INVESTIGATIONS OF FRICTION AND WEAR MECHANISMS OF HOT FORGING TOOL STEELS

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Abstract

Wear is one of the major life-limiting factor of the hot forging tools. A complex interaction of friction-oxidation damages the surface of the tools by the cyclic contact between the hot-worked piece and the tool. The aim of this contribution is to assess some wear mechanisms of a martensitic tool steel at various test temperature.

The tribological tests are performed on a high temperature pin-on-disc tribometer designed in our laboratory. Experiments are carried out for different disc temperatures ranging 20 °C to 950 °C. The disc is heated up by a high frequency induction heating.

Wear mechanisms are investigated by Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometry (EDS). In addition, the state of the art on tribology of oxides is undertaken. The oxides and their thickness play an important part in friction and wear behaviour. In our study, the wear mechanisms are essentially composed of abrasion, plastic deformation and fatigue.

Keywords: Friction, wear, hot forging, martensitic steel, oxides, inelastic strain.
INTRODUCTION

A significant part of the energy in forging is used to break the interfacial junctions established by friction between the tool and the workpiece [1]. Moreover, the formation of an important oxide scale at the workpiece surface leads to the consummation of a part of its substrate. In the same way, the oxidation of the die and the delamination wear can considerably reduce the tool life. At last, a too thick oxide scale on the die surface can influence the flow of the hot material and can delay the cooling effect of the die on the forged piece. All these observations can be translated in economical terms and conclude to a bad contribution of the oxides in forging.

During the hot metal forming process, the forging tools are submitted to thermal and mechanical cyclic stresses [25]. Under such working conditions, tools are usually damaged through complex and interactive mechanisms under cyclic loading like abrasive, adhesive and spalling wear, thermal and mechanical fatigue and plastic deformation [2, 3, 4] (Fig. 1).

Figure 1. Common failure mechanisms for forging dies. 1. abrasive wear; 2. thermal fatigue; 3. mechanical fatigue; 4. plastic deformation. [4].
In fact, for each fabrication operation, temperature variations occur more or less quickly on the working tool surface due to the heat exchange between the hot workpiece and the tool. Out of the contact, the die surface is quickly cooled. Then, transient thermal gradients are developed inside the tool by thermal conduction. These thermal gradients lead to crack the surface by heat checking. Besides, tools undergo mechanical strains during forging [5]. These strains can enhance diffusion ways in the die oxidation that plays an important role in the tool wear. The damage caused by friction may be very different according to the nature and the physical properties of formed oxide layers. At last, under thermal and mechanical stresses, the martensitic steel employed in hot forging tools are inclined to loose their mechanical properties [6, 25, 26]. Also, the die surface damage is the result of a complex process connected with fatigue (cracking origin), friction (wear origin) and test ambience (oxidation origin). The aim of this contribution is to assess some wear mechanisms of a martensitic tool steel at various test temperature.

The friction tests were performed on a high temperature pin-on-disc tribometer developed in our laboratory, in order to control load, speed, temperature, surface conditions and chemical state of the materials.

OXIDATION AND FRICTION

OXIDATION OF TRIBO-ELEMENTS

The tribological behaviour of a couple of two oxidized materials depends on the thickness and the adherence of the oxide scales, and the type of contact. To get better insight to the wear mechanisms between X38CrMoV5 steel and AISI 1018 mild steel, the nature and the morphology of the oxides formed on tribo-elements before friction test should be emphasized.

AISI 1018 mild steel is essentially composed of iron. Thus, the oxides formed on the disc surface are principally iron oxides. The nature and the structure of the oxides depend upon the temperature of oxidation and partial oxygen pressure [10].

Below 560 °C [11], two oxide scales are formed. The top oxide is hematite (Fe$_2$O$_3$) and the inner one is magnetite (Fe$_3$O$_4$). At the metal-oxide interface, depending upon the Si content, a SiO$_2$ scale can be formed. For temperatures inferior than 560 °C, the wustite (FeO) is unstable and transformed in magnetite (Fe$_3$O$_4$).
Above 570 °C, the three iron oxide appear and form a multi-layer oxide composed from the substrate to the surface by FeO, Fe$_3$O$_4$ and Fe$_2$O$_3$. At the interface between the substrate and the wustite scale, the silicium oxide (SiO$_2$) can react with FeO to form a spinel composed, the fayalite (Fe$_2$SiO$_4$).

