The formation and characterization of fretting-induced degradation layers using quenched and tempered steel

Verner Nurmia, Jouko Hintikka, Janne Juoksukangas, Mari Honkanen, Minnamari Vippola, Arto Lehtovaara, Antti Mäntylä, Joona Vaara, Tero Frondelius

Abstract

Fretting movement is dangerous for machines, because it can cause cracking and surface degradation. The aim of this work was to characterize fretting-induced material degradation in large flat-on-flat contacts without edge effects in a sliding direction using quenched and tempered steel 34CrNiMo6. The focus was on the adhesive contact spots, which were formed under a wide variety of operating conditions. Characterization methods were optical microscopy, Vickers hardness tests and scanning electron microscopy. Three different degradation areas were observed: a general deformation layer, a tribologically transformed structure and a third body layer. All the degradation phases have high hardness and low ductility compared to the base material. The formation and behavior of the degradation layers in different operating conditions were discussed.

1. Introduction

In fretting, contact surfaces under normal loading will experience reciprocating relative movement. The size of this slipping movement can be anywhere between a few micrometers and several hundred micrometers. This leads to surface degradation, which also accelerates nucleation of fatigue cracks [1]. Fretting is characterized by surface damage and wear debris that tends to get trapped in the contact [2]. As fretting takes place inside the contact, there may be no discernible sign of damage before the contact is opened or the total failure of component, which is why fretting is so particularly dangerous.

Hintikka et al. [3] and Juoksukangas et al. [4] carried out fretting tests with large-scale flat-on-flat contact configurations. They observed the formation of millimeter-scale adhesive material transfer spots in their specimens of quenched and tempered steel. Hintikka also found a correspondence between these adhesive contact spots and non-Coulomb friction behavior. The coefficient of friction (COF) in a fretting contact can be easily over unity, and can thus have a decisive effect on slip and cyclic stresses. It is also worth noting that the COF can evolve during fretting tests in stable load conditions [5]. Depending on factors such as loading, contact geometry and COF, the contact can be fully sliding (gross slip), slip can occur only in certain regions (partial slip) or the area can be completely stuck (stick). Design and dimensioning against fretting damage is challenging due to uncertainties in the friction and wear behavior in the contact [6–8].

Fretting may lead to severe changes in material microstructure and cause material transfer in the contact surfaces. Pape and Neu studied PH13-8Mo stainless steel in cylinder-on-flat and flat-on-flat contact configurations [9]. Severe plastic deformation occurred in the fretting contact and crack initiation took place within only 200 cycles. Li et al. studied fretting wear with Inconel 600 alloys in ball-on-flat contacts [10]. Cross-section samples made from the fretting scars revealed plastically deformed material (general deformation layer, GDL), extremely hard tribologically transformed structure (TTS) and a third body layer (TBL). Sauger et al. [11] proposed that TTS undergoes phase transformation leading to its thermodynamically stable microstructure, which is ferrite in the case of steels. Strain-induced recrystallization would also lead to a nanocrystalline structure. They found that most of the third body is formed when hard and brittle TTS cracks under contact stresses, milling into smaller particles, which can later sinter back to the surface forming the TBL.

Zhou et al. studied TTS in steels with a ball-on-flat fretting device [12]. TTS formation was only observed in the sliding zone, and they suggested that shear stress is the main factor for TTS formation, rather
than temperature. Sauger et al. [13] stated that TTS formation takes place due to the accumulated plastic strain and the concentration of dislocations. They observed that the TTS contained oxygen as much as the base material, indicating that oxygen does not play a part in the generation of TTS. By evaluating the accumulated dissipated energy of a fretting contact, the threshold value needed for TTS formation can be found [11,14]. Any further increase in the dissipated energy will contribute to wear.

