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A microfluidic device for three-dimensional wear debris imaging in online condition monitoring

Yeping Peng[1], Tonghai Wu[1], Shuo Wang[1], Ying Du[1], Ngaiming Kwok[2] and Zhongxiao Peng[2]

Abstract

Three-dimensional morphologies of wear particles are important information sources for machine condition assessment and fault diagnosis. However, existing three-dimensional image acquisition systems, such as laser scanning confocal microscopy and atomic force microscopy, cannot be directly applied in condition-based maintenance of machines. In order to automatically acquire three-dimensional information of wear debris for online condition monitoring, a microfluidic device consisting of an oil flow channel and a video imaging system is developed. This paper focuses on the control of particle motions. A microchannel is designed to ensure the continuous rotation of particles such that their three-dimensional features can be captured. The relationships between running torque and channel height and particle size are analysed to determine the channel height. An infinite fluid field is considered to make sure that the particles rotate around the same axis to capture 360 degree views. Based on this, the cross section of the microchannel is determined at 5 mm × 0.2 mm (height × width) to capture the wear debris under 200 μm. A CMOS sensor is used to image the particles in multiple views and then three-dimensional features of wear debris (e.g. thickness, height aspect ratio and sphericity) are obtained. Two experiments were carried out to evaluate the performances of the designed system. The results demonstrate that (1) the microfluidic device is effective in capturing multiple view images of wear particles various in sizes and shapes; (2) spatial morphological characteristics of wear particles can be constructed using a sequence of multi-view images.

Keywords

Three-dimensional wear debris analysis, microfluidic device, rotational motion, imaging system, online condition monitoring

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Introduction

Oil condition sensors of viscosity, corrosion and oxidation have been widely investigated for machine condition monitoring.[1–3] However, there are shortcomings of these methods that cannot reveal wear mechanisms of a running machine. Wear particles carried in lubrication oil are by-products of the wear processes, which have a direct relationship with machine conditions. Thus, wear debris sensors have been developed and used to acquire particle characteristics such as size, shape, colour and quantity for oil analysis.[4–6]

Notable progresses of wear debris monitoring sensors have been achieved in the past decades. A review of major existing sensors classified through their operation principles can be found in Wu et al.[4] Optical blockage[7] and magnetic field sensors[8] are both effective techniques adopted to investigate particle concentration. Han et al.[9] and Du et al.[10] used inductive pulse sensors to differentiate metallic and non-metallic, ferrous and non-ferrous wear particles. Ultrasonic detection method also can be utilised to identify metallic and non-metallic particles as well as obtaining solid debris concentration.[11] However, the above debris monitoring sensors are usually focused on detecting materials and examining concentration and size information. In contrast, imaging and

[1]Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Shaanxi, China
[2]School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney, Australia

Corresponding author:
Tonghai Wu, Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China.
Email: wt-h@163.com

magnetic hybrid sensors[12] provide morphological characteristics of wear particles, including quantity, size, shape colour and surface texture, for wear process and mechanism examinations.

Ferrography has been accepted the most common technique to acquire the morphology information from particle images for wear debris analysis (WDA).[13] In particular, with the development of microscopy, further research had been made to extract three-dimensional (3D) characteristics of wear debris to access wear mechanisms since the late 1990s.[14–16] Several methods such as stereo scanning electron microscopy (SEM),[17] laser scanning confocal microscopy (LSCM)[18] and atomic force microscope (AFM),[19] were developed to provide surface information of wear debris. These wear debris image acquisition and analysis methods, however, may not be able to provide 3D morphological information due to the fact that target particle needs to remain stationary while being analysed. Consequently, because of the varying orientation of the particles with respect to the lens and detector, it is very difficult to acquire its thickness.[20] In addition, scanning individual particles is often time-consuming, especially when a large amount of particles need to be imaged and analysed. These methods are regarded as off-line techniques employed in the laboratory, and cannot meet the requirements of online machine condition-based maintenance (CBM).

To overcome problems encountered in preparing particle samples, a method of WDA based on multi-view and 3D images was proposed as a new way to examine wear debris.[21] A flow cell was designed to obtain the desired rolling motion of wear debris. Multi-view images of a single particle were then captured to extract the thickness and approximate volume information. However, in the flow cell design, the rolling motion of the particles is random, which imposes uncertainties in the captured images and causes failures in extracting 3D features. This equipment also cannot be applied to online WDA where a microscope has to be used and complex operations are required.

Online image-based WDA using their morphological features has been rarely reported in accessible literatures. Currently, two typical available sensors are the online visual ferrograph (OLVF)[22] and the LaserNet Fines (LNF).[23] The OLVF system uses a magnetic force to attract wear debris in oil flow to a planar surface. Then the wear particles are captured using a camera. Similar to the analytical ferrograph,[24] wear debris attracted by the magnetic force always form into agglomerated chains. Although efforts have been made to separate particles in these chains,[25] it is still difficult to extract features of individual particles. In contrast, the LNF system, developed by Lockheed Martin Tactical Defence Systems in cooperation with the Naval Research Laboratory, employs a flow cell without using magnetism to acquire wear debris in motion.[26] This system uses a 2D transmitted image to extract shape characteristics of wear debris and has been widely used for wear condition monitoring. However, the LNF is limited in wear mechanism analysis because it cannot provide colour information and 3D features of wear debris. Therefore, online WDA in 3D has been regarded as a bottleneck for CBM. It is necessary to employ multi-view images for 3D wear particle analysis.

