Friction and wear behaviour of tool steels sliding against 22MnB5 steel

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ABSTRACT
Boron steels are used in hot stamping process due to their good mechanical properties. During the stamping process, the dies are exposed to aggressive conditions including adhesive wear, abrasion, thermal stresses and fatigue. In the present work, QRO 90 and UNIMAX slid against 22MnB5 steel in four conditions: with and without hardening treatment and, with and without Al–10%Si coating, in order to evaluate the influence of both coating and austenitization treatment on friction and wear of tool steels. The results showed that Al–10%Si reduces the friction coefficient, while the hardening treatment results in an increase of COF due to Fe₂Al₅ brittle compounds. Wear mechanism of both tool steels is adhesive and oxidative when tested against coated and uncoated 22MnB5, respectively.

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1. Introduction
Automotive industry needs new materials to improve vehicle weight and fuel savings, as well as safety demands. The achievement of this objective requires the improvement of the overall concept of production process; that is, an improved design, the appropriate selection of materials and new production processes. Hot stamping process is very interesting for manufacturing lightweight steel car body parts. Thanks to the final martensitic microstructure, the reduced spring back and the adequate formability that high strength steel exhibits at elevated temperature, thinner and complex sheet metal parts can be produced with a high strength-to-mass-ratio and geometrical accuracy [1]

Among the ultrahigh strength steels (UHSS), boron steels – mainly the 22MnB5 steel grade – is the most used in hot stamping process. Low boron additions to the composition provide high hardenability, improved mechanical properties and weight savings up to 50% compared to conventional steel.

During the hot stamping process a blank – the boron steel sheet – is heated up in a furnace for at least 5 min at 950°C and then transferred into the press to be simultaneously formed and quenched in a closed water-cooled die. Before entering in the furnace, boron steel exhibits a ferritic-perlitic microstructure with a tensile strength of about 600 MPa. After the hot stamping process, it has a martensitic structure with nominal strength of about 1500 MPa. During the quenching, there is some shrinkage that promotes relative sliding, under high loads, between the tool and the steel. Therefore, the working tools withstand severe aggressive conditions including adhesive wear, abrasion, thermal stresses and fatigue. This combination of temperature and mechanical factors may require to short maintenance intervals and

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high tool-maintenance costs. The hot forming dies are typically made of chromium–molybdenum–vanadium alloyed hot work tool steel.

In order to improve the hot stamping process of high strength steels, they are usually coated with a thin film of Al–Si which reduces oxidation of base steel. Several authors have studied friction and wear behaviour during hot stamping operations using specific high temperature tests with varying configurations. Bossetto et al. [2] studied the friction coefficient – COF – of Al–Si coated 22MnB5 at 700 °C by performing pin on disc tests since COF values is an important parameter to improve numerical simulation especially for hot stamping complex geometries. Hardell et al. [3,4] investigated the influence of temperature in friction and wear behaviour of Al–Si coated high strength steel sliding against different tool steels by using a reciprocating friction and pin on disc tribometer. Yanagida et al. [5] developed a tribo-simulator for hot stamping and Kondratiuk et al. [6] used a hot strip drawing simulator to test friction and wear behaviour of coatings for hot steel metal forming.

Ghiotti et al. [7,8] designed a testing procedure to replicate the hot stamping condition within the wear tests. They concluded that the thermal cycle imposed on the pin during their tests is close to the forming dies conditions are subjected to. Thus, the pin/dies temperature reaches a stable value ranging between 120 °C and 170 °C after 20 cycles.

Recently Pelcastre et al. [9] observed that during the hot friction tests, the friction coefficient corresponding to coated and hardened UHSS samples did not show significant differences in comparison to those recorded on coated and non-hardened UHSS samples. They concluded that the tribological behaviour of the Al–Si coating does not change upon cooling and reheating. So, once the stable Fe2Al3 and FeAl2 phases are formed, their subsequent exposure to the temperature of the water-cooled dies, about −20 °C, do not induce further changes on the Al–Si coatings.

Therefore, in the present paper pin on disc tests were used to evaluate two chromium–molybdenum–vanadium alloyed tool steels – commercially known as QRO 90 and UNIMAX – used for hot stamping dies against an ultrahigh strength steel, the 22MnB5, to evaluate the influence of both the coating and austenitization treatment on friction and wear mechanism of the tool steels.