Colombie et al. [15] studied the formation of a debris bed in fretting and its effects on fretting wear. They concluded that in ductile metals wear particle ejection occurs after the plastic deformation of material, and that the formation of wear debris slows down the wear rate of the material. Hintikka et al. [2] obtained similar results about the effect of wear debris on wear rate in large flat-on-flat contact. Everitt et al. [16] studied the evolution of the third body in Ti-6Al-4V in a cylinder-on-flat test device. They found that in gross sliding conditions the TBL is thicker at the center of the fretting scar than it is at the edges, and the TBL is about twice as hard as the base material. Hayes and Shipway [17] studied the effect of temperature on wear in cylinder-on-flat fretting tests. A higher temperature increased the amount of sintered TBL and thus decreased the wear rate of the material.

Most fretting research utilizes Hertzian type contacts, whose contact sizes are relatively small [10,11,16]. In industrial contacts, such as bolted joints and pressure fits, the nominal contact area is typically much larger than it is in laboratory tests, and the nominal contact pressure is lower. However, there has been no coherent study of fretting-induced material behavior in nominally flat-on-flat contact surfaces over a wide range of running conditions. Therefore, the objective of this study is to characterize fretting-induced material degradation in large flat-on-flat contacts without discontinuities in a contact surface in a sliding direction using quenched and tempered steel. The study focuses on the material behavior, and on the surface layers within the vicinity of adhesive contact spots formed under a wide variety of operating conditions. This data will contribute to our fundamental understanding of fretting damage and crack nucleation mechanisms.

2. Fretting tests

The annular flat-on-flat fretting test device that was used in the experiments is described in detail in Reference [3]. In the test device, two identical annular specimens are pressed together to form a large flat-on-flat contact without any edge effects in the sliding direction, thus efficiently simulating practical contact conditions. The test material was martensitic EN 10083-1-34CrNiMo6+QT, which is a typical high-strength steel for machine parts under fatigue loading. Fig. 1 shows the fretting test specimen and a cross-section of the specimens and their holders. The tubular part is 5 mm thick with an inner radius of 7.5 mm and an outer radius of 12.5 mm. The surface roughness values (Sa) of the specimens were between 0.20 and 0.32 μm for all the tests.

During the experiments, normal force is kept constant while one of the specimens is rotated around its central axis to create reciprocating fretting movement between the specimens. The normal load (P), torque (T) and rotation (θ) are measured, from which the coefficient of friction can be calculated [3]. The specimen’s elastic deformation is included in the measurements and it is numerically removed to obtain rotation at the contact interface. Sliding between the contact surfaces is calculated using an average radius of 10 mm. Most of the tests were performed in a gross-sliding regime, but a few were also done in partial slip regime. Nominal normal pressure (p) varied from 10 to 50 MPa. The sliding amplitude in the partial slip tests was from 0.5 to 4 μm and in the gross-slip tests it was from 5 to 65 μm. The fretting loading frequency was 40 Hz. The rotation amplitude was ramped up to the desired value during the first 400 loading cycles and kept constant until the end of the test, after which the rotation amplitude was decreased to zero over 100 cycles. The tests were continued until three million load cycles was reached. Short duration tests of 100, 1000 and 10000 loading cycles.

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**List of symbols and abbreviations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>N&lt;sub&gt;Lc&lt;/sub&gt;</td>
<td>loading cycles</td>
</tr>
<tr>
<td>p</td>
<td>nominal normal pressure</td>
</tr>
<tr>
<td>P</td>
<td>normal load</td>
</tr>
<tr>
<td>Sa</td>
<td>surface roughness</td>
</tr>
<tr>
<td>T</td>
<td>torque</td>
</tr>
<tr>
<td>u&lt;sub&gt;a&lt;/sub&gt;</td>
<td>sliding amplitude</td>
</tr>
<tr>
<td>θ</td>
<td>rotation</td>
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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</thead>
<tbody>
<tr>
<td>BC</td>
<td>band contrast</td>
</tr>
<tr>
<td>BCC</td>
<td>base centered cubic</td>
</tr>
<tr>
<td>EBSD</td>
<td>electron back scattering diffraction</td>
</tr>
<tr>
<td>EDS</td>
<td>energy dispersive spectrometer</td>
</tr>
<tr>
<td>GDL</td>
<td>general deformation layer</td>
</tr>
<tr>
<td>IPF</td>
<td>inverse pole figure</td>
</tr>
<tr>
<td>TBL</td>
<td>third body layer</td>
</tr>
<tr>
<td>TTS</td>
<td>tribologically transformed structure</td>
</tr>
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</table>
excluding the start-up and shut-down periods were also performed. The sliding amplitude in these tests was 35μm and the normal pressure 30MPa. The test conditions are summarized in Table 1.