In our previous works,[27,28] a dynamic image acquisition system to capture moving wear debris was developed and applied to detect oxides for online oxidation wear monitoring. These studies showed that imaging particles under dynamic conditions was feasible for WDA on individual particles. However, the motion control of particles was not considered in the design and particle monitoring in 3D was not implemented. Further improvements on the oil channel are necessary to enable particle rotation movements in order to capture wear debris in multiple views for 3D analysis.

Aiming to develop an imaging system to capture wear particles in different views for real-time 3D analysis, this paper presents a design of a microfluidic flow channel to ensure the continuous rotation of particles. Lubricant oil in the microchannel flows in laminar modes and particles are acted by gradient forces in different laminar layers. Particles are set in rotating movements under the influence of a force couple. The image acquisition system is then able to capture multi-view images, from different directions, of moving wear debris to extract their 3D characteristics. To guarantee an infinite fluid field, the oil channel dimensions are determined to form an infinite microchannel. The performances of the proposed device are evaluated using commercial metal power and particles that are produced from a four-ball test rig and a gearbox.

The rest of this paper is organised as follows. The background theory employed in the design is given in the upcoming section. Next section details the design of the microchannel structure. Subsequently, experimental results are presented and further research is also discussed. Finally, the conclusions are drawn in the last section.

Theoretical background

In general, a visual-based wear particle analysis system often consists of three major components including an oil channel, an imaging sensor, associated flow control hardware and image processing software to extract particle features. A typical building block of the system is illustrated in Figure 1. A flow channel is connected to a lubricating system to form an oil circuit. A CMOS sensor is used to capture images that are sent to a computer for image analysis and to extract particle characteristics. More details of the system can be found in Peng

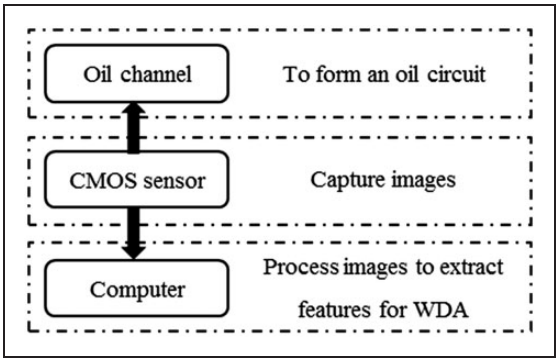

Figure 1. Principle of an online wear debris imaging and analysis system.

et al.[27] In the system, the oil channel is a critical component as moving particles are imaged and the channel dimensions will critically affect the particle motions.

The motion states of wear particle in the microfluid firstly needs to be analysed to obtain the channel design criteria. Movements of wear particles carried by lubricating oil are influenced by the liquid flow state. Generally, the Reynolds number of liquid (R_{el}) in equation (1) is used to determine the fluid flow field[29]

$$R_{el} = \frac{vD_d\rho_l}{\mu} \tag{1}$$

where v is the mean oil flow velocity, D_d denotes the equivalent diameter of the channel, ρ_l and μ are the density and dynamic viscosity of the lubricant.

In order to capture wear debris images, the oil flow channel is made up of two pieces of glass constructed as a microrectangular channel.[22] The equivalent diameter of the channel can be calculated using

$$D_d = \frac{2bh}{b+h} \tag{2}$$

where b and h are the internal width and height of the flow channel, respectively. The oil flow channel is designed in a millimetre-scale according to the size distribution of wear debris, and the flow rate of a digital pump used for oil transmission is controlled in the range from 0 to 10 mL/min.[22] Thus, the Reynolds number is far less than 2300 and the fluid in the microchannel flows in the laminar mode (Figure 2). (The lubricant brand used in this study is "MOBIL LUBRICANT 15W-40": $\rho_l = 850\,\mathrm{kg/m^3}$ and $\mu = 0.081\,\mathrm{Pa{\cdot}s}$.)

In general, the laminar velocity of viscous liquid distributes in a parabolic profile both in the vertical and horizontal directions. The existence of laminar fluid is a requirement to acquire wear particles that are rotating.

Figure 3 shows the motion characteristics of particles carried in the laminar flow. Under the scouring force of the fluid, wear debris moves along the liquid flow direction. The scouring force is the drag force, which is calculated using the following equation[30]

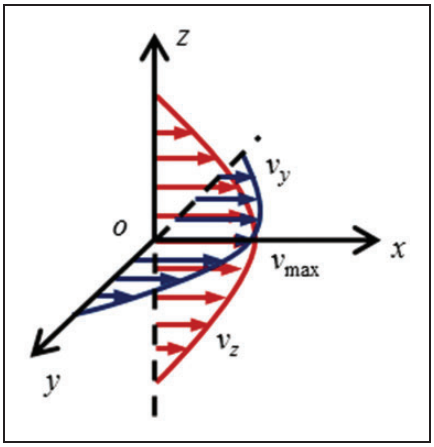

Figure 2. Distribution of laminar fluid velocity: arrows represent the direction of oil flowing, v_y and v_z denote the oil velocity distributing in the width and height directions of the channel respectively, v_{max} is the maximum velocity.

