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THE ROLE OF DYNAMIC RECRYSTALLIZATION IN DRY SLIDING WEAR

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Summary

In dry sliding wear dynamic recrystallization gives a better understanding than grain boundary sliding and fatigue of the process near the contact zone. The process explains the low value of the deformation measured by grain thickness reduction and the absence of visible deformation marks in the case of low melting materials. Dynamic recrystallization explains the almost total consumption of the friction energy by the plastic process. It is also possible to compute the geometry of the worn material in a wear test. This phenomenon is proved experimentally using a copper pin sliding against an SAE 1045 steel ring. Pins of both single crystal and polycrystalline copper were used. The structure was observed by examining thin foils of the material taken from near the contact zone in an electron microscope.

1. Introduction

The importance of plastic deformation in the dry sliding wear of many sliding couples was suggested by Gümbel [1] in 1925. However, at that time plasticity theory was not sufficiently developed to make an appropriate assessment of this proposition. Some time ago this postulation was reconsidered by Dautzenberg and Zaat [2]. The basic idea was that considerable displacement in dry sliding wear occurs by plastic deformation of one or both contact layers. This idea cannot be described quantitatively. Therefore Dautzenberg and Zaat assumed a constant shear stress in a track of width $b$ (small in comparison with the total width of the test piece) and of infinite length. (It can be proved using plasticity theory [3] that the displacement of the material during wear is caused by simple shear.) The track width was divided in small elements and it was assumed that the shear stress in the material below each element reduces in a circular manner. Then the shear stress distribution of the material below the track was derived by integrating over the track width $b$. (In physics this principle is commonly used for computing the light intensity distribution of a finite light source.)
Transformation of the shear stress distribution in an effective stress distribution and use of the Nadai relation [3] allows the effective strain distribution below the track to be derived as a function of the effective strain in the contact surface, the strain hardening exponent, the track width and the coordinates of the location. If deformation occurs in the plane of maximum shear stress it is also possible to calculate the displacement field. (The solution for the middle of the track is given in refs. 4 and 5; the general solution is given in ref. 3.) If the maximum effective strain, some material constants and the wear velocity are known it is possible to calculate the power necessary for this wear process.

The analysis shows that in order to control the model the effective strain must be determined. This is done by a method proposed by Dautzenberg and Zaat [21]. They derived the following expression for the effective strain $\bar{\varepsilon}$ in this stress state:

$$\bar{\varepsilon} = \frac{d_0}{d} \sqrt{3} \quad d_0 \gg d$$ (1)

where $d_0$ and $d$ are the average linear intercepts of the original and the deformed grains. Comparison of the theoretical an effective strain in the good agreement [3] except in two important cases: an effective strain in the contact surface of 400 is required for a quantitative description of the displacement field (Fig. 1 shows a displacement field); when the plastic deformation power has to be equal to the friction power an effective strain of 400 is also required. However, the measured values of the effective strain are in the range 40 - 100. (These values refer to copper sliding against SAE 1045 steel.) Referring to eqn. (1) this means that the measured values of $d$ for both cases are too high. From a metallurgical viewpoint this can be caused by one of the following mechanisms: grain boundary sliding; cyclic softening (similar to fatigue behavior); dynamic recrystallization. The first mechanism was proposed by Dautzenberg and Zaat [5] and the second by Suh and Sridharan [6]. The third mechanism is the most probable and can be distinguished by examining electron micrographs of thin foils of material near the contact surface.

Apart from the direct control of the proposed model with deformation measurements, it is also possible to use the same model to calculate [7] the metallurgical texture of worn surfaces [8, 9]. These texture measurements also support the proposed model for a number of sliding pairs.

Fig. 1. The displacement field of a worn copper pin made visible by placing an aluminium foil between the two halves of the pin which was cut perpendicular to the displacement direction and pressed together before the wear test against SAE 1045 steel.
2. Specimen preparation and testing

Sliding tests were performed on a pin-on-ring machine [2]. The OFHC polycrystalline copper pins, which were cylinders 30 mm long and 8 mm in diameter with an axial cylindrical hole 20 mm long and 3.5 mm in diameter for holding a thermocouple, were vacuum annealed for 3 h at 750 °C. The average grain diameter of the pin was between 10 and 15 μm. The rings were flat disks of normalized SAE 1045 steel 80 mm in diameter and 10 mm thick.