Between 570 °C and 700 °C, FeO scale increases with the temperature at the expense of the other oxide scales. Above 700 °C and until 910 °C, the oxide layer consists basically of a wustite scale [12]. But above 910 °C, FeO scale decreases in aid of the hematite and magnetite scales which increase again [13].

The oxidation of X38CrMoV5 steel is quite different from the AISI 1018 steel oxidation. The wustite (FeO) is not usually formed whatever the conditions of oxidation [14]. It is reported [14, 15, 16, 17] that a chromium content above 2 % leads to the disappearance of the wustite scale over 570 °C.

Then, the oxide scale formed on the X38CrMoV5 steel surface is duplex [18]. The two layers are uniform and approximately equi-thickness. These layers are very thin, about 100 µm after an oxidation of 150 hours at 650 °C.

The inner layer in contact with the parent metal results in internal oxidation whereas the outer layer results in external oxidation. Also, the outer oxide scale is formed by an iron-rich oxide and the inner scale is a mixed spinel containing the alloying elements. The latter is made of an outer layer of hematite (Fe$_2$O$_3$) and an inner layer of magnetite (Fe$_3$O$_4$) alloyed with spinel of chromium (FeOCr) and vanadium (FeVO) [19].

WEAR BEHAVIOUR OF OXIDES

In general, the wear behaviour of iron oxides is complex [10, 20, 21, 22]. When a FeO scale is formed with a sufficient thickness, this scale takes in charge the shear forces. At high temperature, an important oxide scale of wustite tends to reduce friction coefficient and wear rate.

In the same way, the magnetite (Fe$_3$O$_4$) is known to play a lubricant role and to tend to decrease the wear rate and the friction coefficient, whereas the hematite (Fe$_2$O$_3$) is considered as an abrasive oxide which can enhance considerably the high temperature wear and friction.

These behaviours are linked to the hardness level of iron oxides (Table 1). The hematite(Fe$_2$O$_3$) presents the highest hardness and therefore is very much prone to plastic shear accommodation. The stress flow of the wustite (FeO) or the magnetite (Fe$_3$O$_4$) is lower than the substrate one. The plastic deformation of oxide scales prevents the wear of the substrate. So these
oxide layers can be deformed before the bulk and they are considered as a kind of solid lubricant.

Table 1. Hardness of iron oxides measured at room temperature [10]

<table>
<thead>
<tr>
<th>Oxide</th>
<th>FeO</th>
<th>Fe$_3$O$_4$</th>
<th>Fe$_2$O$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (Hv)</td>
<td>270 – 300</td>
<td>420 – 500</td>
<td>1030</td>
</tr>
</tbody>
</table>

It seems important to precise that the plastic deformation of oxide scales is usually due to diffusionnal-creep (Coble and Nabarro-Herring) mechanisms and intergranular sliding [27, 28, 29, 30]. So, the plastic deformation of oxides at temperature is quite different from the plastic deformation of metals by dislocations movements.

The wear behaviour of the oxides also depends on both the thickness and the adherence of oxide scales. It is established that the friction coefficient decreases when the adherence of the oxides decreases and the thickness increases [1, 23, 24].

Moreover, the thickness growth leads to an increase of the thermal resistance. So, the thermal transfer at the friction interface can be reduced.

**EXPERIMENTAL EQUIPMENT, PROCEDURE AND MATERIALS**

**HIGH TEMPERATURE PIN-ON-DISC TRIBOMETER**

The high temperature tribometer developed in our laboratory was previously presented [7, 8].

The disc (Fig. 2 (1)) has a continuous rotating movement with an angular speed ranging from 30 to 300 rpm. Depending upon radius of the wear track, the linear velocity ranges from 0.05 to 50 ms$^{-1}$. To reach the test temperature, the disc can be heated up to 1100 $^\circ$C by a high frequency induction heating system (Fig. 2 (2)). The static disc surface temperature is measured by a spot-welded K-thermocouples on a disc peripheral diameter. During the rotation, the disc temperature is controlled by an IR-pyrometer placed out of the contact area. A thermal screen protects the engine shaft from the radiation of the disc at high temperature (Fig. 2 (3)).
The pin presents a hemispherical contact surface with a radius of curvature of 20 mm.

