Scuffing mechanism during oil-lubricated block-on-ring test with diamond nanoparticles as oil additive

Hsiao Yeh Chu\textsuperscript{a}, Wen Chen Hsu\textsuperscript{b}, Jen Fin Lin\textsuperscript{b,c,*}

\textsuperscript{a} Department of Mechanical Engineering, Kun Shan University, Tainan County 710, Taiwan
\textsuperscript{b} Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan
\textsuperscript{c} Center for Micro/Nano Science Technology, National Cheng Kung University, Tainan 701, Taiwan

**A B S T R A C T**

In the present study, the mechanisms and microstructures of surface seizure induced scuffing in oil lubrication were investigated using experimental data including the profile of scuffing cavities and their surrounding plateaus, the chemical elements generated at these cavities, the selected area diffraction pattern of the lower specimen’s cross-section surface, and the energy dispersive spectrum. The materials in the plateaus were indentified as the upper specimen (SKD11 steel) transferred to the lower specimen (SKD61 steel) by adhesive wear. A reaction layer of Fe\textsubscript{2}O\textsubscript{3} formed on the substrate of the lower specimen from the analysis of the substrate piece obtained from the scuffing cavities. γ-Fe was found in the cavities; it was produced from the original α-Fe substrate when it reacted at a temperature of above 912°C. Many cavity arrays in hexagonal form were found in scuffing cavities obtained under certain operating conditions. They are believed to have been formed by the Benard cells of a fluid operating at a high temperature as well as by natural convection. The Grashof number corresponding to the oil vapor came closest to the critical Grashof number beyond which Benard cells were created. Results show that the nano-diamond particles additive is beneficial to resist scuffing since it can reduce the possibility of Benard cell-like structure formation by both increasing the surface hardness and reducing the friction power during the block-on-ring wear tests.

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**1. Introduction**

Scuffing is a local severe wear phenomenon on sliding surfaces and is accompanied by a sudden friction coefficient increase and contact temperature rise. It can thus damage machine parts. Therefore, a lot of researchers have conducted scuffing related studies in order to analyze scuffing both theoretically or experimentally. Carper and Ku\textsuperscript{[1]} suggested some critical values for the relationship of velocity and scuffing wear. Czichos\textsuperscript{[2]} experimentally studied the effects of surface temperature, velocity, and load on scuffing. Jackson et al.\textsuperscript{[3]} experimentally studied by a four-ball tester and the effects of surface temperature, velocity, and load on scuffing. Adsorption theory has been used to explain scuffing wear. Lee and Cheng\textsuperscript{[6]} tried to link the contact temperature with adsorption theory. They proposed the critical temperature–pressure (CTP) theory and proved it experimentally\textsuperscript{[7]}. They considered that an increase of critical scuffing temperature would increase the contact pressure and therefore reduce the adsorption between the surface and lubricant molecules, leading to the failure of the protection film.

Grew and Cameron\textsuperscript{[5]} described the chemical reactions on the contact surfaces and explained the relationship between the lubricant additives and scuffing wear. Adsorption theory has been used to explain scuffing wear. Lee and Cheng\textsuperscript{[6]} tried to link the contact temperature with adsorption theory. They proposed the critical temperature–pressure (CTP) theory and proved it experimentally\textsuperscript{[7]}. They considered that an increase of critical scuffing temperature would increase the contact pressure and therefore reduce the adsorption between the surface and lubricant molecules, leading to the failure of the protection film.

The effects of surface roughness on scuffing wear have also been researched. Cogdell et al.\textsuperscript{[8]} found that a parameter called the plastic index, which contained surface roughness, had a special relationship with scuffing wear. However, the study of Park and Ludema\textsuperscript{[9]} indicated that the plastic index was not a practical index for scuffing wear. Kelly et al.\textsuperscript{[10]} found that a reduction in surface roughness can increase the scuffing resistance and allow the surface to bear higher temperature and load.

