Triboconditioning: In-Manufacture Running-in Process for Improving Tribological Properties of Mechanical Parts Made of Steel or Cast Iron

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Summary

Component rig tests suggest that the tribological properties of camshafts, cylinder liners, and rocker arm shafts may gain significant improvements due to triboconditioning. Extreme-pressure mechanical treatment of the component surface in combination with a tribochemical deposition of a low-friction antiwear film based on tungsten disulfide allows one to produce, in a single finishing operation, a smoother surface with a significantly reduced coefficient of boundary friction and improved wear-resistance and load-carrying capacity. The treatment proved to be especially efficient for reducing friction and wear in lubricated contacts under high tribological stress.

1. Introduction

Friction and wear are inherent in operation of nearly all machines and mechanisms and often have detrimental effects on performance and lifetime. Lubricants and coatings are two well-known ways to solve friction and wear problems [1]. Advances in the field of tribology have significantly enriched our knowledge about the role and function of various classes of friction modifiers and extreme pressure antiwear additives [2-5] providing a rationale for understanding the running-in/breaking-in phenomenon. In motor sports, for instance, breaking-in is a well-established procedure for training new or rebuilt engines in order to maximize their power output and durability. Breaking-in smoothes down surface irregularities and reduces localized pressure between rubbing parts; the ring/bore system and valve train, especially for flat-tappet cammed engines, being the primary points of concern [6,7]. From a tribological viewpoint, the beneficial effect of breaking-in is explained by a combined effect of surface burnishing and tribofilm formation: The surface burnishing reduces asperities and improves parts conformity, while the tribofilm resists cold welding and minimizes fatigue accumulation.

Triboconditioning is a dedicated surface finishing process improving the tribological properties of mechanical components made of steel or cast iron [8]. The process combines elements of extreme-pressure mechanical burnishing of the component surface with a tribochemical deposition of a low-friction antiwear film of tungsten disulphide WS2. The mechanical treatment is essential for improving the surface finish by levelling off asperities and building up compressive stresses within the underlying material and for initiating the tribo-reaction, leading to the in situ formation and interfacial nucleation of tungsten disulfide onto the surface.

2. Experimental

Technical aspects of the ANS triboconditioning method are disclosed in Pat. Appl. PCT/SE2010/050850. Triboconditioning of camshafts (for Ford 1.6L Sigma GTDI engine) have been carried out using an in-house built rig as shown in Fig.1.
The ANS triboconditioning rig used for treatment of camshafts: The camshaft (1) is rotated in a turning machine. The tool (2) is pressed and slid against each lobe to induce the triboreaction between WS$_2$ precursors contained in the process fluid which is supplied through the nozzle (3). Contact pressure between the tool and the lobe is maintained by using the tension springs (4).

With minor adjustments in process conditions, the same rig has been used for triboconditioning of rocker arm shafts.

Triboconditioning of cylinder liners (for Volvo heavy-duty diesel engine D13) has been carried out using a standard honing machine from Nagel. The honing head has been modified to accommodate a set of triboconditioning tools in place of the honing stones and the honing oil has been replaced by a special process fluid required for the triboconditioning. The corresponding tool configuration is shown in Fig. 2.
Tribological testing of tribocycled camshafts and rocker arm shafts has been carried out using a specially engineered test rig (see Fig.3).

Figure 3 / Scheme of the rig used for friction measurements on rocker arm shafts and camshafts. The shaft in study (1) is put into sliding contact with an appropriate friction probe (2) mounted in a holder equipped with a friction force gauge (3). The shaft can be rotated at different speeds by using a turning machine. A certain normal force is applied to the probe by using a tension spring (4). Maximum, minimum and average friction coefficients are obtained by dynamically monitoring digital output from the friction force gauge.

Tribological testing of tribocycled cylinder liners has been carried out using a reciprocating ring/bore friction and wear tester resembling the common high-frequency reciprocating rig. A segment cut from the compression ring was put into a conform contact with the liner surface and oscillated back and forward at a given normal load. The friction force was dynamically measured with a digital force gauge, whereby the average coefficient of friction was determined.