2. Experimental

2.1. Dry sliding test

Wear tests were carried out using a tribometer with a pin-on-disc configuration. A first batch of pins was fabricated from a hot stamping die made of QRO 90, chromium–molybdenum–vanadium alloyed hot work tool steel with a Vickers hardness of 565 HV. The second batch of pins was fabricated of UNIMAX, chromium–molybdenum–vanadium alloyed tool steel which is characterized by its excellent toughness and ductility as well as good wear resistance, with a Vickers hardness of 704 HV. The pin shape, dimensions and chemical composition of both steels are gathered in Fig. 1 and Table 1, respectively.

The pins were tested against 22MnB5 steel sheets of 39 mm × 39 mm × 1.5 mm supplied by Gestamp-Estampaciones Bizkaia S.A. The samples were provided with and without austenitization treatment at 900 °C – onwards called hardening treatment – as well as coated with Al–10%Si alloy. Samples were named as M1–M4 according to Table 2.

Prior to any test, all the samples and pins were degreased, rinsed with ethanol and dried in an air flow.

Pin-on-disc sliding tests were performed with a normal load of 9 N at 600 rpm and a total sliding distance of 500 m without lubrication. Table 3 summarizes the pin-on-disc sliding conditions. Every 100 m of sliding distance, the pin was removed from the pin holder, ultrasonically cleaned with ethanol and optically evaluated, to track the change of its contact area. Subsequently, the pin is relocated in the pin holder to continue the sliding test against a new 22MnB5 steel sample. This procedure was repeated for five times, so at the end of the tests the pin has slid 500 m against

![Fig. 1 – Shape and dimensions of the pin fabricated from QRO 90 and UNIMAX steels.](image)

<table>
<thead>
<tr>
<th>Table 1 – Chemical composition and hardness of the steels used to fabricate the pins for the sliding test.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>QRO 90</td>
</tr>
<tr>
<td>UNIMAX</td>
</tr>
</tbody>
</table>
five different steel samples of the same type. Conversely, the wear track formed on each steel sample is thus only due to 100 m of sliding. This test attempts to mimic the friction against several new blanks during the hot forming.

Friction coefficients were continuously registered during the test. In general, the COF recorded on the five samples showed a high reproducibility. Therefore, only one of them has been used for comparison purposes to elucidate the influence of the hardening treatment and the Al–10%Si coating on COF.

### Table 2 – Samples of 22MnB5 steel evaluated as the counter bodies of the tribological pair.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Condition</th>
<th>Thickness (μm)</th>
<th>R₄ (μm)</th>
<th>Hardness (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Al–10%Si coating</td>
<td>26.10 ± 1.32</td>
<td>0.272 ± 0.020</td>
<td>602 ± 27</td>
</tr>
<tr>
<td>M2</td>
<td>Uncoated</td>
<td>–</td>
<td>0.481 ± 0.043</td>
<td>171 ± 3</td>
</tr>
<tr>
<td>M3</td>
<td>Al–10%Si coating + 900 °C</td>
<td>30.10 ± 1.23</td>
<td>1.144 ± 0.943</td>
<td>*297 ± 22/881 ± 35</td>
</tr>
<tr>
<td>M4</td>
<td>900 °C</td>
<td>–</td>
<td>0.784 ± 0.161</td>
<td>331 ± 31</td>
</tr>
</tbody>
</table>

* Bilayer structure: outer/inner hardness.

### Table 3 – Sliding test conditions.

<table>
<thead>
<tr>
<th>Test procedure</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>RT</td>
</tr>
<tr>
<td>Normal load</td>
<td>9 N</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>600 r.p.m. (10 Hz)</td>
</tr>
<tr>
<td>Sliding distance</td>
<td>100 m*</td>
</tr>
<tr>
<td>Sliding speed</td>
<td>0.3 m/s</td>
</tr>
<tr>
<td>Track diameter</td>
<td>10 mm</td>
</tr>
<tr>
<td>Pin</td>
<td>QRO 90/UNIMAX</td>
</tr>
<tr>
<td>Counterpart</td>
<td>22MnB5 metal sheet with/without Al–10%Si coating and with/without 900 °C pre-treatment</td>
</tr>
</tbody>
</table>

* Repeated five times for each tribological pair pin-sample. Total sliding distance of the pin after the completion of the test is 500 m.

2.2. Characterization of tool steels and 22MnB5 steel samples

Topography and roughness measurements of the 22MnB5 samples were performed using a Sensofar plµ 2300 confocal profilometer, while the wear tracks were analyzed by means of a contact profilometer SurfTest 401 Mitutoyo comprised by a conical diamond stylus of 5 μm in radius and 90° that moves vertically in contact with a sample and then moved laterally across the sample for an 8 mm distance and 4 mN contact force.