Although scuffing wear had been widely investigated, there had been no study on the microstructure of the scuffed worn surface and on the cause of scuffing cavity formation. In our study, the mechanisms and microstructures of surface scuffing were investigated using experimental data including the profile of scuffing cavities.
and their surrounding plateaus, the chemical elements generated at the cavities, the selected area diffraction pattern of the lower specimens by TEM, and the energy dispersive spectrum. The iron phase change in microstructures and the oxides formed in the cavities were identified; and they were used to determine the causes and temperature conditions of surface scuffing occurrence. Many hole arrays in hexagonal form in the scuffing cavities are believed to be related to the Benard cells generated at the natural convection between two solid surfaces with different temperatures. The Grashof number defined for the appearance of these Benard cells is used to evaluate the values for liquid iron, lubricating oil, and the vapor of lubricating oil. These Grashof numbers are then compared with the critical value of the Grashof number required to initiate Benard cells in order to identify the fluid type that produced these hexagonal hole arrays. The mechanism of surface scuffing during oil lubrication is proposed.

2. Experimental details

The nano-diamond particles used in this study were provided by a commercial source (Chanyu Superhard, China). The basic

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**Table 1**

<table>
<thead>
<tr>
<th>Material (specimen)</th>
<th>Chemical compositions (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>SKD11 (upper)</td>
<td>1.40–1.60</td>
</tr>
<tr>
<td>SKD61 (lower)</td>
<td>0.32–0.42</td>
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</table>
nano-diamond lubricant additive was vibrated supersonically to obtain uniform dispersion. This nano-diamond lubricant additive was then added into a commercial oil (CPC circulation oil R68, Taiwan) in various volume percentages. The tribological performances of the sample oils with various concentrations of additives were determined on a wear test machine (Falex #6, USA). A data acquisition system (Red Lion CSMSTRSX, USA) was used to record the experimental data of oil temperature, electrical contact resistance (ECR), and friction torque in the testing process. A block-on-ring configuration was applied to simulate the tribological behavior at the sliding motion of oil lubrication. The reason to choose block-on-ring test is to simulate the piston ring and cylinder pair in an internal combustion engine. Three blocks made of SKD11 steel were pressed against the stationary lower specimen made of SKD61 steel and operated under various contact pressures and sliding velocities. The schematic diagram of the upper and lower specimens is shown in Fig. 1. The dimensions of the blocks and their adapter and the lower specimen in ring form are shown in Fig. 2. The configuration of the block is a 2.4 mm × 4.8 mm × 6.3 mm rectangular parallelepiped. Fillets were prepared for the two edges of the block's contact surface perpendicular to the sliding direction in order to have smooth motion. The upper specimens (blocks), with the chemical compositions shown in Table 1, were prepared without any heat treatment to give a hardness value of 334 ± 30 Hv (equivalent to HRc 29.8–36.6). The lower specimens, with the chemical compositions shown in Table 1, had their hardness values of 567 ± 31 Hv (HRc 52.3–56.8) using a heat treatment. The contact surfaces of the upper specimens were controlled to have a roughness of $R_s = 0.499 \pm 0.131 \mu m$ and the lower specimen was controlled to have $R_s = 0.044 \pm 0.016 \mu m$ before the oil lubrication test.

The operating conditions of tribological testing in the present study were arranged to have three contact pressures (3.54 MPa, 4.33 MPa, and 5.11 MPa) and three sliding velocities (4.87 m/s, 6.084 m/s, and 7.30 m/s). Three oil samples with different concentration of the nano-diamond lubricant additive (1 vol.% and 2 vol.%) and the base oil without nano-diamond additive were tested in order to investigate the tribological performances of friction, wear, and antiscuffing. The rheological properties of CPC R68 commercial oil are shown in Table 2. The total sliding distance for every test was fixed as 26280 m. Therefore, the testing time varied

![Fig. 4. Variations of the oil temperature, friction coefficient, and ECR vs. test time. The operating conditions of the nano-diamond lubricant additive concentration, test load, and specimen's speed are: (a) 0 vol.%, 4.33 MPa, and 6.084 m/s; (b) 1 vol.%, 5.11 MPa, and 4.867 m/s, respectively.](image-url)
Table 2
Rheological properties of CPC R68 oil.