Surface analysis of tribocycled parts has been carried out using scanning electron microscopy (SEM, Zeiss LEO440) and X-ray photoelectron spectroscopy (XPS, PHI Quantum 2000).

3. Results and Discussion

3.1 Effect of tribocycling on friction and wear

When focusing on friction measurements, it is important not to lose wear from consideration. This circumstance is often overlooked in tribological studies and very misleading conclusions are arrived at as a result. It should be remembered that, in most cases, any reduction in friction achieved at a price of increase in wear is totally unacceptable as it shortens lifetime and affects functionality of components.

It is not unusual that the coefficient of friction is decreasing in the course of a tribotest carried at constant speed and load. The reason for that is wear.

As wear is progressing with time during the entire duration of the tribotest, the effective contact area between the rubbing surfaces is expanding and the contact pressure is, accordingly, dropping. As a result, the Hersey number is increasing, and correspondingly, a gradual shift from boundary to hydrodynamic lubrication is taking place in the course of friction measurements.
The only objective way to compare friction levels by using accelerated tribotests as depicted in Fig. 3 is by measuring the Stribeck diagrams for the triboconditioned and the original surfaces. Unfortunately, this cannot be done in practice as the contact pressure is unknown.

A simple workaround is to record diagrams of friction vs sliding velocity while using symmetric up and down velocity ramps as explained in Fig. 4. In the mixed lubrication regime, the measured coefficient of friction decreases with increasing the sliding velocity and, if there is no wear, it returns back to the initial value at the end of the experiment. If there is wear, the final coefficient of friction will be lower than the initial coefficient of friction. The slope of the line joining the start and the end points can, therefore, be considered as a measure of wear: large slope – much wear, small slope - little wear.

![Figure 4](image.png)

*Figure 4 / Velocity ramp profile used in friction measurements for camshafts and rocker arm shafts.*

This methodology has been implemented in this study for tribological characterization of camshafts and rocker arm shafts. The corresponding friction curves and wear patterns for the original and triboconditioned parts are shown in Fig. 5 and 6. As a result of triboconditioning, the coefficient of friction for rocker arm shafts (vs bearing steel) was reduced by 10 to 30% and wear was reduced by 10 to 20 times.
Similarly, triboconditioning of camshafts has been found to lead to significant friction reduction in the valve train for flat-tappet cammed engines, with simultaneous tappet wear reduction by up to 10 times.

**Figure 5** / Friction and wear measurements for original and triboconditioned rocker arm shafts. Friction and counter-surface wear (shown in the insert) are both significantly reduced.

**Figure 6** / Effect of triboconditioning of flat-tappet camshaft lobes on lobe/lifter friction. Two lobes were triboconditioned and two left intact to serve as reference.
Previously, it has been demonstrated by component rig tests that triboconditioning of cylinder liners affords significant friction reduction in the top ring / bore system in the boundary lubrication regime [8]. The observed effect can be attributed to the following two factors: (i) increase of the load-bearing area as seen in the SEM images and confirmed by the bearing area curve shape change, and (ii) formation of a low-friction tribofilm containing tungsten disulfide as evidenced by surface chemical analysis.

However, fired engine tests show rather little effect of bore triboconditioning on fuel economy and the effect is limited to a low-rpm range. This result is to be expected based on the following considerations: It is believed that frictional losses in the engine account for just about 10% of fuel consumption. These losses split into 9:1 ratio into viscous dissipation (dominated by oil viscosity) and boundary friction (dominated by boundary lubricity) parts [1]. Hence, even though bore triboconditioning does allow one to reduce boundary friction by 10 to 60%, the overall effect on fuel economy will not exceed 0.1 to 0.6% (i.e. 10% out of 10% out of 10-60%). In fact, as shown in Fig. 7, the friction-reducing effect of triboconditioning is limited to the areas near the top- and bottom-end centers. It is also noteworthy that, unless properly optimized, bore triboconditioning may have a detrimental effect on hydrodynamic-film-controlled friction playing an especially important role for the oil-control ring. This is explained by the fact that rendering the bore system smoother shifts the tribosystem further to the right in the hydrodynamic part of the Stribeck diagram, resulting in increased energy losses due to the hydrodynamic drag effect.