The specimens were cleaned with solvent before the tests, thus mirroring dry contact conditions. Even distribution of the contact pressure was ensured by using pressure-sensitive paper, and contact alignment was adjusted if necessary. The full duration tests were carried out in a laboratory environment with a temperature and relative humidity between 25–30°C and 22–44%, respectively. The short duration tests were done at different time, when the temperature was in the range of 19–25°C and the relative humidity in the range of 14–24%.

### 3. Characterization methods

A typical contact surface with fretting scars is shown in Fig. 2, representing operating parameters of 35μm sliding amplitude and of 10 MPa normal pressure. The most severe fretting scars are initiated and then spread out from the adhesion material transfer spots, hereafter referred as adhesion spots. The main point of interest in this study was the material behavior within these adhesion spots.

After the fretting tests, the procedure was first to clean the contact surfaces with acid detergent to remove loose debris from the surfaces, and then document the contact surfaces with a Leica MZ75 stereo-microscope. The cross-section samples were prepared in parallel with the slip amplitude as shown in Fig. 2. The cutting line of the cross-section sample was intended to be through the center of an adhesion spot.

The cross-section samples were mounted on a thermoset with carbon additive. The surface of the cross-section was ground and given a final polish with 1μm diamond suspension. After polishing, the samples were etched with 4% Nital (HNO₃) to reveal the microstructure of steel.

A Leica DM 2500M optical microscope (OM) and a Philips XL 30 scanning electron microscope (SEM) together with an EDAX DX4 energy dispersive spectrometer (EDS) were used to document the fretting scar cross-sections. The elemental line analyses were performed with a Zeiss Crossbeam 540 SEM and an Oxford Instruments XMaxN EDS. The hardness measurements were performed with a Struers Duramin-A300 and an MMT-X7 Matsuzawa. Electron Backscatter Diffraction (EBSD) measurements were performed with a Zeiss ULTRAplus SEM, equipped with HKL Premium-F Channel EBSD system with a Nordlys F400 detector to study plastic deformation in fretting scars.

### 4. Results and discussion

All the fretting tests caused some degree of surface damage. The damage was most severe near the adhesion spots, which were the focus of this study. Greatest damage occurred in the samples which had suffered gross-sliding conditions and three million load cycles. As had previously been observed in the literature [10,11], there were three different degradation layers, see Fig. 3. Moving outwards from the base material to surface, these layers are the general deformation layer (GDL), the tribologically transformed structure (TTS) and the third body layer (TBL). The degree to which their properties and structure deviate from the base material follows the same in order in that; closer the layer is to the surface, the more changes the material has undergone. All three degradation phases are harder than the base material, and are discussed in more detail below in separate subsections 4.1-4.3.

The SEM studies showed no sign of plastic deformation outside immediate presence of fretting scars. According to the literature, microstructure reorientation within the grains can take place in martensite, even though no plastic deformation has occurred [18]. However, it seems that all the major changes in the material have taken place within the adhesion spots. Major cracks initiated only on the sides of the adhesion spots. Fig. 3 is a typical example. Cracks grew at an average angle of 26° measured from the contact surface. The length and

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**Table 1**

<table>
<thead>
<tr>
<th>Running condition</th>
<th>Loading cycles</th>
<th>Normal pressure $p$ [MPa]</th>
<th>Sliding amplitude $u_a$ [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross slip</td>
<td>$3 \times 10^6$</td>
<td>10</td>
<td>5, 20, 35, 50, 65</td>
</tr>
<tr>
<td>Gross slip</td>
<td>$3 \times 10^6$</td>
<td>30</td>
<td>5, 20, 35, 50, 65</td>
</tr>
<tr>
<td>Gross slip</td>
<td>$3 \times 10^6$</td>
<td>50</td>
<td>20, 35, 50</td>
</tr>
<tr>
<td>Partial slip</td>
<td>$3 \times 10^6$</td>
<td>30</td>
<td>0.5, 1, 2, 3, 4</td>
</tr>
</tbody>
</table>

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**Fig. 2.** The white lines represent the cutting positions. The white arrow shows the direction from which the metallurgical sample was observed.