The loading is carried out using dead weight (maximum capacity 100 N (Fig. 2(5)). The tangential force is measured using a strain gauge sensor placed parallel to the friction plane (Fig. 2(6)). The friction coefficient is recorded via a software developed on Labview in-house.

![Figure 2. High temperature pin-on-disc tribometer [8].](image)

After every test, wear surfaces are observed by optical microscopy and/or Scanning Electron Microscopy (SEM) with dispersive energy analysis capability.

**TEST PROCEDURE**

The disc is first heated up to a given constant temperature and kept at temperature during one hour. During the disc heating, the pin is kept out of the contact at room temperature. After one hour of heating of the disc, the pin is put on the disc and the friction test is started immediately.

Thus, we consider that the initial contact between the pin and the disc is in fact metal on oxide formed at high temperature.

To assess the effect of the disc temperature on wear damage, the normal load (20 N) and the linear sliding speed (0.167 \(\text{ms}^{-1}\)) are kept constant. Test conditions are summarized in Table 2.
Table 2. Friction test conditions

<table>
<thead>
<tr>
<th>Pin initial hardness (HRC)</th>
<th>Normal load (N)</th>
<th>Sliding speed</th>
<th>Test duration (s)</th>
<th>Disc temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>20</td>
<td>Rotate 100 rpm Linear 0.167 ms⁻¹</td>
<td>3600</td>
<td>20 200 500 700 800 950</td>
</tr>
<tr>
<td>47</td>
<td>20</td>
<td>Rotate 100 rpm Linear 0.167 ms⁻¹</td>
<td>3600</td>
<td>20 200 500 700 800 950</td>
</tr>
</tbody>
</table>

MATERIALS

The pin is made of a 5% chromium martensitic steel grade (X38CrMoV5 steel, AISI H11 steel). Whereas the disc is a ferritic-pearlitic mild steel (XC18, AISI 1018 steel). This X38CrMoV5 steel is widely used for forging dies [4, 9], whereas AISI 1018 mild steel is used as a forged material in automotive industry. The chemical composition of the both steels is reported in Table 3.

The 5% chromium steel was studied in quenched and tempered conditions. The heat treatments were performed to achieve two initial hardness, 42 and 47 HRC with a tempered martensitic microstructure. The initial hardness of AISI 1018 steel is about 168 HV at room temperature. The initial arithmetic roughness of the disc and the pin are respectively 0.04 µm and 0.32 µm.
Table 3. Chemical composition of test materials

<table>
<thead>
<tr>
<th>Elements (wt, %)</th>
<th>PIN X38CrMoV5 / AISI H11 steel</th>
<th>DISC AISI 1018 mild steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.40</td>
<td>0.16–0.22</td>
</tr>
<tr>
<td>Cr</td>
<td>5.05</td>
<td>&lt; 0.40</td>
</tr>
<tr>
<td>Mn</td>
<td>0.49</td>
<td>0.40–0.70</td>
</tr>
<tr>
<td>V</td>
<td>0.47</td>
<td>—</td>
</tr>
<tr>
<td>Ni</td>
<td>0.20</td>
<td>&lt; 0.40</td>
</tr>
<tr>
<td>Mo</td>
<td>1.25</td>
<td>&lt; 0.10</td>
</tr>
<tr>
<td>Si</td>
<td>0.92</td>
<td>0.15–0.35</td>
</tr>
<tr>
<td>P</td>
<td>—</td>
<td>&lt; 0.035</td>
</tr>
<tr>
<td>S</td>
<td>—</td>
<td>&lt; 0.035</td>
</tr>
<tr>
<td>Fe</td>
<td>Bal.</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

FRICTION AND SURFACE DAMAGE

FRICTION EVOLUTION

Whatever the hardness of the pin (X38CrMoV5 steel), a decrease of the average coefficient of friction is observed on the hole of tribological tests when the temperature of disc increases. The average values of friction coefficient are in the range from 0.60 to 0.20 (Table 4 and Fig. 3).