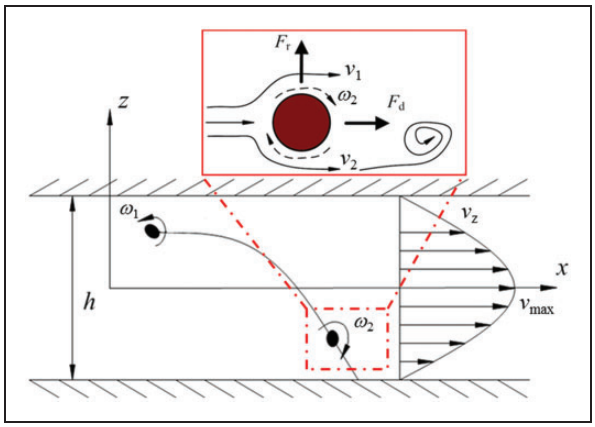

Figure 3. Motion characteristics of particles in liquid under laminar condition.

$$F_d = \frac{C_d v^2 \rho_l A}{2} \tag{3}$$

where F_d denotes the drag force, C_d is drag coefficient and A is the projected area of particles perpendicular to the flow direction.

From the enlarged drawing in Figure 3, the flow velocity on the upper side of a particle close to the channel bottom is higher than that on the lower side, that is, $v_1 > v_2$. Accordingly, the drag force on the upper surface is larger than that on the lower surface, which gives rise to a force couple. Therefore, the particle is set in rotation with an angular velocity ω.

In addition, according to the conservation law of mechanical energy, the pressure is inversely proportion to the flow rate. The pressure difference thus leads to a lifting force. Furthermore, the gravity and buoyancy are in opposite directions. Particles are

suspended in the liquid when the lifting force is large enough. However, metal debris generally moves in the bottom of the oil channel because its density is much larger than that of the lubricant (Figure 4).

The movement of particles can be divided into four types: stationary, translation, rolling, translation & rolling. From Figure 4, the torque acting on a particle can be calculated by

$$M = F_d R_d - (mg - F_b - F_r) R_{mg} \tag{4}$$

where M is the torque, R_d and R_{mg} are the moment arm of F_d and mg, respectively. For the same particle, the torque depends on F_d and F_r, which are influenced by the fluid velocity distribution in the oil channel.

Design of microchannel structure

The above analysis can be summarised as follows: (a) The rotational movement is a prerequisite to capture multiple views of wear debris, (b) the velocity distribution of laminar flow produces a torque to set particles in rotation, and (c) the laminar microfluidic flow are affected by the height and width of the flow channel. However, the particle is in rotating motion not only along the y-axis but also the z-axis. To allow the CMOS sensor to capture 360 degree views of the particle and to reduce image processing time, it is desirable to constrain the rotation to the y-axis only. This means that the rotation motion about the z-axis needs to be reduced. This can be achieved by designing an infinite fluid field.

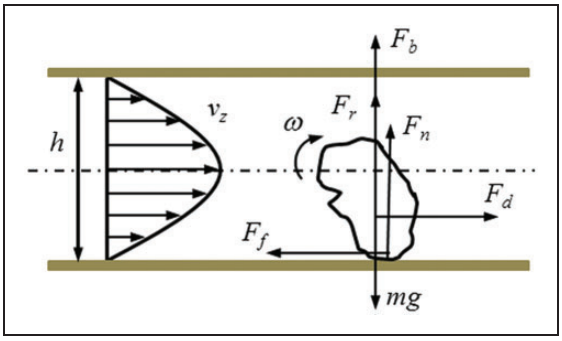

Figure 4. Forces acting on particles in the bottom of flow channel: h – internal height, F_b – buoyancy, F_r – lift force, F_n – support force, F_f – friction force, mg – gravity.

Determination of the channel height

As described in section 'Theoretical background,' the rotational motion of wear debris is dependent on the action forces and their arms, and the arms of forces vary with the changes of particle orientations. It can be seen in Figure 5 that R_{mg} is greatly affected by the position of the centre-of-gravity, and $R_{mg} = 0$ when the barycentre and the supporting point are aligned in a vertical line (Figure 5(b)). The drag force, F_d, becomes the main element of a force couple that generates the torque.

Furthermore, the drag force is influenced by the shape of a particle, which can be seen in equation (3). Thus the analysis of rotating movements is very complicated because the particles have a wide variety of shapes and sizes. In order to identify the relationship between the internal height of oil channel and the sizes of particles, the wear debris is simplified to a sphere, as illustrated in Figure 6.