The copper single crystal pin (Ø 5.5 mm) was pressed against a ring which had been used previously in a test with a polycrystalline copper pin. All tests were carried out in a normal atmosphere. The pin was pressed against the ring with an adjustable normal force and the sliding velocity of the ring was also adjustable. During testing the frictional force, the axial displacement of the pin (used for measuring the wear rate) and the temperature of the pin were recorded.

Thin foils were taken from the pins according to the method of van Dijck [10]. The temperature of the pin was kept at -20 °C during the thinning process.

The displacement field in the copper was made visible by placing an aluminium foil between two halves of a pin which had been cut perpendicular to the subsequent friction direction and pressed together before the wear test.

3. Experimental results

Table 1 gives the wear data for all the copper pins used for making one or more electron micrographs. Figure 2 shows an electron micrograph of a section of a copper pin taken 12 μm beneath the sliding surface by making a cut perpendicular to the sliding surface and parallel to the frictional force. Elongation of the grains can be seen in the sliding direction. Figures 3 and 4 were prepared from the sliding surface of a copper pin sectioned by a cut parallel to the sliding surface. Figure 3 shows small and highly elongated grains together with equiaxed grains. Both the equiaxed and light grains and possibly the highly elongated grains are recrystallized. A difference in dislocation density is obvious. Figure 4 is a selected area electron diffraction pattern of the same area (3 μm²) as Fig. 3. Apart from the very different orientations of the grains, a texture is also evident. Figures 5 - 7 show a section perpendicular to the sliding surface and parallel to the frictional force. Apart from the displacement marked by arrows, Fig. 6 is the continuation of Fig. 5. In the upper part of Fig. 5 a layer which was deposited electrochemically to make a thin foil [10] is visible. There is a difference in dislocation density and grain elongation in the sliding direction. This effect can also be seen in Fig. 3. At greater distances from the sliding surface the grains are larger and longer (Fig. 6). A selected area (3 μm²) electron diffraction
TABLE 1
Wear data for the copper pins used for electron micrographs

<table>
<thead>
<tr>
<th>Normal force</th>
<th>Sliding velocity (m s⁻¹)</th>
<th>Frictional force (N)</th>
<th>Wear rate (mm³ s⁻¹)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
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<td>40</td>
<td>2</td>
<td>36</td>
<td>0.23</td>
<td>1</td>
</tr>
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<td>40</td>
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<td>2</td>
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<td>0.18</td>
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<td>2</td>
<td>38</td>
<td>0.25</td>
<td>5, 6, 7</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>40</td>
<td>0.13</td>
<td>8, 9</td>
</tr>
</tbody>
</table>

Fig. 2. Electron micrograph of long drawn grains obtained 12 μm from the contact zone of a polycrystalline copper pin sectioned parallel to the frictional force and perpendicular to the contact plane.

pattern (Fig. 7) 6 μm from the sliding surface shows that the grains are real. From Figs. 3, 5 and 6 it is evident that following recrystallization many grains have again deformed. This indicates that recrystallization has occurred during the sliding process.

Figures 8 and 9 show electron micrographs of a thin foil from a worn copper single crystal. The thin foil was obtained from a cut perpendicular to the sliding surface and parallel to the frictional force. Figure 8 shows the poly-
Fig. 3. Electron micrograph of the contact zone of a polycrystalline copper pin sectioned parallel to the sliding surface.

Fig. 4. Selected area electron diffraction pattern (3 μm²) of part of Fig. 3.
Fig. 5. Electron micrograph of a polycrystalline copper pin sectioned parallel to the frictional force and perpendicular to the contact plane. The electrochemically deposited layer in the upper part should be noted. (Courtesy of J.A. Klostermann.)

Fig. 6. Electron micrograph of a polycrystalline copper pin sectioned parallel to the frictional force and perpendicular to the contact plane. Apart from the displacement indicated by the arrows Fig. 6 is a continuation of Fig. 5. (Courtesy of J.A. Klostermann.)
Fig. 7. Selected area electron diffraction pattern (3 $\mu$m$^2$) of a part of Fig. 6 taken 5 $\mu$m from the contact zone. (Courtesy of J.A. Klostermann.)