**Fig. 3.** Different surface layers in fretting. Test parameters: $u_a = 20\mu m$, $p = 30\text{ MPa}$ and $N_{LC} = 3 \times 10^6$. 
depth of the majority of the cracks varied from tens to hundreds of micrometers.

The material around the cracks is plastically deformed (GDL), which is essential for cracking. Farther away from the adhesion spots only the undeformed martensite (base material) and an occasional thin layer of sintered wear debris were found, the TBL being less than 5 μm thick.

### Table 2

Hardness measurement results from the base material and the GDL. The mean values and standard deviations are both higher in the deformed martensite. The measurements of the deformed martensite are made within the adhesion spots.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean Value</th>
<th>Maximum Value</th>
<th>Minimum Value</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Material (HV 0.05 kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 μm, 10 MPa, $3 \times 10^6$</td>
<td>342 HV</td>
<td>382 HV</td>
<td>238 HV</td>
<td>39 HV</td>
</tr>
<tr>
<td>35 μm, 30 MPa, $3 \times 10^6$</td>
<td>375 HV</td>
<td>400 HV</td>
<td>357 HV</td>
<td>14 HV</td>
</tr>
<tr>
<td>GDL (HV 0.05 kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 μm, 30 MPa, $3 \times 10^6$</td>
<td>658 HV</td>
<td>906 HV</td>
<td>416 HV</td>
<td>145 HV</td>
</tr>
<tr>
<td>35 μm, 30 MPa, $3 \times 10^6$</td>
<td>517 HV</td>
<td>689 HV</td>
<td>384 HV</td>
<td>76 HV</td>
</tr>
</tbody>
</table>

### Table 3

Base material composition measured with EDS.

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt %</th>
<th>Si</th>
<th>Mo</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>1.3</td>
<td>0.8</td>
<td>95.8</td>
<td>1.3</td>
<td>100.0</td>
</tr>
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</table>

Fig. 4. SEM image (A) shows the locations of the orientation maps. The major cracks are marked by white lines. The IPF maps superimposed on the BC maps are collected from the region between the two major cracks' ends (B and C) and near the contact surface (D and E). The colors in the IPF maps correspond to the orientations (martensite, BCC) perpendicular to the observed plane as indicated by the IPF coloring key. This sample was run with test parameters of $u_0 = 50 \mu m$, $p = 50 MPa$ and $N_{LC} = 3 \times 10^6$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
4.1 General deformation layer

The general deformation layer (GDL) consists of plastically deformed martensite. The contact stresses have plastically deformed martensite making it heterogeneous in both its appearance and its mechanical properties. As can be seen in Fig. 3, the martensite under the adhesion spot is orientated parallel to the face of the crack. Table 2 presents the results of the hardness measurements of the martensite. On average, the measured hardness values of the base material were close to its typical values, except the minimum value of series (238 HV), which was clearly an exception. Inside the adhesion spots hardness values were 50–70% higher than in the base material. This result is interesting, because the hardness in the adhesion spots is higher than the theoretical hardness of totally work hardened material [19]. Either some phase transformations have taken place in material or compressive stresses are generated to disturb measurements [20].

Table 3 presents the elemental distribution of the steel used in our tests, measured with an SEM-EDS. The composition of the base material corresponds well to the test material’s general specifications. It should be noted that the amount of carbon cannot be verified with EDS. The steel contains only small amounts of alloying materials.