Table 4. Evolution of friction coefficient versus the disc temperature

<table>
<thead>
<tr>
<th>Disc temperature (°C)</th>
<th>20</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average friction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coefficient $\mu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42 HRC</td>
<td>0.60 ± 0.045</td>
<td>0.63 ± 0.050</td>
<td>0.53 ± 0.020</td>
</tr>
<tr>
<td>47 HRC</td>
<td>0.59 ± 0.060</td>
<td>0.60 ± 0.041</td>
<td>0.49 ± 0.020</td>
</tr>
<tr>
<td>Disc temperature (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average friction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coefficient $\mu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42 HRC</td>
<td>0.46 ± 0.045</td>
<td>0.45 ± 0.044</td>
<td>0.19 ± 0.040</td>
</tr>
<tr>
<td>47 HRC</td>
<td>0.52 ± 0.020</td>
<td>0.44 ± 0.050</td>
<td>0.36 ± 0.049</td>
</tr>
</tbody>
</table>

At room temperature, the value of friction coefficient is characteristic of a metal-metal contact. Between 500 °C and 800 °C, there is not a significant
Figure 3. The evolution of friction coefficient versus the disc temperature.

evolution of friction coefficient. It stays around 0.50. But beyond 800 °C, the friction decreases drastically. Whatever the initial pin hardness, a break in the linear friction evolution (between 20 °C and 700 °C) versus tempering is observed above 700 °C. The evolution of friction observed on the friction curves (Fig. 4) was represented for different pin hardness a) 42 HRC and b) 47 HRC. A non significant evolution of friction is observed versus the hardness of the pin substrate. Below 700 °C, the friction coefficient decreases slightly with hardness. At 500 °C, the friction coefficient stabilizes after 450 s around an average value. With the temperature, the noise of the signal increases until 800 °C to decrease again at 950 °C. But between 700 °C and 800 °C, the friction does not achieve a stabilization and seems to decrease continuously. At 950 °C, the friction stabilizes again after a running-in period of about 300 s, but with a more important noise than at 500 °C.

According to these friction curves, a high wear damage can be expected between 500 °C and 950 °C.

Also, a critical point seems to exist between 700 °C and 800 °C from which the friction behaviour of the couple X38CrMoV5 steel / AISI 1018 steel is modified versus the disc temperature and the pin hardness.
Figure 4. Evolution of friction coefficient with a pin hardness of a) 42 HRC and b) 47 HRC.
SURFACE DAMAGE

The surface damage are observed by SEM both on the disc and the pin for each test temperature.

On the disc. From room temperature to 500 °C, the oxide debris present in the contact come from the abrasion of the surface asperities. They can enter in the contact already as oxidized debris or they can be abraded as metallic debris and be oxidized in the contact under shear force. Below 570 °C, FeO does not exist and the Fe$_2$O$_3$ and Fe$_3$O$_4$ oxides are very thin layers especially at 20 °C.

These oxide debris are gradually agglomerated and compacted to form partial compacted layers on the contact surface. Over 570 °C, the three oxides are present on the disc surface and have a significant thickness. These oxides now interfere in the contact between pin and disc and no more the initial metallic substrate. With the temperature, these compacted oxide layers tend to become thicker and larger. So, the circulation of oxide debris in the contact could come from the surface damage of compacted layers. At low temperature, the debris are agglomerated but badly compacted compared with the high temperature. The thermo-mechanical stresses favour the decohesion of layers and a new and high generation of free debris in the contact appears (Fig. 5 (a)). So, the friction coefficient remains quite high.

At 800 °C, the oxide debris form an important glazed surface in the wear track of the disc (Fig. 5 (b)). So the formation of glazed surfaces in the contact can be responsible of the softness of the friction coefficient at very high temperature because they increase the carrying surface.

At high temperature, the cracks of glazed surfaces by fatigue could lead to departures of matter of these layers by delamination and there is very little free oxide debris in the contact (Fig. 5 (c) and (d)). At last, by the side of the wear track, oxide debris are ejected from the contact and constitute an agglomerated debris layer which increases with temperature. At high temperature, these debris are compacted and contribute to extend the wear track.