In an infinite flow field (details can be seen in section 'Design of the infinite microchannel'), the oil velocity can be calculated using a 2D model, which is expressed by[31]

$$v_z = \frac{6q}{bh^3}\left(hz - z^2\right) \tag{5}$$

where q denotes the fluid flow rate, and z is a variable in the range of [0, h]. Thus the average flowing velocity at the spherical particle is obtained from

$$\overline{v} = \frac{3qd}{8bh^3}(8h - 5d) \tag{6}$$

where $\overline{v}$ is the average flowing velocity and d is the diameter of the spherical particle. To calculate the

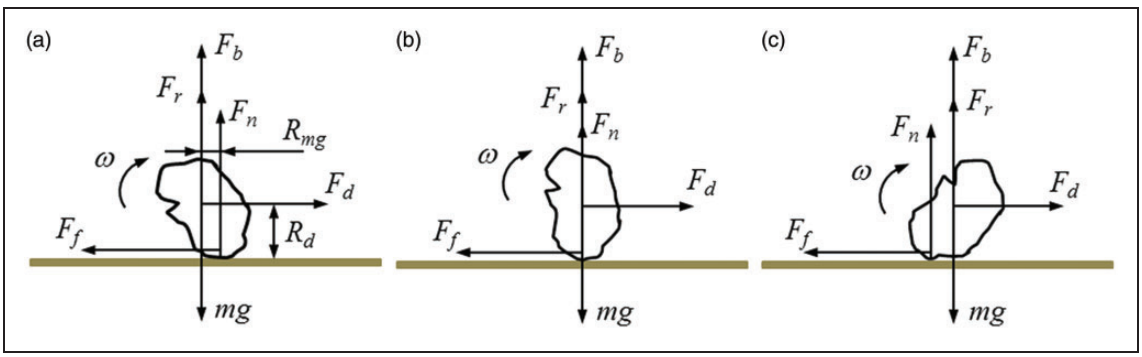

Figure 5. Different postures of a particle: (a), (b) and (c) the barycentre are on the left, in the middle and on the right side, respectively.

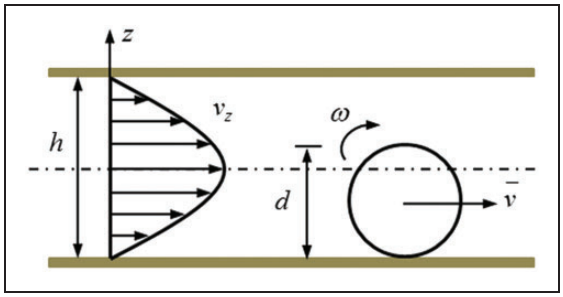

Figure 6. Simplified force analysis of wear debris.

drag force, its coefficient that depends on the Reynolds number of debris (R_{ed}) needs to be obtained. The calculation of R_{ed} is similar to that of R_{el} in equation (1), i.e.

$$R_{ed} = \frac{\bar{v} d \rho_l}{\mu} \tag{7}$$

From the discussion in section 'Theoretical background,' it is known that $R_{ed} < 1$ when the dimension of wear debris is less than 1 mm. For this reason, the drag coefficient can be calculated using the following equation[30]

$$C_d = \frac{24}{R_{ed}} = \frac{24\mu}{\bar{v} \mathrm{d} \rho_l} \tag{8}$$

Thus the drag force is

$$F_d = 3\pi\mu d\bar{v} \tag{9}$$

Therefore, the running torque is

$$M = \frac{9\pi\mu q d^3}{16bh^3}(8h - 5d) \tag{10}$$

Two relationships can be identified from the above analyses, they are:

i. For a given channel structure and particle dimension, the torque is proportional to the dynamic viscosity (μ) and the flow rate (q) of the lubricant oil. It means that the rolling movements of wear debris can be ensured by increasing the liquid flow velocity when the viscosity of lubricating oil is small.
ii. The torque is inversely proportional to the width (b) of the flow channel when other factors are constant.

The relationship between the torque and the microchannel height and particle sizes needs to be further analysed. It is assumed that the internal height is less than 1 mm because the size of wear particle is in microscale. At the same time, let $q = 1$ mL/min, and $b = 5$ mm be preliminarily selected according to our previous experience.[22] The relationship between the

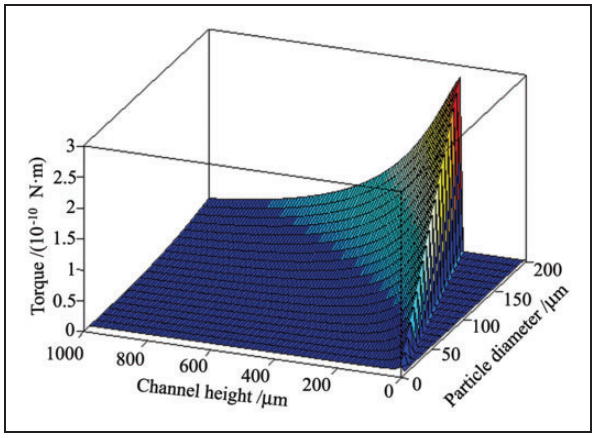

Figure 7. The torque changes with the channel height and particle diameter.

above three factors are drawn in Figure 7. From the surface plot, we can obtain the third relationship that the torque decreases with the increasing channel height when the other variables are given. According to the statistical distribution of particle sizes, the equivalent maximum diameter of a particle is as large as 160 μm.[32] Considering the irregularity, the channel height is set as 200 μm to avoid blocking of particles in the flow channel.