EBSD measurements were used to study plastic deformation of the martensite structure within the adhesion spots and especially near the major fretting cracks. Fig. 4 shows an SEM image (Fig. 4A) from one adhesion spot showing two of the major cracks, and four normal direction inverse pole figure (IPF) orientation maps superimposed on band contrast (BC) maps (Fig. 4B–E) collected from the crack areas. The colors in the IPF map correspond to the crystallographic orientations (martensite with body-centered cubic (BCC) structure) perpendicular to the observed plane as indicated by the colored stereographic triangle.

Table 4

<table>
<thead>
<tr>
<th>u₀, p, N₀</th>
<th>Mean Value</th>
<th>Maximum Value</th>
<th>Minimum Value</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 μm, 30 MPa, 3 × 10⁶</td>
<td>895 HV</td>
<td>1036 HV</td>
<td>782 HV</td>
<td>90 HV</td>
</tr>
<tr>
<td>35 μm, 10 MPa, 3 × 10⁶</td>
<td>1051 HV</td>
<td>1149 HV</td>
<td>896 HV</td>
<td>80 HV</td>
</tr>
<tr>
<td>20 μm, 30 MPa, 3 × 10⁶</td>
<td>963 HV</td>
<td>1076 HV</td>
<td>782 HV</td>
<td>105 HV</td>
</tr>
</tbody>
</table>

Table 5

Oxygen content results (EDS) from TTS in different samples. Only the oxygen contents are reported, as they the only variation from the base material. Because EDS is not a highly accurate tool for studying oxygen content, the results are rounded up or down to the closest whole percent.

Table 6

<table>
<thead>
<tr>
<th>u₀, p, N₀</th>
<th>35 μm, 10 MPa, 3 × 10⁶</th>
<th>35 μm, 30 MPa, 10⁶</th>
<th>20 μm, 30 MPa, 3 × 10⁶</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt-%</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>At-%</td>
<td>4</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>
the plastic deformation level is obviously very high and the amount of
exceeding the ultimate strain level of martensite [13]. As TTS occurs
TTS layers were tens of micrometers thick. TTS always occurred within
many, but not all samples. Still, in the most gross-sliding samples the
strain may exceed the ultimate strain.

Fig. 5 shows an adhesion spot, in which there are thick layers of the
TTS below and the TBL above. The TTS is located above the GDL, where
the plastic deformation is high. Hardness measurement marks separate
the TTS from the TBL in terms of their mechanical properties. Marks in
oxidized TBL behave as in typical ceramic material, where cracks are
induced to corners of hardness mark. Hardness measurement marks in
TTS behave more like in ductile material, and cracks are not induced to
corners.

As can be seen in Fig. 6, the TTS is a highly cracked area. The cracks
often run at a 45° angle to the contact surface. This kind of cracking was
not detected in either the TBL or the GDL. The cracking takes place
because the TTS is an extremely hard and brittle phase [13]. Fig. 6B
shows a high magnification image which reveals that the cracks can
occur as densely as in every micrometer.

Table 4 shows the TTS hardness measurements from three different
samples. The mean values of hardness are extremely high, from 900 to
1050 HV (0.05 kg). These levels of hardness are also found in the lit-
erature, even for different materials [11]. The operating parameters do
not seem to have any major effect on the hardness values, which are far
higher than the hardness of totally work-hardened base material
(martensite), so this indicates phase transformation. It is most likely
that the strain- and dislocation-induced phase transformation takes
place in a TTS, forming thermodynamically stable phases of steel, i.e.,
ferrite. This ferrite phase is so hard because of the nano-sized grains. As
the Hall-Petch equation indicates, the reduction of grain size enhances
the mechanical properties of the material [26].

In theory, the TTS's hardness could be explained by the formation of
oxides, but our elemental distribution analysis showed otherwise, as
seen from Table 5. The TTS has only oxidized mildly, oxygen's atomic
percentage varying from 4 to 7%. Even though the EDS cannot give
very accurate results about the amount of oxygen, the limited scale of
the oxidation is clear and the TTS is largely composed of non-oxidized
steel.

4.3. Third body layer

The highly oxidized third body layer (TBL) occurred commonly in
the samples. Fig. 7 shows the TBL in the adhesion spot presented above
in Fig. 5. Admittedly, this debris bed is one of the thickest found in the

Table 6
TBL hardness results from three different samples.