On the other hand, since triboconditioning improves piston/bore seal and allows safe transition to low-viscosity lubricants without risking excessive component wear, the overall effect of the treatment is positive both for fuel economy and engine durability. For instance, by change from SAE40 to SAE30 engine oil, one will typically reduce viscous losses by 25%, which should improve fuel economy by about 2.5% (25% out of 10%). Therefore, the combined effect (triboconditioning + thinner oil) is not insignificant, with expected 2-3% improvement in fuel economy and extended service life of the treated components.

Figure 7 / Expected effect of triboconditioning of cylinder bore on piston/bore friction.
3.2 Surface chemistry behind triboconditioning

The ANS triboconditioning method uses a process fluid carrying a tungsten source and a sulfur source which can be surmised to undergo the following transformations in the tribocounter between the tool and the workpiece:

\[
\begin{align*}
RSR' + Fe & \rightarrow FeS + RR' \\
WO_3 + Fe & \rightarrow FeWO_3 \\
FeWO_3 + FeS & \rightarrow WS_2 + FeO
\end{align*}
\]

The above three reactions can be combined into

\[
RSR' + Fe + WO_3 \rightarrow WS_2 + FeO + RR'
\]

In one or another way, the ANS triboconditioning results in the formation of a non-stoichiometric tribofilm, of 10 to 100 nm thickness, composed of tungsten, iron, oxygen, sulfur and carbon as shown by EDX and XPS analyses (Table 1).

**Table 1** / Elemental composition of triboconditioned liner surfaces by EDX and XPS.

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance (%At)</th>
<th>EDX, plateaus</th>
<th>EDX, valleys</th>
<th>XPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>17</td>
<td>5</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>28</td>
<td>44</td>
<td>39</td>
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<td></td>
</tr>
<tr>
<td>S</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>39</td>
<td>19</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>

Due to transitional nature of tribofilms exhibiting normal gradients in atomic concentrations near the surface, it does not appear to be possible to translate the above data into relative concentrations of specific stoichiometric compounds, such as metal oxides, sulfides, sulfates, carbides, adsorbed organosulfur compounds, etc., all of which are almost certainly present.

The information depth at the higher end of the used acceleration voltage range (3 to 20 keV) proved to be much larger than the thickness of the tribofilms. This means that a large part of the detected EDX signal originates from the substrate. In order to estimate the thickness of the tribofilm, Monte-Carlo simulations of electron flight were used for a bulk iron substrate covered by a thin film of WS₂ and WO₃, the thickness of which was varied to fit the observed element peak distribution. The back scatter coefficient for each element was calculated according to [9]. At least 10 000 trajectories were used in the simulations to obtain enough statistical significance (see Fig. 8). These simulations suggest that triboconditioning creates a tribofilm of 10 to 100 nm thickness containing WS₂ in its composition.

Even if WS₂ may be affected by certain chemistries (oxygen, peroxides, alkaline buffer) and may gradually be etched away from the surface, it is believed that triboconditioning provides a long-lasting positive effect owing to improved surface finish and surface integrity, and reduced fatigue accumulation during the finishing and subsequent exploitation.
Figure 8 / Principle of tribofilm thickness evaluation based on Monte-Carlo simulation of electron trajectories. Higher electron acceleration voltage leads to deeper electron penetration increasing EDX signal intensity for the elements present in the substrate.

4. Conclusions

Component rig tests suggest that the tribological properties of camshafts, cylinder liners, and rocker arm shafts gain significant improvements due to triboconditioning. Extreme-pressure mechanical treatment of the component surface in combination with a tribochemical deposition of a low-friction antiwear film based on tungsten disulfide allows one to produce, in a single finishing operation, a smoother surface with a significantly reduced coefficient of boundary friction and improved wear-resistance and load-carrying capacity. The treatment proved to be especially efficient for reducing friction and wear in lubricated contacts under high tribological stress.

References