<table>
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<th>Grade No.</th>
<th>R68</th>
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<td>Specific gravity at 15.6 °C</td>
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<tr>
<td>Viscosity, Kin., cSt (at 40 °C)</td>
<td>67.83</td>
</tr>
<tr>
<td>(at 100 °C)</td>
<td>8.62</td>
</tr>
<tr>
<td>Viscosity index</td>
<td>98</td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>12</td>
</tr>
<tr>
<td>Flash point, COC (°C)</td>
<td>264</td>
</tr>
<tr>
<td>Color (ASTM D1500)</td>
<td>L1.0</td>
</tr>
<tr>
<td>Total acid number (mg KOH/g)</td>
<td>0.08</td>
</tr>
<tr>
<td>Carbon residue, Rams. (%)</td>
<td>0.08</td>
</tr>
<tr>
<td>Emulsion, 54 °C, 40–40–0 (min)</td>
<td>20</td>
</tr>
<tr>
<td>Product No.</td>
<td>LA60343</td>
</tr>
</tbody>
</table>

The block-on-ring assembly was immersed in an oil cup filled with the oil samples according to the different sliding velocities. The block-on-ring assembly was immersed in an oil cup filled with the oil samples [11].

The microstructures on a worn surface with and without scuffing cavities were investigated. An optical microscope (Olympus BX51, Japan) was used to observe the textures of the worn surface. A micro figure measuring instrument (Ambios XP-2, USA) was used to scan the profile of a 0.25 mm × 0.25 mm region with scuffing cavities. An indenter with a tip radius of 0.2 μm in this instrument was used to measure the plateau heights and cavity depths. The SEM morphology of a worn surface including scuffing cavities was obtained using a high-resolution thermal field emission scanning electron microscope (Jeol JSM-7000, Japan). The chemical elements generated at the scuffing cavities and the plateaus surrounding these cavities were identified using an energy dispersive spectrometer (EDS; Metek, USA) attached to a transmission electron microscope (Fei Tecnai G2 20 S-Twin, USA). TEM was used to show the bright/dark field images and the selected area diffraction pattern of a thin specimen’s lateral surface. This thin specimen was prepared using a dual-beam focused ion beam (Fei Nova-200 NanoLab Compatible, USA). To maintain the integrity of the cutting piece, Pt or C was deposited on the specimen as the protective layer. A multipurpose X-ray thin film diffractometer (Rigaku RINT 2000, Japan) with Cu as the target material was employed to indentify the lattice constant and directions which can be used to determine the crystal system of the microstructures formed at various locations.

3. Results and discussion

3.1. The effect of diamond nanoparticles on the scuffing

The worn surfaces of the lower (ring) specimens after wear test shown in Fig. 3(a) and (b) were obtained at 0 vol.% and 1 vol.% of additive concentrations, respectively. Cavities in a separate or successive form were distributed over the worn surfaces which were full of straight grooves. The tribological parameters, including oil temperature, electrical contact resistance (ECR), and friction coefficient, corresponding to the operating conditions shown in Fig. 3(a) and (b) are shown in Fig. 4(a) and (b), respectively. As shown in these figures, the oil temperature and friction coefficient curves shown in Fig. 4(a) and (b) have jumps (increases) at the same time in the testing process. The ECR spectra also show a sharp drop at the time of the jump. Since the lubricating oil in the present study is an insulator for electrical current, a high ECR means that there was the

![Image of optical micrograph and 3D micrograph of a worn surface of the lower specimen.](image-url)
Fig. 6. The (a) SEM image, and the EDS analysis at the location of (b) plateau marked as (1), and (c) the cavity marked as (2) in the SEM image of the scuffed area.

Fig. 7. Variations of average hardness increment of the lower specimens with different nano-diamond additive concentration. Each nano-diamond additive concentration is an average of 9 tests (3 contact pressures × 3 sliding velocities).

Fig. 8. FIB images of the lower specimen surfaces. (a) Unworn surface, and (b) worn surface of a scuffing cavity obtained just after the friction coefficient jump.

lubricant between the upper and the lower specimen, decreasing the possibility of mutual asperity contact between the two surfaces. The sharp drop in ECR revealed that the oil film was instantly broken when the seizure occurred. Scuffing was immediately produced following the seizure; the ECR gradually increased again when the lubricating oil entered to fill the cavities behind the scuffing. The friction coefficient level was slightly higher after a jump, as was the oil temperature. A comparison between Figs. 3 and 4 indicates that the jumps in the oil temperature, friction coefficient and ECR spectra were due to the formations of seizures, which resulted in many cavities at the worn surface.