<table>
<thead>
<tr>
<th>(u_a, p, N_{LC})</th>
<th>Sintered Third Body Layer Hardness (HV 0.05 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Value</td>
</tr>
<tr>
<td>35 μm, 30 MPa, 3 (\times 10^6)</td>
<td>748 HV</td>
</tr>
<tr>
<td>35 μm, 10 MPa, 3 (\times 10^6)</td>
<td>676 HV</td>
</tr>
<tr>
<td>20 μm, 30 MPa, 3 (\times 10^6)</td>
<td>613 HV</td>
</tr>
</tbody>
</table>

i.e. the IPF coloring key. The BC map represents the quality of the Ki-
kuchi diffraction pattern for each measurement. In the BC map, white
signifies that the pattern quality is good, i.e. it can be indexed and the
crystal orientation can be determined (corresponding color in the IPF
map). Black signifies that the pattern quality is poor, in this case be-
cause of the plastic deformation of the martensite, the presence of ex-
remely refined martensite crystals or phase transformation. In these
cases the pattern cannot be indexed as martensite BCC structure.

Fig. 4D, the BC map overlaid with an IPF map, was collected near the
contact surface. Based on the EBSD results, plastic deformation has
occurred around the major cracks. Indexing the martensite structure
has not been successful close to or above the crack, but below the crack,
nearer to the base material, the level of plastic deformation is lower and
indexing is possible. According to Fig. 4E, the grain size reduces near
the cracks compared to the base material (Fig. 4B) and grains are or-
ientated in the direction of the crack. Fig. 4B and C shows that the
plastic deformation is less severe towards the end of the major crack.
The grain size between the cracks is smaller than in the base material
and some reorientation of the grains has occurred.

The EBSD results from the major crack area show that plastic de-
formation is severe around and between the major cracks. It strengthens
the idea of cracking due to accumulated plastic strain, as has been
shown in earlier research [21–24]. The level of deformation is clearly
lower at the end of the crack end than it is at its initiation point in the
specimen surface. In principle, the potential plastic deformation due to
minor movement between crack surfaces might lead to TTS formation,
but such behavior was not detected in this study. If TTS forms between
crack surfaces, layer thickness would be very small. Microstructural and
micromechanical modelling could be used to study plastic deformation
and cracking in a fretting contact [25].
tests, but it is very representative in other ways. The high porosity of the layer is obvious, being the result of the third body sintering back to the contact surface. Fig. 7B also shows that the TBL is not cracked as it is in the TTS layer. Fig. 7 appears to confirm the sintering theory, as the layer consists of small, micron- and submicron-size pieces, with many pores between them. The pores form when non-compatible pieces of debris sinter together. Only small areas between single pieces adhere to each other, and pores are formed between them.

Table 6 presents the hardness values from the TBL in different samples. The mean values are from 600 to 750 HV. In theory, the hardness could be higher, but the high porosity decreases the material’s mechanical properties. Nevertheless, this layer is harder than the GDL. The high standard deviation of the results (over 100 HV), can also be explained by the high porosity. As the hardness measurements were taken with a relatively low weight (0.05 kg), the diamond only leaves a small hardness mark. The porosity in that small a region can vary a lot.

Table 7 shows the measured hardness values from the TBL in different samples. The mean values are from 600 to 750 HV. In theory, the hardness could be higher, but the high porosity decreases the material’s mechanical properties. Nevertheless, this layer is harder than the GDL. The high standard deviation of the results (over 100 HV), can also be explained by the high porosity. As the hardness measurements were taken with a relatively low weight (0.05 kg), the diamond only leaves a small hardness mark. The porosity in that small a region can vary a lot.

4.4. Effect of the running conditions

The effect of running conditions on the occurrence of degradation layers is discussed here. Figures from 8A to 8D show the effect of slip amplitude on the generation of degradation layers. Lower slip amplitudes produce less TTS and TBL than higher slip amplitudes. Figures E to G show the effect of normal pressure on the generation of degradation layers. Normal pressure had no obvious effect on the generation of TTS and TBL. Figure H shows a SEM image from a short test with 10000 cycles. 10000 cycles produced a small amount of TTS, and TBL did not occur. The reader should note that the images were not took with same magnification, and the scales are different in the images.