The thickness of the Al–10%Si coating was measured using a Dual Scope FMP100 Fischer. The average thickness ranges about ~26 and ~30 μm for the untreated and thermally treated samples.

Hardness measurement on tool steels – QRO 90 and UNIMAX – and 22MnB5 steel samples were done using a Vickers indenter with 500 g and 10 g load respectively.

A complete description of the 22MnB5 samples previously to the sliding test is gathered in Table 2.

During the dry sliding tests, every 100 m of sliding, both elements of the tribological pair tested pin-22MnB5 steel sample were evaluated. The contact area of the pin was analyzed by optical microscopy using an Olympus GX51 inverted microscope. At the end of the sliding test, 500 m, the final contact area of the pin was also evaluated by scanning electron microscopy and EDS microanalysis, using a Hitachi 4800S FEG-SEM.

The phase-analyses have been performed in the grazing-angle geometry using Co K$_{\alpha1}$ ($\lambda = 1.790300$ Å) radiation in a

![Fig. 2 – (Up) Appearance of the contact surface of the QRO 90 pin periodically inspected, every 100 m; (Down) Appearance of the wear tracks performed on each M2 samples after 100 m of sliding.](image-url)
Bruker D8 Discover diffractometer with a cobalt anode. The experimental peaks have been assigned to the corresponding phases by means of the index card of the Joint Committee on Powder Diffraction Studies (JCPDS).

3. Results and discussion

3.1. Sliding tests. COF values

Pins fabricated of QRO 90 and UNIMAX steels were tested against the sample M2 – uncoated 22MnB5 steel without hardening treatment. Fig. 2 shows a representative image corresponding to the change of the contact area experienced by the QRO 90 pin and the track produced on each steel samples every 100 m of sliding distance.

Fig. 3a compares the representative COF records corresponding to the tribological pairs QRO 90-M2 and UNIMAX-M2. Both cases show an initial running-in step with an increase of COF values during the first 25 m of sliding. Then, COF describes very stable values of about 0.6 during the tests performed using both pins until the end of the test.

A similar behaviour is observed for the tribological pair formed with the non hardened coated 22MnB5 sample – M1 – Fig. 3b. As it can be seen in the running-in stage the friction coefficient exhibits a drastic drop from 0.7 to 0.4, value that remains steady until the end of the sliding. This value ranges in the same order of the values reported in literature for hot friction tests against hot work quenched and tempered tool steel and AISI H11, respectively [8,10,11].

The tribological pairs formed either with sample M1 and M2 reveal no differences in COF values regardless the tool steel used to fabricate the pin, QRO 90 and UNIMAX.

However, interesting differences in COF values are observed comparing the tribological pair formed with the coated, M1, and uncoated, M2, 22MnB5 steel samples. The sliding tests performed on sample M1 exhibits lower COF values than on sample M2. This result indicates that the presence of the Al–10%Si coating on M1 samples, besides preventing from oxidation, decarburization and scaling [9,12], supplies a lubricant effect reducing friction in comparison to the uncoated 22MnB5 – M2. Literature mainly reports the influence on friction of the Al–Si coating at high temperatures. Hardell et al. [3,4] reported a decrease in friction at 500 °C, 600 °C, 800 °C as result of the formation of oxides and/or intermetallic compounds and consequently, reduced adhesion. Conversely, Borsetto et al. [2] reported the opposite trend, lower COF values at 700 °C than at 900 °C. According to them the friction
condition at the sheet/die interface is also strongly influenced on the coating chemical composition, since roughness increased with Fe diffusion. Therefore, the lower the heating temperature, the lower the Fe diffusion and friction.

The influence of the hardening treatment on friction behaviour has been evaluated through the tribological pairs formed with samples M3, M4 and QRO 90 or UNIMAX. Fig. 4a compares the COF values corresponding to the tribological pairs formed with uncoated 22MnB5 steel samples – M2 and M4 –. Both cases COF show a stable value of about 0.6 during the whole test. This result suggests that the hardening treatment does no promote significant changes on friction. These results area opposed to those of Hardell, Pelcastre and Prakash [13] for the tribo-pair formed by plasma nitride tool steels and ultra-high strength boron steel, at different temperatures (400 °C, 400 °C and 800 °C). According to their findings, the friction was lower at all temperatures in comparison to unhardened UHSS due to the formation of an oxynitride layer on the surface. This is not the case in the present study. So, our study invites us to consider a very slight influence of the oxide layer produced during the thermal treatment in the friction behaviour.