Fig. 8. Electron micrograph of the contact zone of a single crystal copper pin sectioned parallel to the frictional force and perpendicular to the contact plane.
crystalline structure. Figure 9, which is a selected area (3 μm²) electron diffraction pattern of Fig. 8, shows that the single crystal has recrystallized and that the differences in orientation between grains are great. All the selected area diffraction patterns clearly show texture which had previously been revealed by X-ray examination [8, 9]. The grain diameter estimated from the spots on the selected area diffraction ring is in agreement with the grain diameter obtained from the electron micrographs.

4. Discussion

There are three possible causes of the difference between the experimentally measured and the computed displacement fields: grain boundary sliding, fatigue and dynamic recrystallization. These also affect the friction and plastic power.

4.1. Grain boundary sliding

This postulation due to Dautzenberg and Zaat [5] is unlikely. This process is normally only possible at temperatures greater than two-thirds of the melting temperature. In dry sliding wear the temperature is usually much lower. However, it is possible that the low temperature could be compensated by the very high deformation of the material. In grain boundary sliding the grain boundaries in the material follow a zigzag pattern. Therefore diffusion, which is dependent on time and temperature [11], is
needed to maintain continuity of the material during sliding wear. In dry sliding wear the deformation rate is very high \((10^3 - 10^4 \text{ s}^{-1})\) and the temperature can be relatively low so that material transport by diffusion is not possible.

Grain boundary sliding does not explain the segmentation of long drawn grains in small almost equiaxed grains with large orientational differences (Figs. 3, 5, 6 and 8). For this process the grain size of the deformed material (perpendicular to the frictional force and parallel to the sliding surface) has to be the same as that of the original undeformed grains but Fig. 3 contradicts this completely.

4.2. Fatigue

This mechanism was proposed by Suh and Sridharan [6]. If only the friction and plastic power are considered it may be a good solution. However, the computed power for the measured displacement field, i.e. the power to transfer material from the pin to the beard, is similar to the friction power. Also there is no power for the oscillation of material between pin and beard. This is one of the most important objections to a fatigue mechanism.

4.3. Dynamic recrystallization

During dry sliding wear the contact between pin and ring is not continuous but is a discontinuous contact which is dependent on the experimental conditions with a frequency of several hundred cycles [3]. The material has to recrystallize during the contact time. This is the only possible explanation of the different deformation states shown in the electron micrographs of thin foils of material obtained near the contact surface (Figs. 2, 3, 5, 6 and 8). These deformation states are not only taken from the form of the equiaxed and different long drawn grains but also from the high and low dislocation densities inside the grains. The process must also produce grains [12] such as those that can be seen in the electron micrographs of thin foils obtained from the sliding surface (Figs. 3, 5, 6 and 8). These grains also have considerable orientational differences (Figs. 4, 7 and 9).

The only process that can satisfy the different properties is not static recrystallization but dynamic recrystallization which occurs many times during the deformation process. After the first recrystallization eqn. (1) is no longer valid so that the grain thickness cannot be used to calculate the deformation. The different etching behaviour of various parts of the cross section of a worn pin can also be explained in terms of dynamic recrystallization. Material near the sliding surface shows a different etching response. Another property of dynamically recrystallized material is that of lowering the shear stress [12]. This is similar to a strain-hardening exponent with zero value [4] responsible for the concentration of shear in the zone near the sliding surface. It can also explain the almost complete absence of deformation marks in dry sliding wear of low melting point materials. The only problem concerning these experiments on dynamic recrystallization is the low process temperature in comparison with the process temperatures of other investiga-
tions of this phenomenon [13]. It is estimated that for a copper–steel sliding pair under the conditions of this work the maximum temperature including the flash temperature is below 500 °C [3]. However, this phenomenon can also occur at much lower temperatures owing to the very high deformation. It is probable that the very high deformation lowers the dynamic recrystallization temperature.

5. Conclusions

The following phenomena observed in dry sliding wear can be explained by assuming that dynamic recrystallization occurs near the contact zone:
- the difference between the computed and measured deformation;
- the concentration of shear;
- the almost complete absence of deformation marks in low melting point materials;
- the segmentation of long drawn grains;
- the presence of fine grains in selected area electron diffraction patterns;
- the different dislocation densities in the grains;
- the different etching response of the material near the contact surface compared with the bulk material;
- the difference between the computed and measured displacement field;
- the difference between the computed and measured power necessary for plastic deformation.

Acknowledgments

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