Generally, the oxidation levels of the TBL are high, even in the shorter test of 10000 cycles. The difference between the TBL and the TTS is remarkable, and helps to explain the formation mechanisms for both layers. The TTS has had no chance to oxidize as much as the TBL. On the other hand, some areas of the TBL had the same level of oxidation as TTS. As stated above, the oxidation ratio of the TBL depends on how long the particle was loose between the surfaces and on how easily oxygen can penetrate the TBL confined between specimens. However, the hardness results and the appearance are also different, so distinguishing between these phases should not be too difficult.

**Fig. 8.** Figures A to D show effect of slip amplitude on the generation of degradation layers. Lower slip amplitudes produce less TTS and TBL than higher slip amplitudes. Figures E to G show the effect of normal pressure on the generation of degradation layers. Normal pressure had no obvious effect on the generation of TTS and TBL. Figure H shows a SEM image from a short test with 10000 cycles. 10000 cycles produced a small amount of TTS, and TBL did not occur. The reader should note that the images were not took with same magnification, and the scales are different in the images.

### Table 7

<table>
<thead>
<tr>
<th>u₀, p, N₀,C</th>
<th>35 μm, 10 MPa, 3 × 10⁶ cycles</th>
<th>35 μm, 30 MPa, 10⁷ cycles</th>
<th>20 μm, 30 MPa, 3 × 10⁶ cycles</th>
<th>20 μm, 30 MPa, 3 × 10⁶ cycles</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt-%</td>
<td>4</td>
<td>18</td>
<td>6</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>At-%</td>
<td>13</td>
<td>43</td>
<td>17</td>
<td>46</td>
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Hardness measurements were not performed, because the surface layers were very thin, from 2 to 5μm. In the samples which had smaller sliding amplitude than 3μm there was absolutely no evidence of TTS. In the gross-sliding tests, any increase in the size of the slip amplitude increased the observed amount of TTS. Indeed, in the samples which had undergone 50 and 65μm slip in the tests, the TTS also occurred farther away from the adhesion spot (crack pair). An increase in the sliding amplitude might increase the plastic deformation level, which is needed for TTS formation, but it also increases the dissipated energy. The formation of TTS is still not completely understood. In the future,
The objective of this study was to characterize fretting induced material changes and damage formation within the adhesion spots which appear in large scale flat-on-flat contacts. Three different degradation areas were observed as follows: the general deformation layer (GDL), the tribologically transformed structure (TTS) and the third body layer (TBL). All the degradation phases have high hardness and generally slightly lower (<5 at-%) than it is in the TTS and there are no cracks. In the interface between the TBL and the GDL is not as sharp (Fig. 9A). Although cracks may separate the two phases in some locations, in other locations the change is gradual. In the IPF map, indexing TTS according to its martensite structure was not possible due to the severe plastic deformation of the martensite, or the phase transformation from martensite to the extremely refined ferrite crystals [11]. Based on the SEM image and EBSD results, the martensite just under the TTS, i.e. the GDL, is plastically deformed and flattened in the direction of the TTS interface. Within a distance of 30 μm from the TTS-GDL interface, the martensite gradually changes from being highly deformed to the undeformed base material.

The difference between the TBL-GDL and the TTS-GDL interfaces lies in the depth and degree of the plastic deformation zone. In the TBL-GDL interface, there is a sharp change between the martensite and the TBL. The TBL is composed of sintered wear debris, so its formation on the surface does not require very high stresses. High plastic deformation is needed for the formation of the TTS, and that is why the martensite has a high degree of deformation under TTS. This is one more indication that TTS is generated by plastic strain and dislocations.

Judging from the SEM images and the EBSD results, the interface between the TBL and the GDL is very sharp (Fig. 9A). The martensite just under the TTS, i.e. the GDL, is plastically deformed and flattened in the direction of the TTS interface. Within a distance of 30 μm from the TTS-GDL interface, the martensite gradually changes from being highly deformed to the undeformed base material.