Fig. 5 shows the optical micrograph (OM) and α-stepper micrograph of a worn surface of the lower specimen with cavities due to seizure occurrences. There are plateaus around these cavities, which are believed to have been formed by the trapped wear particles that adhered to the lower specimen by the compression force between the two contact surfaces. The bottom surfaces of some cavities were measured to be at a depth below the worn surface without plateaus.

The chemical elements formed at the plateaus and the cavities shown in Fig. 6(a) are shown in Fig. 6(b) and (c), respectively. They were determined using an energy dispersive spectrometer.
Fig. 9. FIB images of (a) the reaction layer and the strip-like hole formed at the bottom surface of a scuffed cavity, and (b) unscuffed area of the same worn lower specimen's surface.

(EDS) (METEK, USA). The weight percentages of C, Cr, and Fe shown in Fig. 6(b) are the same as those found in the upper specimen (SKD 11 steel). This indicates that the plateaus formed in the lower specimen resulted from the material transferred from the upper specimen in the form of adhesive wear. The elements C, O, Si, S, Cr, and Fe were found using EDS analysis for the cavity region. The weight percentage of C is higher than that in the lower specimen because it is partly due to the contribution of the lubricating oil. Furthermore, the appearance of the S element confirmed the fact that the cavity was filled with oil when scuffing was created. The O element is believed to be related to the oxidation of iron in the cavities at a sufficiently high temperature.

The surface hardnesses of the lower specimens were measured both before and after the wear test in order to realize the role of diamond nanoparticle additive on scuffing. Fig. 7 shows the variations of average Vickers hardness increment of the lower specimens with different nano-diamond additive concentration. The hardness increment is defined as the hardness difference between after and before the block-on-ring tests. The hardness increment of each nano-diamond additive concentration shown in Fig. 7 is the average of 9 readings (3 contact pressures × 3 sliding velocities) obtained under the same nano-diamond additive concentration. The purpose for taking the average hardness increment value in this way is to compare the hardness variation due to different additive concentration only. The hardness increment increases when increasing the nano-diamond additive concentration. This behavior shows that the addition of nano-diamond additive can elevate the surface hardness under heavy loads, and is thus beneficial for the suppression of scuffing initiation.

There are two possibilities which may increase the surface hardness [12]. One is that the particles were pressed and embedded into the rubbing surfaces. The other is that the surface hardness increased due to the surface polishing of these particles, which leads to the strain hardening (work hardening) effect on the rubbing surfaces [12]. The latter is caused by the dislocation movements within the crystal structure of the material. A micro-Raman microscope (Jobin Yvon, France) was used to detect the sp³ structure of the carbon on the worn surfaces of the specimens operating at different nano-diamond additive concentration in the present study. No noticeable peak was found between 1000 and 2000 cm⁻¹ in the Raman spectra. This shows that the increment of specimen's

Fig. 10. TEM images of the (a) materials surrounding the strip-like hole, and (b) four layers between the hole and the reaction layer.
hardness is not caused by the nano-diamond particles embedded into the rubbing surfaces. The increase in the surface hardness can thus be attributable to the work hardening effect of nano-diamond particles on the rubbing surfaces.

3.2. The microstructure analysis on the scuffed surface

A dual-beam focused ion beam (Nove-200 NanoLab Compatible, USA) was used to prepare a very thin specimen for the TEM inspection. Fig. 8(a) shows the surface of the lower specimen before the wear test, whereas Fig. 8(b) shows the lateral surface of the lower specimen obtained shortly after a seizure was created. The nano-diamond additive concentration, test load, and specimen’s speed of this specimen are 1 vol.%, 4.33 MPa, and 7.3 m/s, respectively. The Pt layer acted as a protective layer during the cut-off process.

The main distinction between Fig. 8(a) and (b) is the existence of a reaction layer between the Pt layer (the protective layer) and the SKD 61 steel substrate in the scuffing cavity of the worn sample surface. Fig. 9(a) shows the magnification of the reaction layer formed at the bottom surface of a cavity. There are strip-like holes at this reaction layer. The lateral surface cut-off at the worn surface without scuffing cavities is shown in Fig. 9(b). No reaction layer was formed between the Pt layer and the SKD61 steel substrate. Therefore, it can be concluded that the reaction layer was formed only at the areas with cavities, which had a sufficiently high temperature.