Design of the infinite microchannel

An infinite flow field of laminar liquid is required to ensure that the particles rotate around the same axis to enable images captured from different view angles. In general, an infinite flow field is obtained when the width of the channel cross section is much larger than its height. In this case, the flow velocity distribution in the microchannel can be expressed in two dimensions. This signifies that the maximum and average velocities calculated using a 2D model are close to those obtained using a 3D one. Therefore, the deviations of the above two parameters are utilised to determine the channel height according to the infinite flow criterion. Define the deviations of the maximum and average velocities between the 2D and 3D models as δ_1 and δ_2, which can be calculated using the following equations (The 3D model of flow velocity distribution in the microchannel is:[31]

$$v_{y,z} = \sum_{n=1}^{\infty} -\frac{24bq(1-\cos n\pi)}{(n\pi h)^3}\frac{\alpha+\beta-\gamma-1}{\gamma+1}\sin\frac{n\pi z}{b}$$
$$\text{and } \alpha = e^{n\pi y/b},\ \beta = e^{n\pi(h-y)/b},\ \gamma = e^{n\pi h/b}$$

where $v_{y,z}$ denotes the flow velocity connected with y- and z-coordinate values.)

$$\delta_1 = |\max\{v_{3D}\} - \max\{v_{2D}\}| \tag{11}$$

$$\delta_2 = |\mathrm{mean}\{v_{3D}\} - \mathrm{mean}\{v_{2D}\}| \tag{12}$$

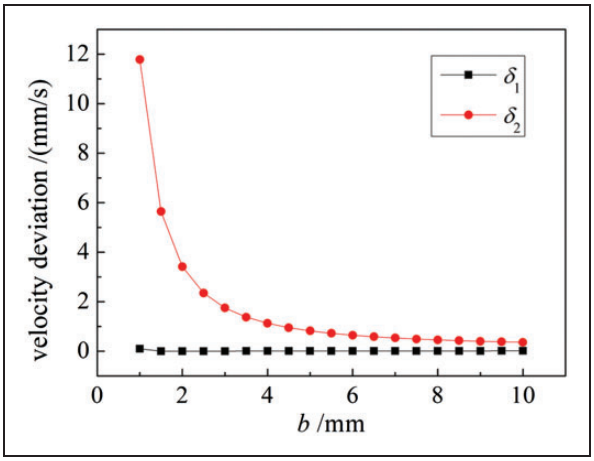

Figure 8. Velocity comparison calculated using the 2D and 3D models with different widths.

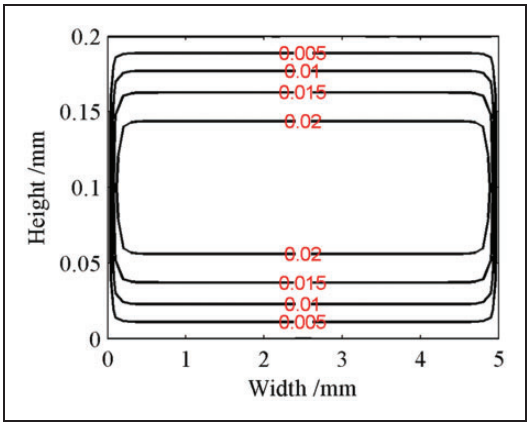

Figure 9. Three-dimensional distribution of fluid flow in the designed channel.

where v_{3D} and v_{2D} are the velocity respectively calculated by the two models, max{·} and mean{·} denote the maximum and average value, respectively. When the flow rate is equal to 1 mL/min and the channel height is 0.2 mm ($q = 1$ mL/min, $h = 0.2$ mm), the values of the deviations, δ_1 and δ_2, are displayed in Figure 8.

As shown in Figure 8, the differences of maximum and average velocities between 2D and 3D calculations are both very small (<1 mm/s) when the width is larger than 4.5 mm. It can be considered that the microchannel is an infinite flow channel when its cross-section dimensions are in this range. The channel width is finally selected as 5 mm considering that the torque acting on particles decreases with the increasing width. To show the 2D flow conditions in the microfluidic channel, the flow field was simulated and the velocity distribution is drawn in Figure 9. It can be seen that the fluid flows in two dimensions when the channel width is in the range of 1–4 mm. This meets the requirement to image microscale particles in multiple views.