The EDS line analyses (Fig. 10) confirm the observations made about the surface layers in sections 4.3 and 4.2. In general, the TBL has a higher oxygen content nearly (30 at-%) than the TTS, whose oxygen content is below 10 at-% (Fig. 10A). In the TTS layer, there are noticeably high oxygen peaks in some of the surface cracks due to the remaining colloidal oxygen-containing silica suspension used for the final polishing of the SEM sample. In the GDL, the oxygen level is generally slightly lower (<5 at-%) than it is in the TTS and there are no high peaks because there are no cracks. In the interface between the TBL and the GDL (Fig. 10B), the oxygen content drops from high (~30 at-%) to low (~2 at-%).

Normal pressure did not have any obvious major effect on the generated amount of TTS or TBL. Fig. 8E and G shows this effect.

4.5. The interfaces

The interfaces between these different degradation areas tell us much about their formation mechanisms. This section studies the interfaces with conventional SEM images and EBSD measurements. The test parameters of the sample discussed below were 10 MPa nominal pressure, 35 μm sliding amplitude and three million loading cycles. All the expected degradation areas exist in the SEM image presented in Fig. 9A: TBL on the surface, TTS below it and then GDL above the base material.

The interface between the TBL and the GDL is sharp (Fig. 9A). There is no gradual change from one phase to the other. Even though both phases are porous and cracked, they are clearly different in appearance, which indicates that they are formed differently. The interface between the TTS and the GDL is not as sharp (Fig. 9A). Although cracks may separate the two phases in some locations, in other locations the change is gradual. In the IPF map, indexing TTS according to its martensite structure was not possible due to the severe plastic deformation of the martensite, or the phase transformation from martensite to the extremely refined ferrite crystals [11]. Based on the SEM image and EBSD results, the martensite just under the TTS, i.e. the GDL, is plastically deformed and flattened in the direction of the TTS interface. Within a distance of 30 μm from the TTS-GDL interface, the martensite gradually changes from being highly deformed to the undeformed base material.

The difference between the TBL-GDL and the TTS-GDL interfaces lies in the depth and degree of the plastic deformation zone. In the TBL-GDL interface, there is a sharp change between the martensite and the TBL. The TBL is composed of sintered wear debris, so its formation on the surface does not require very high stresses. High plastic deformation is needed for the formation of the TTS, and that is why the martensite has a high degree of deformation under TTS. This is one more indication that TTS is generated by plastic strain and dislocations.
surface layers. The formation of the TTS layer with high hardness occurs on the surface of the adhesion spot or in its immediate vicinity. Slip was found to be essential for TTS formation, as higher slip produced more extensive TTS layer. With a contact pressure of 30 MPa and a sliding amplitude of 35 μm, TTS was observed to develop already between 1000 and 10000 load cycles. The nominal contact pressure has no major effect on the TTS layer in the range of 10–50 MPa; however true stresses and strains within the adhesion spot may well play a role in formation of the TTS.

The third body layer is the result of wear and the sintering process in fretting. This layer has high porosity and there are large variations in its high hardness. TBL occurred in all the measured gross-sliding conditions, and it increased as the slip amplitude increased. The partial slip samples contained far less TBL, and no TBL occurred after 10000 load cycles in gross-sliding conditions. The TBL can be distinguished from the TTS layer due to its clearly higher levels of oxygen and porosity.

In the GDL, severe plastic deformation occurred in the adhesion spots, the level of deformation being higher the nearer it was to the contact surface. The martensite is reoriented and the grains flattened along in the direction of the major cracks, which reinforces the idea of the crack initiation due to accumulated plastic strain.

The interface between the TBL and the martensite is sharp, and shows that the martensite has undergone only minor deformations, staying much like the base material. The interface between the GDL and the TTS is not as sharp. Although cracks separate the two phases in many locations, in other locations the change is gradual. The martensite immediately below the TTS is plastically deformed and flattened in the direction of the TTS interface.

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