The microstructures of the materials surrounding the strip-like holes (see Fig. 10(a)) were investigated using TEM (Fei Tecnai G2 20 S-Twin, USA). The four layers shown in Fig. 10(b) were found in the microstructures of the materials; they are labelled 1–4. The bright field images of these four layers are shown in Fig. 11(a–d), respectively. The outmost layer (layer 1) is the reaction layer. In the present study, the crystalline microstructures and the chemical compositions of these four layers were identified with the aid of the selected area diffraction of TEM and energy dispersive spectrum (EDS). The diffraction pattern shown in the upper right corner of Fig. 11(d) shows layer 4 to be some kind of crystallized
microstructure. Fig. 12 shows the selected area diffraction of layer 4. It was identified to be ferrite ($\alpha$-Fe) with a body-centered cubic crystal lattice. The weight percentages of Si, Cr, and Fe, as shown in the energy dispersive spectrum in Fig. 13(a), are quite close to the chemical compositions of the SKD 61 steel (the material of the lower specimen). Therefore, layer 4 was confirmed to be the same material as the lower specimen (SKD 61 steel).

Layer 1 is the outermost of the four layers from the hole. The bright field image and the selected area diffraction pattern are shown in Fig. 11(a). The diffraction pattern is identified as amorphous by electron microscopy. According to the energy dispersive spectrum in Fig. 11(a), the diffraction pattern shows the substrate material to be $\alpha$-Fe. At a small depth near the interface of the substrate and the reaction layer (labelled (1)), the microstructure is identified to be a composite material of $\alpha$-Fe (ferrite) and $\gamma$-Fe (austenite); the $\alpha$-Fe in the Bravais lattice is body-centered cubic (BCC), and $\gamma$-Fe is face-centered cubic (FCC). According to the Fe–C phase equilibrium diagram [13], partial transformation of $\alpha$-Fe into $\gamma$-Fe occurred at this thin layer. This transformation must have occurred at a temperature above 912 °C. With the C content of the lower specimen of about 0.4 wt.%, the Fe–C phase equilibrium diagram shows that $\gamma$-Fe (FCC) existed when the temperature at 912 °C. Apart from $\alpha$-Fe and $\gamma$-Fe, the selected diffraction pattern also shows the Bravais lattice of Cr to be hexagonal closed-packed (HCP) in the crystal system. The crystal diffraction of Cr in Fig. 14(c) with the HCP lattice coincides with the XRD spectra shown in Fig. 15 which was obtained using an X-ray diffractometer for the lower specimen before wear test. Fig. 15 shows that the first principal diffraction plane of Cr is (1 1 1), which proves the crystal structure of Cr to be the FCC crystal structure. The crystal structure of iron in the original lower specimen material (SKD 61 steel) is identified as the BCC structure since the first two sets of principal diffraction planes of iron shown in Fig. 15 are (1 1 0) and (2 0 0). With a chromium content in the SKD 61 steel of 4.5–5.5 wt.%, the crystal structure transformation of the iron from $\alpha$-Fe (BCC) to $\gamma$-Fe (FCC) takes place when the temperature is in a range of 846–1300 °C according to the Fe–Cr phase diagram [13]. This shows that the surface temperature at the scuffed cavity was at least higher than 846 °C. Therefore, the change in the chromium lattice structure may be also related to the temperature rise due to the frictional heat created during the sliding process.

3.3. The Benard cells microstructure on the scuffed surface

Micro holes in the hexagonal shape were occasionally found forming in a scuffed cavity due to the scuffing wear. Fig. 16(a) shows hexagonal hole arrays formed at a scuffed cavity. The nanodiamond additive concentration, test load, and specimen’s speed of this specimen are 2 vol.%, 4.33 MPa, and 7.3 m/s, respectively. The magnified image of these arrays is shown in Fig. 16(b). It should be mentioned that these hexagonal hole arrays were formed before FIB was used to prepare the TEM specimens. However, they appeared only when the operating conditions of the wear tests were sufficient to create cavities. These hexagonal holes are similar to the Benard cells formed under natural convection of a liquid arising between two parallel plates with different temperatures (the colder surface is located at the upper plate, and the hotter surface is located at the lower plate). These hexagonal cavities were created by one of the following three fluids: (1) liquid iron, (2) lubricating oil, or (3) the vapor of lubricating oil generated at a high temperature. The existence of the Benard cells is governed by the Grashof number (Gr), which is defined as:

$$Gr = \frac{g\rho(T_1 - T_2)\delta^3}{(\mu / \rho)^2},$$

where $\rho$ is the fluid density, $\mu$ denotes the dynamic viscosity of the fluid, $\beta$ is the mean volume expansion coefficient, $g$ is the gravity acceleration, $\delta$ represents the distance between the upper and lower plates, and $T_1$ and $T_2$ are the temperatures of the hot plate and cold plate, respectively. In the present study, the $\delta$ value is unavailable so it is assumed to be 5 μm in the evaluations of the Grashof number for the above three fluids. According to the literature [14], the Benard cells are created when the Grashof number of a fluid has a value greater than 1700. Such micro hexagonal-shaped holes,
as shown in Fig. 16(c), were also found on another scuffed cavity of the same specimen as Fig. 16(a). They were also observed on the surface of scuffed cavity in other specimens. The encircled areas in Fig. 16(d) show similar hole structure created at the scuffed cavity of the specimen with nano-diamond additive concentration, test load, and specimen’s sliding velocity to be 1 vol.%, 4.33 MPa, and 7.3 m/s, respectively.

Table 3 lists the values of material properties of liquid iron, lubricating oil, and oil vapor, and the temperatures of the upper and lower plates for the calculations of the Gr number. \( T_1 \) and \( T_2 \) are also unavailable. The \( T_2 \) value for iron is the lowest temperature at which it is in the liquid form; the \( T_2 \) values for the lubricating oil and the lubricating-oil gas are both assumed to be 100 °C. The \( T_1 \) value for liquid iron is 2000 K, and the \( T_1 \) values for the lubricating oil and the lubricating-oil vapor are assumed to be equal to the boiling temperature of general lubricating oils. Therefore, 350 °C (623 K) is assumed for these two fluids. The Grashof numbers obtained using the data in Table 3 follow the sequence: \( (Gr)_{\text{oil vapor}} \geq (Gr)_{\text{lubricating oil}} \geq (Gr)_{\text{liquid iron}} \). However, these three Grashof numbers are much smaller than the critical Grashof number \( (Gr = 1700) \). Nevertheless, the Grashof number of the lubricating-oil vapor was the closest to the critical

<table>
<thead>
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<th>Material</th>
<th>Liquid iron</th>
<th>Lubricating oil</th>
<th>Oil vapor</th>
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<tr>
<td>( \gamma ) (K)</td>
<td>102 \times 10^{-6}</td>
<td>348 \times 10^{-6}</td>
<td>(348 \times 10^{-6}) \times 250</td>
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<tr>
<td>( T_1 ) (K)</td>
<td>2000</td>
<td>623</td>
<td>623</td>
</tr>
<tr>
<td>( T_2 ) (K)</td>
<td>1810</td>
<td>373</td>
<td>373</td>
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<td>( \delta ) (m)</td>
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<td>5 \times 10^{-6}</td>
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<td>( \mu ) (kg m⁻¹ s⁻¹)</td>
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<td>33.05 \times 10^{-6}</td>
<td>-</td>
</tr>
<tr>
<td>( \rho ) (kg m⁻³)</td>
<td>6860</td>
<td>805.89</td>
<td>-</td>
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<tr>
<td>( \eta ) (m² s⁻¹)</td>
<td>0.617 \times 10^{-6}</td>
<td>0.410 \times 10^{-7}</td>
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</tr>
<tr>
<td>( Gr )</td>
<td>6.24 \times 10^{-5}</td>
<td>6.35 \times 10^{-2}</td>
<td>15.88</td>
</tr>
</tbody>
</table>
value (1700). Therefore, it is inferred that these hexagonal cavities were created by the high-pressure imprint of the oil–vapor Benard cells on the softened/liquefied iron substrate operating at a high temperature (≥912 °C).