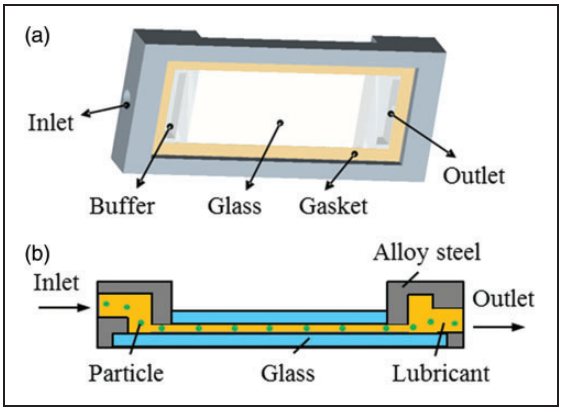

Figure 10. Schematic diagram of oil flow channel: (a) 3D model, and (b) simplified sectional view.

Experiments and results

Assembly of the oil channel and experimental setup

Figure 10 is a schematic diagram of the oil flow channel. The parallel pair of glass is placed inside alloy steel brackets. To form a channel, a gasket with 200 μm thickness is inserted between the two glass plates. All of these components are sealed with a mixture of window sealant and strong adhesive.

The experiment setup is shown in Figure 11. Oil samples were prepared with different types of wear particles including commercial metal power and debris that were produced from a four-ball test rig and a gearbox. The speed of video processing using our software is 17.64 frames per second (fps). Correspondingly, the videos of moving particles were captured using a CMOS sensor with a sampling

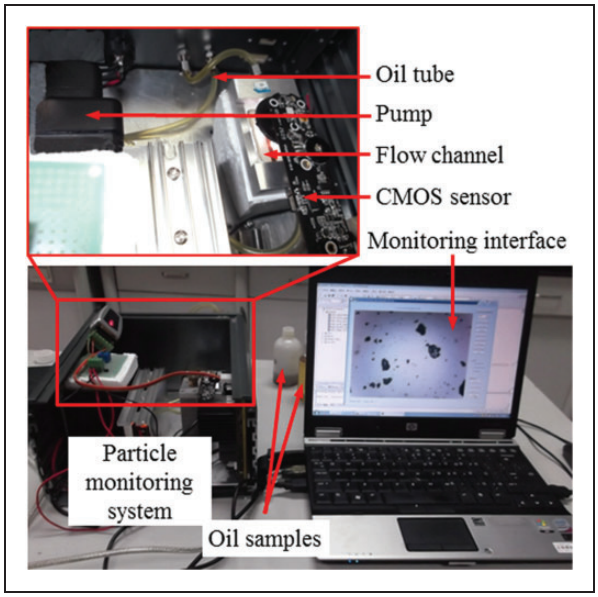

Figure 11. Experimental setup for monitoring wear debris using the microfluidic channel.

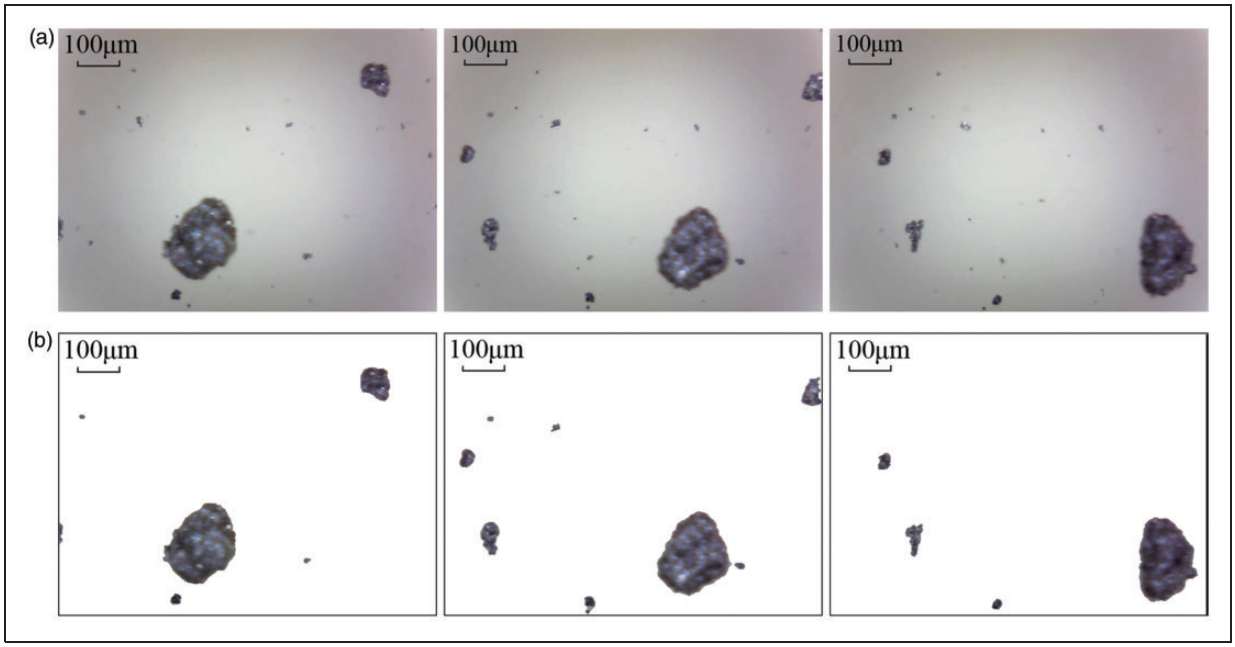

Figure 12. Three views of moving particles and the segmentation results: (a) three images extracted from a video and (b) segmented images of (a).

rate of 15 fps for real-time monitoring purpose. All image frames were stored in the JPEG format with a resolution of 640×480 pixels.