Furthermore, the influence of the hardening treatment on coated 22MnB5 steel is greater, as it can be seen in Fig. 4b. In sample M3, the treatment induces a notably increase of the COF values from 0.4 to 0.8, revealing the loss of the lubricant effect supplied by the AlSi coating. Some authors have pointed out to the change in roughness as the responsible for the increase of the COF values of such AlSi coatings [2,13], while others suggest that the transformation of the layer into intermetallic compounds, more brittle and harder, is the ultimate responsible for such changes [9].

Literature has described the evolution of the Al-Si coating depending on the hardening temperatures and soaking times, explaining that the presence of voids both in the inner and the top layer, results of the diffusion processes inside the coating that creates Al vacancies, which agglomeration results in the formation of cavities [14]. Moreover, the
combined effect of void formation and intermetallic phase at the surface induces an increase of roughness and a higher friction coefficient [15–17].

SEM analysis of the cross sections of both M1 and M3 revealed relevant changes in composition and structure of the AlSi layer promoted during the austenitization treatment at 900 °C (Fig. 5). Samples M1 showed a bi-layer structure, comprised by an inner layer of 5 μm in thickness, enriched in Fe (20–15 at.%), Al 60–70 at.%, and Si (8–10 at.%) and outer thicker layer of ~17 μm in thickness composed of aluminium with embedded Si-enriched acicular morphologies. Fan et al. [14] identified this inner layer as Fe₂Al₇₋₈Si intermetallics phase. These authors stated that this inner layer is always formed in hot dip coating process preventing the rapid formation of Fe₂Al₅ both in the hot dip coating and in the hot stamping process at temperatures lower than 550 °C.

The hardening treatment performed at 900 °C activated the diffusion processes between the Al–10%Si coating and
that the substrate. Fig. 5b shows cross section of heat treated and coated sample, M3. A multi-layer structure was formed on the steel substrate. An inner layer in contact with the steel substrate – 2 – of 13 μm in thickness and mainly composed of Al and Fe whose content is about 60–65 at.% and 30 at.% respectively, corresponding to the Fe₂Al₅ phase; a thinner aluminium layer with embedded Si particles – 3 –; and an outer layer – 4 – that exhibits the same composition that – 2 –, pointing out the high iron diffusion from the substrate to the Al–Si. The Al–Fe–Si phase has shifted outwards and the previously observed Fe₂Al₅.4Si phase has dissolved during the hardening treatment at 900 °C and only Fe₂Al₅ and Fe₂Al₅Si phase are observed [9,16].

For a further analysis of the intermetallics phase XRD analysis were carried out. The diffraction patterns (Fig. 6a) confirm that the hot dipped Al–10%Si coating is mostly constituted by an Al layer where the Si is dissolved in the solid solution. A slight widening of the Al peaks located at 2θ values of 45°, 77.5° and 94°. Additionally, as a consequence of the iron diffusion during the hot dip process a non stoichiometry Al-rich compound namely FeAl₁₃ is also observed. In the literature, the presence of such phase on the sliding surface is considered beneficial to reduce the friction while the softer and brittle phases Fe–Al are related to the increase of friction coefficient on steel submitted to austenitization treatment [18].

X-ray diffractograms for the hardened samples M3 (Fig. 6b), also confirm the aforementioned aluminium matrix transformation into the intermetallics compound, Fe₂Al₅.

Therefore, it appears that the high COF values recorded for the tribological pair formed with samples M3 may be related not only with the increase of roughness but also to the presence of Fe₂Al₅ phase. The presence of such hard but brittle intermetallics explains the higher COF values recorded [12]. During the sliding the layer breaks and delaminates (Fig. 7) promoting and an abrasive effect either on the pin or the track.

3.2. Characterization of the pin and 22MnB5 steel samples after the sliding tests

The contact area of the pin increases with the sliding distance (Fig. 7). Both type of pins exhibit the highest contact areas for the wear tests performed against M1 samples (Fig. 8). The area increases from ~0.5 to ~2.25 mm² and ~0.125 to ~2.25 mm² for QRO 90 and Unimax tool steel, respectively, during the successive sliding steps against the steel samples. A similar asymptotic increase is measured for the pin QRO 90 during the wear test performed against the five successive M3 samples. While the pin area appears to stabilize for the M3 sample at the second wear track, for the M1 the pin area reaches stable values at fourth or fifth track.

