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Oxidation wear monitoring based on the color extraction of on-line wear debris

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ABSTRACT

Oxidation associated wear usually involves high temperature and often accelerates lubrication degradation and failure processes. The color of oxide wear debris highly corresponds with the severities of oxidation wear. Therefore, on-line detection of oxide wear debris has the advantage of revealing the wear condition in a timely manner. This paper presents a color extraction method of wear debris for on-line oxidation monitoring. Images of moving wear particles in lubricant were captured via an on-line imaging system. Image preprocessing methods were adopted to separate wear particles from the background and to improve the image quality through a motion-blurred restoration process before the colors of the wear debris were extracted. By doing this, two typical types of oxide wear debris, red Fe_2O_3 and black Fe_3O_4, were identified. Furthermore, a statistical clustering model was established for automatic determination of the two typical types of oxide wear particles. Finally, the effectiveness of the proposed method was verified by performing real-time oxidation wear monitoring of experimental data. The proposed method provides a feasible approach to detect early oxidation wear and monitor its progress in a running machine.

1. Introduction

Metallic oxidation, often caused by high temperature at metal-to-metal contacts due to overload and/or lack of lubrication, is one of the main causes of tribological failures. High flash temperature generated in the wear process will not only tender the tribo materials but also deteriorate the lubricant in use. Therefore, early detection of oxidation wear is of significance for preventive maintenance of mechanical systems [1,2].

Wear debris is the direct by-product generated in a wear process and contains valuable information about machine conditions. Thus the features of wear debris are characterized for machine condition monitoring and fault diagnosis. Among these features, the colors of wear debris are used as critical information for oxide wear debris identification. For instance, the predominant oxide products of most tribo-systems made of steel (Fe–C alloy) are Fe_2O_3 and Fe_3O_4, which can be identified by examining their special colors. In addition, the oxide films of low alloy steel, from inside to outside, are FeO (FeO cannot be produced under 600 °C), Fe_3O_4 and Fe_2O_3 layer [3]. If the oxidation film breaks up to form wear debris, it means that severe wear with a high wear rate occurs and the types of oxide wear particles can reveal the wear degree. At present, color-based classification of oxide wear debris has been studied extensively and accepted as a theoretical base for oxidation wear analysis [4,5].

Color extraction of wear debris is an essential step for oxidation wear monitoring using off-line analysis techniques. Myshkin [4] used optical microscopy to acquire wear debris images and extract their colors. By using a multi-scale classification criterion, wear particles were classified into red oxide (Fe_2O_3) and black oxide (Fe_3O_4) based on their colors. Compared with off-line approaches such as Myshkin's work, on-line monitoring technology has the advantage of capturing real-time machine data [6,7]. Color images of wear debris can also be captured using on-line ferrograph technology to identify wear sources. Identification of some typical metal particles, including copper, iron and aluminum debris was achieved through extracting their colors from on-line images [8]. However, this method is effective only when wear debris images are clear. Unfortunately, wear debris images sampled with an online sensor are often fuzzy because of a number of reasons, e.g. the movements of the particles and lubricant. Also, reported on-line monitoring systems applied the ferrograph approach to capture iron particles [9]. Consequently, the particles are often in a chain pattern and overlapping, which make it difficult to separate wear particles. Color recognition of moving wear debris thus remains a bottleneck for on-line wear monitoring.

Video-based image processing technology provides a new approach for dynamic characteristics extraction, and has been

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successfully applied in medical diagnosis [10], robot vision [11] and intelligence transportation [12]. Specifically, video acquisition can avoid the agglomeration of motion particles to achieve accurate characteristics extraction of multiple wear particles. Although the motion of wear debris introduces image blurring, color information can be obtained using color image enhancement methods [13,14].

Aiming at on-line oxidation wear monitoring, this work investigated the color extraction of wear debris from on-line sampled images. An image capturing system was constructed to acquire the color images of moving wear particles. To extract the colors of wear debris effectively, the methods of improving on-line images quality were studied, the color information was extracted, and wear particles were classified based on their colors for on-line oxidation wear monitoring. The practicability of the proposed method was evaluated experimentally using a four-ball wear tester.

2. Dynamic wear debris image acquisition system

An experimental system for oxidation wear testing and monitoring was designed and is illustrated in Fig. 1. A typical four-ball wear tester was adopted as a testing machine that the on-line monitoring equipment was set up on. Particles produced by the friction pair flew into the oil tank and then were directed to the designed oil flow path by a digital pump. Videos of dynamic wear debris were captured using a video sensor with light-emitting diodes (LED). A single chip microcomputer was utilized to drive the digital pump and the LED. To avoid the circulation of analyzed particles in the oil system, an oil bottle was set up in the return pipe. The clean oil in the upper portion of the oil bottle was drained by another digital pump into the oil tank. The return oil with wear debris was sent to the bottom of the oil bottle so the particles could be deposited.