Results

To evaluate the performances of the wear debris monitoring system, two experiments were carried out. One was to examine the ability to capture multiple views of different types of particles. The other was to verify that particles rotate around the same axis, and the multiple view images of a particle could provide 3D features. The experimental results are described below.

Figure 12(a) shows three image frames extracted from a video of moving wear debris. These images display the largest particle at different views. In order to acquire morphological features, target particles need to be segmented from their background. It can be found that the backgrounds of the three images in Figure 12(a) are similar. Hence, background difference methods can be used to separate wear debris, which can be found in our previous work.[33] The particle separation results are shown in Figure 12(b). As can be seen, the segmented particles retain their edge and shape information.

To verify that the developed system is able to image particles with various sizes and shape morphologies, the particle acquisition results are divided into two sets. As shown in Figure 13(a), the particles are grouped into three classes, small (<50 μm), medium (50–100 μm) and large (>100 μm). With reference from Du et al.,[34] the sizes of abnormal wear debris are ranged from 50 to 100 μm. In Figure 13(b), three typical wear particles, including sphere-, flake- and fibre-like particles, are imaged. It can be seen that the debris images in different views are acquired, showing that the particles in different sizes and shapes are in rotational motions when they are imaged.

Dynamic image sequences of a rotating particle are shown in Figure 14(a), which reveals different appearances of the particle. Two-dimensional features can then be extracted from each image by utilising digital image processing. Image binarisation is firstly performed, and then the particle pixels are scanned to extract three 2D fundamental parameters including area, length and width. It can be seen from Figure 14(b) that the length of the rotating particle in different frames is similar, which is in the range of 130 ± 8 μm. Therefore, the particle approximately rotates around its vertical axis. This indicates that an infinite flow field of the microchannel is obtained. It is also shown in Figure 14(b) that the largest and smallest areas are obtained. From the similar variation trend between area and width, the smallest width can be considered as the thickness of the particle. Furthermore, some typical spatial characteristics including the height aspect ratio[35] and sphericity[36] can be constructed. With the ability of spatial morphological feature extraction, 3D wear debris characterisation and identification can be realised using the developed system.

Discussion

The above experimental results confirm that the developed microfluidic device is able to image moving particles from different directions for 3D wear debris analysis. By designing a micro-channel with laminar

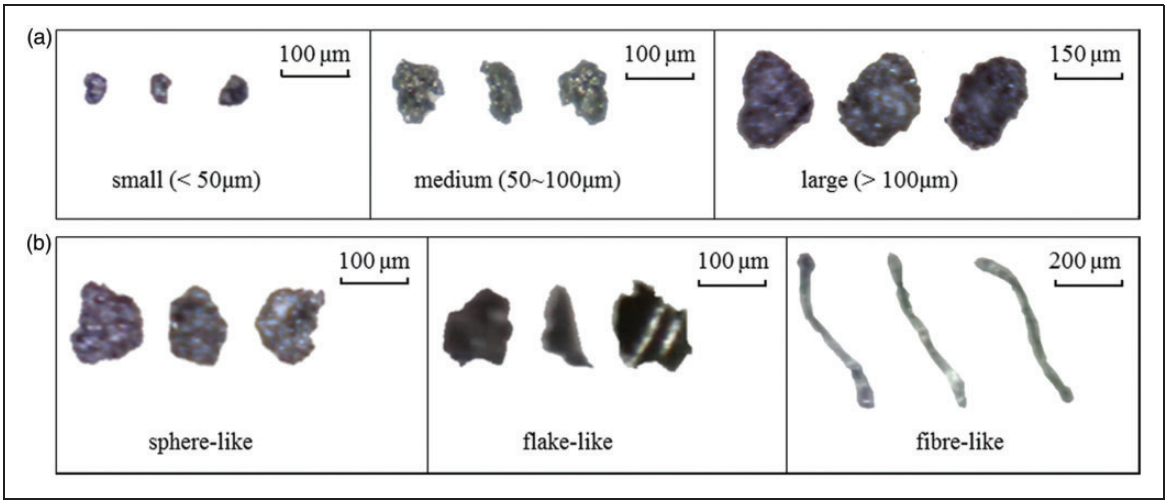

Figure 13. Different types of particles captured by the proposed system: (a) particles grouped by their sizes, and (b) particles classified according to their shapes.