The lowest increase in contact area of the pins is observed for the test performed against the M2 samples, uncoated manganese-boron steel. Both pins QRO 90 and UNIMAX show an increase of the contact area from ~0.25 mm² to ~0.75 mm².

The SEM analysis of the surface of the pins reveal similar appearance showing no differences depending on the tool steel used to fabricate the pin. Fig. 9 show the final surface appearance of the QRO 90 pins after 500 m of sliding against five successive 22MnB5 steel samples used as counterbody.
Thus, metal mainly composed of Al and Si pointing out to the occurrence of material transference from the Al-10%Si coating during the sliding against the M1 sample as result of the adhesive wear mechanism. Both tool steels show at the end of the test similar contact areas, suggesting that both QRO 90 and UNIMAX exhibit similar material adhesion. Boher et al. [19] reported similar results for both tool steels using a Deep-Drawing Process Simulator (DDPS).

Fig. 9b corresponding to the surface of the pin QRO 90 tested against M3 samples – coated and treated 22MnB5 steel – shows similar features. Al and Si are also observed on the surface; nevertheless, in this case some scars are also visible on the pin surface due to the abrasive effect of hard iron-aluminides, \( \text{Fe}_7\text{Al}_5 \), pointing out to a double contribution to the wear of the pin both adhesive and abrasive. Ghiotti, Sgarabotto [7] pointed out to the oxides formed both at the pin and the surface materials as responsible for the debris causing abrasion, but they also mention the relevance of the detached particles from the coating as responsible for the severe adhesive wear.

Finally, Fig. 9c and d correspond to the QRO 90 pins tested against the uncoated manganese-boron steel either untreated or treated, samples M2 and M4, respectively. Both cases the contact area of the pin is characterized by a flat surface enriched in oxygen resulted of the oxidative wear mechanism.

Width and depth of the wear scars of the manganese-boron steel sheets were measured using a contact profilometer and inspected by optical microscopy. Fig. 10 gathers the width and the depth of each track corresponding to the tribological pairs QRO 90-22MnB5 samples and UNIMAX-22MnB5 samples, respectively. Neither the width nor the depth of the wear scars appears to be dependent on the order of the track. Thus, it appears that there is no significant influence of the wear of the pin on the scar produced on successive samples. To characterize the wear behaviour of the tribological systems the average value of the width and depth of the tracks have been compared in Fig. 10c. As it can be seen, the width of the wear tracks are higher on samples M1 – coated 22MnB5 steel – no matter the pin used QRO 90 or UNIMAX.

On the other hand, the deepest tracks are exhibited on samples M3 – coated and heat treated – showing no differences depending on the pin used during the sliding test (Fig. 10c). This result appears to be related to the presence of hard and brittle \( \text{Fe}_7\text{Al}_5 \) intermetallics in the coating. Delaminated particles of the coating might contribute to wear debris, abrading the surface of the pin and the steel producing heterogeneous wear tracks and the typical abrasion scars on the track (Fig. 9c).

Fig. 9 – SEM micrographs and EDS analysis at different locations of the contact area of the pin QRO 90, after 500 m of sliding against: (a) M1, coated 22MnB5; (b) M3, coated and treated 22MnB5; (c) M2, 22MnB5; (d) M4, treated 22MnB5.
4. Conclusions

Pin on disc tests were performed using tool steels for pin and 22MnB5 steel sheets as counterbody. It has been evaluated the wear mechanism on each tribological pair highlighting the influence of the austenitization/hardening treatment and the presence of Al–Si10% coating.

Al–10%Si coating over the raw material produces a lubricant effect reducing the friction coefficient compared to the 22MnB5 steel. However, the austenitization treatment at 900 °C results in an increase of COF values, as consequence of the transformation of the layer. The treatment of the coating induces the iron diffusion promoting the formation of hard but brittle intermetallics compound Fe2Al5.

Wear behaviour of the pins QRO 90 and UNIMAX is mainly adhesive when tested against aluminized 22MnB5 resulting of an asymptotic mass transfer. Nevertheless, some contribution of the abrasive wear mechanism is observed when tested with M3 samples, hardened coated samples. Conversely, both tool steels reveal an oxidative wear mechanism when tested against uncoated 22MnB5 samples either hardened or not hardened.

Despite the increase of the contact area experienced by the pin, the tracks revealed similar features in width and depth. Wear tracks occurred on the boron steel samples indicate that the deepest tracks appear on coated and hardened boron steel, M3 samples, resulting of the delamination of the coating and the abrasive effect of the debris.

Conflicts of interest

The authors declare no conflicts of interest.

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