On the pin. An edge of compacted oxide debris is formed in the front of the wear track (Fig. 6 (a) and (c)). At 500 °C, we observe little debris edges in the back of the wear track too (Fig. 6 (a)). The size of this edge increases with the contact temperature.
The pin wear track changes with the temperature. Below 500 °C, the pin surface damage presents scatters and compacted debris layers. The width and the homogeneity of the layers increase with the temperature. At 500 °C, the wear track is constituted by a layer which is composed of two zones (Fig. 6 (a) and (b)). The dark zones contain a quantity of oxide more important than the white zone. We suppose that the dark zones are iron oxides and the white zones are close to the chemical composition of the metallic matrix. These white areas could correspond to plastic deformation of asperities of the matrix. These zones form a metal-oxide mixed zone (Fig. 6(b)). At 700 °C, this mixed zone is gradually covered by a compacted layer of oxide debris which tends to become glazed with higher temperature (Fig. 6 (c) and (d)). At 800 °C, the mixed zone disappeared totally under the glazed surface which presents cracks (Fig. 6 (e) and (f)).

(a) Generation of oxide debris from crack of wear. Track at 700 °C.

(b) Formation of oxide glazed surface at 800 °C.

(c) Crack of disc wear tracks at 700 °C.

(d) Crack of glazed surface leading to delamination at 800 °C.

*Figure 5. Wear damage on the disc.*
Figure 6. Wear damage on the pin.
At 800 °C, we observe the crack of superficial oxide scale by the side of the disc wear track (Fig. 7). So, we can suppose that the oxides present in the contact, on the pin like on the disc, are hematite coming from the disc.

![Figure 7. Crack of the superficial oxide scale by the side of the disc wear track.](image)

In addition, another damage mechanism feeding the wear in the couple X38CrMoV5 steel on AISI 1018 steel is fatigue wear in the oxide layers. The form of the cracks permit to find their physical origin (Fig. 8). The form of the fatigue cracks is a horseshoe form. The form of thermal cracks is close to the heat checking cracks. We could attribute fatigue cracks to friction stress but the cooling of the disc after test could be responsible of the thermal cracks.

**DISCUSSION – CONCLUSION**

With the increase of the test temperature, we observed a decrease of friction coefficient. Whatever the hardness of the X38CrMoV5 pin substrate, the evolution of friction is quite linear versus the temperature until 800 °C. Over 800 °C, a different behaviour is observed depending on the hardness. The 47 HRC pin stays linear while the 42 HRC pin becomes parabolic and decreases drastically.
So, at high temperature, the flow stress of the 47 HRC steel stays superior to the flow stress of the 42 HRC steel. With temperature and shear stress, pin contact area presents plastic deformation. The plastic deformation of the 42 HRC pin may have a stronger influence on the friction and wear behaviour of studied materials couple.

At each test temperature, the wear mechanisms identified on the disc like on the pin are quite close. On the disc like on the pin, the oxides, observed out of wear tracks like on the wear tracks, are essentially composed of iron oxides. These iron oxides could essentially come from the disc oxide scale.

At the tribo-elements surfaces, more or less compact layers of oxide debris are formed. The thickness and the density of these layers tend to increase with the test temperature. Under thermo-mechanical stresses, these oxide debris layers crack and generate free debris in the contact, responsible of a high friction coefficient. The edges of compacted debris observed at the back of the contact are the witness of a strong circulation of oxide debris in the contact. With the increase of the temperature, the formation of glazed surfaces is easier. The formation of these surfaces depends strongly on the contact temperature, but not on the hardness of the pin substrate. These glazed surfaces could decrease the contact pressure. So, at high temperature, the formation of glazed surfaces and the capability of plastic flow of the pin contact area under shear stresses could be responsible of the decrease of the friction coefficient. In this case, the low friction coefficient observed is not an admissible material property because it is due to the lost of pin mechanical properties.
In fact, wear mechanisms generated between X38CrMoV5 steel and AISI 1018 steel are essentially a combination of wear by abrasion, plastic deformation of the matrix and superficial fatigue of both (oxide layers and matrix).

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