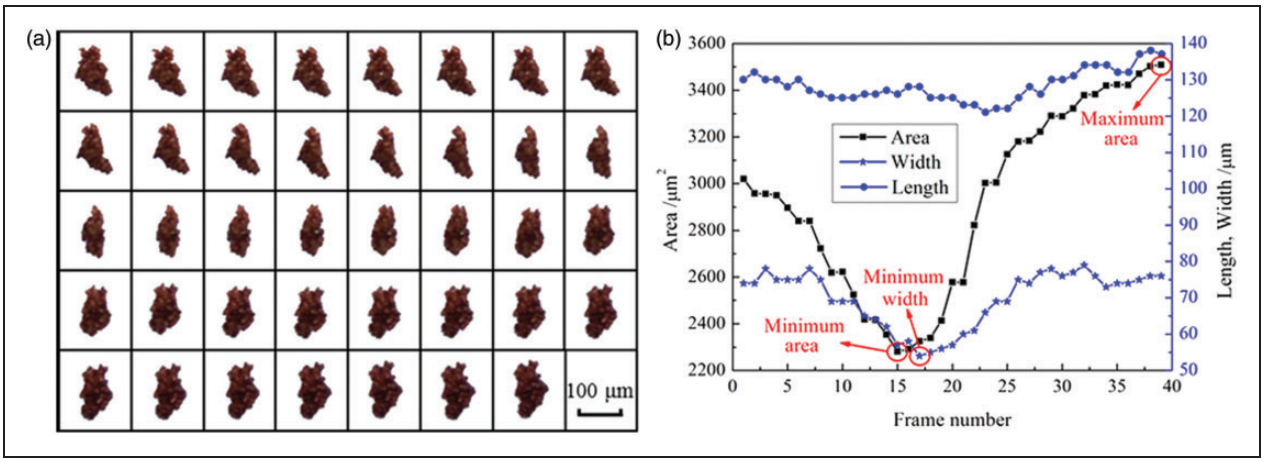

Figure 14. Information extracted from frame sequences with different views: (a) 39 image frames of a dynamic particle, and (b) the area, length and width obtained from (a).

flow, dynamic particle rotation in the oil is realised, and multi-view images are captured to extract 3D particle characteristics. Without magnetisation and scanning operations, individual particles are easier to be captured using the proposed device than the analytical ferrography approaches.[24,37,38] Different to the LaserNet Fines[23] described in the introduction section, the developed device can provide more information, such as colour, surface texture and spatial morphologies, by capturing multi-view colour images. Compared with the multi-view image capturing system reported in Dan,[21] the current work provides the basis of theoretical design and the system can be further developed for wear debris characterisation in online condition monitoring.

Furthermore, the proposed monitoring system can be applied to other engineering applications of wear state identification. In general, the quantity or concentration of wear particles is used to characterise wear rate and wear severity while individual particles are moving in the microfluidic device. Referring to the statistics of traffic flow, moving wear debris can be counted by employing object recognition and tracking.[33] Various trends of particle quantity can be obtained when a continuous monitoring is carried out. Different wear states of a running machine can be correspondingly identified. Therefore, the presented device is not limited to acquiring morphological features for wear mechanism analysis; it can be developed to examine wear rate for comprehensive wear state characterisation.

Further work is identified to improve the proposed system. First, factors including particle shape and oil density, affect the rotational motion of particles, but they have not been considered because of the need to simplify the force analysis on moving particles. In future work, hydrodynamics analysis software, e.g. Fluent, will be used to simulate two-phase flow (solid–liquid) to further optimise the oil flow channel design. Meanwhile, we will try to adjust the oil flow rate and change the channel inclination angle to facilitate rotational motion of wear debris. Second,

contaminants like dust and bubbles may cause mistakes of target particle segmentation. This issue is not taken into consideration because this work focuses on the hardware part instead of software program. Target recognition using their size, shape, colour and pixel values information will be further investigated to eliminate the contaminant effects. Third, it is necessary to employ more video frames to extract 2D features from different views to construct 3D features because the debris shapes are irregular. Correspondingly, some feature matching methods will be applied to construct stereo model of particles to extract 3D information for reliable wear debris analysis.

Conclusions

Three-dimensional characteristics of wear debris can be used for the understanding of wear mechanisms. Taking advantages of video image processing techniques, a new analytical instrument and method has been proposed for 3D wear debris analysis. As illustrated by the experimental results, conclusions can be drawn as follows.

i. A microfluidic channel designed based on hydrodynamics analysis is realised to make the lubrication oil in laminar flow. Wear particles carried by the oil are set in rotating movements under the effects of a torque.
ii. The microchannel is designed in infinite flow conditions, which is necessary to make the particles rotate around the same axis to image them from different angles. Based on this, spatial information such as thickness (the minimum width), height aspect ratio and sphericity can be constructed using a series of image sequences in different views.
iii. This developed system is effective to capture many kinds of particles. They can be various in sizes, small ($<50\,\mu m$), medium ($50–100\,\mu m$) and large ($>100\,\mu m$), and/or in different shapes, such as sphere-, flake- and fibre-like.

In summary, the newly proposed method provides a practical and effective solution for online condition monitoring using 3D wear debris analysis. Future investigation is directed to optimise the instrument, improve the accuracy of object recognition and explore 3D particle construction using multiple view images.

Declaration of Conflicting Interests

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