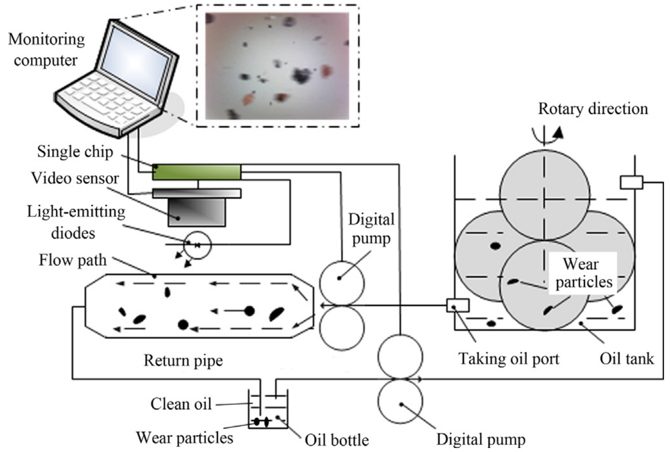

Fig. 1. Schematic illustration of the on-line monitoring equipment installed on a four-ball rig.

The videos of dynamic particles were processed to extract particle images. A typical wear debris image extracted from the video stream is shown in Fig. 2(a). As can be seen, wear particles in different colors were captured. By comparing with the analytical ferrograph image in Fig. 2(b), two drawbacks of the on-line image are revealed.

1) The background varies with light conditions and oil transparency, resulting in a low contrast between the particles and background.
2) The resolution of the on-line image is less than that of an off-line ferrograph image, which is caused by the movement of the particles and lubricant involvement.

These issues make it difficult to extract the color information of the wear debris. In order to effectively extract the information, the background of the image needs to be segmented and the image quality needs to be improved. Details of the wear debris image segmentation and enhancement methods will be presented in the next section.

3. Color extraction of dynamic wear debris

Images of moving particles captured by the video acquisition system contain their color features for particle identification. However, it is difficult to extract color information from the dynamic image because of the two issues described in Section 2. Thus image segmentation and color enhancement are necessary before acquiring useful color information.

3.1. Color segmentation of wear debris image

As depicted in Fig. 2, a particle image can be divided into two parts: wear debris and background. For image segmentation, a background subtraction method [15] was employed to separate the wear debris. A series of images were extracted from a video clip to reconstruct a real-time background of the images. Fig. 3 gives nine frames selected from the images sampled in 12 s. The

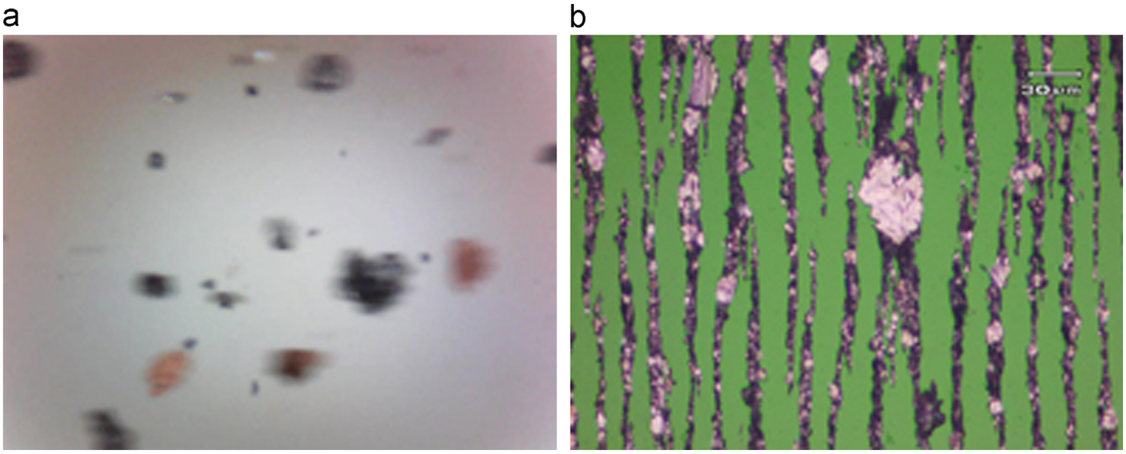

Fig. 2. Typical images carried by on-line monitoring equipment and analytical ferrography: (a) on-line acquisition image and (b) analytical ferrograph image.