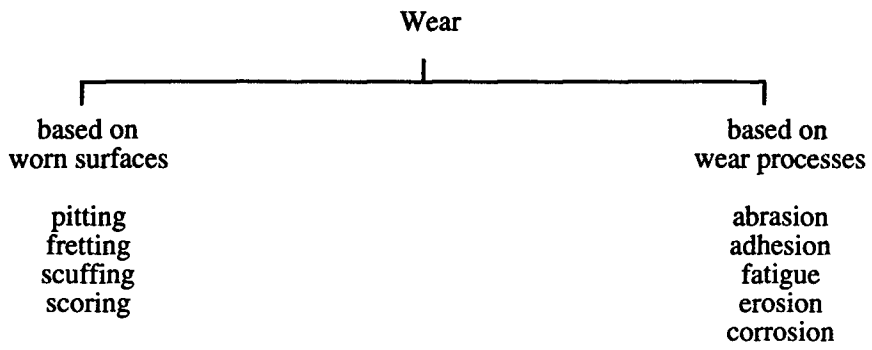

Figure 3. Classification of wear.

While wear processes can be investigated by the examination of worn surfaces, wear debris features can also provide indications of the tribological interactions by which they were formed. For many years, wear debris analysis has been used to provide cost-effective and continuous monitoring of the degradation of machinery components without dismantling the machines. As the number of studies of wear debris has been increased, the amount of knowledge about it has taken a more significant position in the area of wear. A better understanding of the relationship between wear debris features and the relevant wear modes will enrich our knowledge of wear. Because of their importance, it is fair to say that the phenomena occurring in relation to wear debris should be included in the conventional classification of wear.

In addition to worn surface phenomena and the wear processes, traditional classification of wear is extended to accommodate wear debris phenomena (Figure 4). In both conventional and extended classification, there are two backbones: one is the results of wear and the other is the underlying processes. Between two classifications, the difference is that: in the extended classification of wear, the phenomena of wear debris as well as worn surface are considered as the results of wear. The motivation for the extended classification is two-fold: first, wear debris phenomena should be included for the completeness of classification of wear. Second, identifying processes of wear modes based on the analysis of wear debris should be recognized in conventional framework of wear-so that more attempts can be made to discriminate the

validity of claims and counter-claims in wear debris analysis. In this way, the interpretation of wear debris would become more reliable.

An Extended Classification of Wear

based on worn surfaces	based on wear processes	based on wear debris
pitting	abrasion	curling
fretting	adhesion	scratching
scuffing	fatigue	etc.
scoring	erosion	
	corrosion	

Figure 4. An extended classification of wear.

Summary: The phenomenological approach to wear debris analysis can be a useful tool in digging out significant correlations which can bridge the gap between wear debris and the relevant wearing conditions. The concept of wear debris phenomena and the extended classification of wear are proposed not only to make a systematic effort, but also to make wear debris analysis recognized in conventional framework of wear-so that the acquired knowledge can be easily screened.

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