3.4. Mechanisms of forming Benard cell-like holes

The schematic diagrams of forming the Benard cell-like micro hexagonal holes are shown in Fig. 17. They are illustrated as follows:

(a) Frictional heat generation: Fig. 17(a) shows two mutually sliding surfaces. Oil is entrapped in the asperity valleys (denoted by “region A’s”); the contact surfaces are heated to a higher temperature at the frictional contact areas (denoted by “region B’s”).

(b) Oil temperature rise: As the upper specimen slides leftward, the oil between the asperity contact surface areas can be heated by the hot surfaces, as shown in Fig. 17(b). The natural convection similar to the Benard cell form occurs due to the hot lower surface (asperity peak) and the cool upper surface (valley). Besides, heat transfer (heat conduction from the upper hot surface + forced convection due to sliding viscous shear)

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**Fig. 15.** XRD spectra of the unworn lower specimen.

**Fig. 16.** (a) Micro hexagonal-shaped holes on the surface of the scuffed cavity with nano-diamond additive concentration, test load, and specimen’s speed of this specimen are 2 vol.%, 4.33 MPa, and 7.3 m/s; (b) magnified image of the micro hexagonal-shaped holes; (c) micro hexagonal-shaped holes on the surface of another scuffed cavity in the same specimen as (a); (d) micro hexagonal-shaped holes on the surface of scuffed cavity in another specimen. The nano-diamond additive concentration, test load, and specimen’s speed of this specimen are 1 vol.%, 4.33 MPa, and 7.3 m/s, respectively.
denoted by “↑” will also occur in the hotter regions (denoted by “region B’s”) on the upper surface. (c) Oil evaporation: As the upper surface slides, the oil entrapped inside region A’s is repeatedly heated as illustrated in Fig. 17(a) and (b), it finally evaporates and becomes bubbles, as shown in Fig. 17(c). (d) Oil vapor bombardment on the hotter and softer region B’s: High-pressure oil bubbles impinge both the upper and lower surfaces. Since these asperity contact areas (as denoted by “region B’s” in Fig. 17(a)) are much hotter than those uncon- tact areas, these asperity contact surfaces are thus softer than other surface areas. As the oil starts evaporating, the volume expands rapidly. This drastic volume expansion leads to the bombarding on the surfaces, as shown in Fig. 17(d). The hexagonal-shaped holes will form on these softer surfaces. Benard cell-like hexagonal holes are thus developed.

From the mechanisms of forming Benard cell-like holes on the scuffed surface, it is clear that if the friction power generated by the mutually sliding motion is less, or the hardness of the surface is higher, the possibility of scuffing initiation will be less. Since the addition of nano-diamond particles can not only increase the surface hardness during the block-on-ring wear tests, as shown in Fig. 7, but also reduce the friction power [11], it shows the nano-diamond particles additive is beneficial to resist scuffing.

4. Conclusion

Adhesive wear occurred in the oil lubrication in a form of a material transfer from the upper specimen to the lower specimen. The worn surface of the lower specimen had scuffing cavities after seizure took place. This was accompanied by a sudden jump in friction coefficient and oil temperature. Seizures and scuffing were thus occurred at small contact areas of the two sliding surfaces, where high contact temperatures were generated due to the concentrated frictional heat. The high temperature in the cavity region allowed the production of a reaction layer on the lower specimen substrate. This thermal reaction layer was identified to be amorphous Fe$_2$O$_3$. At the thin layer between the lower specimen substrate (α-Fe) and the reaction layer, α-Fe and γ-Fe coexisted. γ-Fe formation indicated that the temperature at this thin composite layer was above 912 °C. This temperature was confirmed by the Fe–C phase diagram. The surfaces could be protected from the reaction layer after the scuffing took place due to high temperatures during the scuffing.

Cavity arrays in a hexagonal shape were found at the scuffed cavities when the Grashof number of the fluid operating at high temperatures exceeded the critical value in which Benard cells of a fluid were generated between two surfaces with different temperatures in a form of natural convection. The Grashof number evaluated for the lubricating-oil vapor was closest to the critical Grashof number. These hexagonal Benard cells-like cellular arrays onto the softened SKD 61 steel substrate were formed by the imprints of these high-pressure oil vapors. The nano-diamond particles additive is beneficial to resist scuffing since it can both increase the surface hardness and reduce the friction power during the block-on-ring wear tests.

References