Tribological performances of new steel grades for hot stamping tools

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Abstract. In the last years, the use of High Strength Steels (HSS) as structural parts in car body-in-white manufacturing has rapidly increased thanks to their favourable strength-to-weight ratio and stiffness, which allow a reduction of the fuel consumption to accommodate the new restricted regulations for CO2 emissions control. The survey of the technical and scientific literature shows a large interest in the development of different coatings for the blanks from the traditional Al-Si up to new Zn-based coatings and on the analysis of hard PVD, CVD coatings and plasma nitriding applied on the tools. By contrast, fewer investigations have been focused on the development and test of new tools steels grades capable to improve the wear resistance and the thermal properties that are required for the in-die quenching during forming. On this base, the paper deals with the analysis and comparison the tribological performances in terms of wear, friction and heat transfer of new tool steel grades for high-temperature applications, characterized by a higher thermal conductivity than the commonly used tools. Testing equipment, procedures as well as measurements analyses to evaluate the friction coefficient, the wear and heat transfer phenomena are presented. Emphasis is given on the physical simulation techniques that were specifically developed to reproduce the thermal and mechanical cycles on the metal sheets and dies as in the industrial practice. The reference industrial process is the direct hot stamping of the 22MnB5 HSS coated with the common Al-Si coating for automotive applications.

1. Introduction

The increasing demand for fuel-efficient vehicles, improved safety, and crashworthiness [1], has led automotive industry to introduce new alloys in car manufacturing, characterized by a high stiffness and strength-to-weight ratio. To meet the need to form these new materials, hot stamping has been widely applied in the automotive industry [2] to produce car body-in-white parts with a high strength-to-weight ratio, which allows a reduction of the fuel consumption [3] and preserves the passengers’ safety. Despite the advantages that the hot stamping leads in terms of (i) shorter process chain, especially in the case of direct hot stamping, (ii) increase of mechanical properties just after the deformation process and without the need of additional heat treatments, (iii) reduction of the total weight of the vehicles thanks to thinner components maintaining the frame stiffness, (iv) high shape precision [4], (v) absence of lubricants that are often hazardous for the environment and require expensive cleaning operations [5], friction and wear become particularly critical for the sheet sliding in the dies cavities and their service life [6] and the heating phase, with the subsequent inevitable contact with air during transport and forming, causes the oxidation and decarburization of the metal sheets [7]. For these reasons, the 22MnB5 steel sheets that
are used in hot stamping are commonly coated to avoid the oxidation and decarburization during the heating stage and the Al-Si coating is the most common used.

Anyway, the survey of the technical and scientific literature shows a large interest in the development of coatings for the blanks different from the traditional Al-Si up to new Zn-based coating, with improved frictional and wear performances, as shown by Ghiotti in [8]. Other Authors are focused on the analysis of hard PVD and CVD coatings, plasma nitriding, applied on dies, in order to increase the tool life, reducing the wear rate that is established, as explained by J. Hardell in [9] and M. Vilasecca in [10]. Conversely, fewer investigations have been focused on the development of new tool steels grades capable to improve the wear resistance and the thermal properties that are required for the in-die quenching during forming. Using a laboratory pilot plant based on a deep drawing process simulator at elevated temperatures, C. Boher [11] and S. Le Roux [12] investigated commercial tool steels with different chemical compositions observing a material transfer mechanism due to the adhesion of the strip-coating particles during the hot-strip sliding. Unfortunately, the most common materials used to manufacture dies and tools are not designed for such purposes yet, and start to be a critical limit to speed up the processes.

The present paper focuses on the investigation of a new steel grade specifically developed for hot stamping applications, with high surface hardness and elevated heat transfer coefficient values to ensure the maximum heat exchange rate in the quenching phase. A novel high temperature tribological testing procedure was applied to investigate the tribological conditions of the dies material with thermo-mechanical cyclic loads in the temperature range from 600°C up to 800°C.

2. Materials

2.1. Sheet metal

The sheet steel grade under investigation is the boron steel 22MnB5, typically used in hot stamping and provided in 1.5 mm thick sheets. In the as-received condition, the steel grade has a ferritic-pearlitic microstructure and presents low strength and elevated ductility. The chemical composition and the mechanical properties of the as-delivered material are reported in Table 1. The sheets were provided with Al-Si coating, the most commonly used in direct hot stamping.

| Chemical compositions in wt% |
|-----------------------------|
| C | Mn | Si | Cr | Ti | B |
| 0.21-0.25 | 1.1-1.4 | 0.15-0.35 | 0.15-0.30 | 0.02-0.05 | 0.03-0.005 |

2.2. Al-Si coating

Al-Si coating is the traditional coating used for the commercial USIBOR1500™ that was originally developed to prevent the oxidation at elevated temperatures and deposited by hot-dip galvanizing process [13]. The Scanning Electron Microscope (SEM) analyses and the surface topography measured through a 3D surface profilometer Sensofar Plu Neox show that the coating is characterized by large plateau areas corresponding to the Al matrix, with small cavities representing the Si precipitates, and an average surface roughness Sa equal to 1.292 (±0.006) µm, see Figure 1(a), (b) and (d). According to the Energy Dispersive X-ray spectroscopy (SEM-EDX) analyses, it contains approximately the 13% of silicon. The cross-section shows an average coating thickness of 25 (±10) µm and three different zones can be identified: the coating, where aggregates of silicon are embedded in the aluminium matrix (Zone I), the interface area between the coating and the steel substrate (Zone II), and the steel substrate (Zone III). The interface zone is a ternary system containing iron, aluminium and silicon in weight percentages of 58.26%, 12.23% and 29.51%, respectively, according to EDX analyses. The average Al and Si wt%
in the coating are reported in Figure 1(c) and (e), and they range from are 93.78% and 6.11% in the outer layers and to the 1.37% and 0.26% in the inner layers, according to the EDX.

Figure 1. Al-Si coating in the as-delivered condition: (a) SEM surface, (b) topography of the surface, (c) coating cross-section, (d) metal sheet profile measured along the rolling direction and (e) chemical EDX analysis in the cross-section.

2.3. Tool steels
The tool steel grade used in the research activity is a patented formulation produced by Rovalma™. This typology of tool steel is commercially available with the name of High Thermal Conductivity Steel (HTCS®), provided in one grade named HTCS3 [14]. Such steel, specifically designed for hot stamping processes, present a thermal conductivity up to 60 W/mK, which is more than twice of the thermal conductivity of conventional hot stamping steels, such as the EN X38CrMoV5-1 alloyed steel. After the machining operations to obtain the pins for the tribological tests, the steel grade was heat treated in order to increase its wear resistance and obtain a final surface hardness of 56(±1.5) HRC.

Figure 2. Surface topography of the pins after machining observed with the (a) SEM and (b) 3D profiler. (c) Maps and (d) quantity of the elements measured with the SEM-BSE and SEM-EDX.
Figure 2(a) and (b) show the pin surface observed through the SEM Electron Back Scattered (EBS) and the 3D profiler. Figure 2(c) and 2(d) show a map of the elements of the material and its chemical concentration measured through the Energy Dispersive X-ray (EDX) detector of the SEM. The solubility of the elements is formed from small agglomerates of molybdenum, which could help to increase the corrosion resistance as well as the strength at elevated temperatures. Table 2 reports the values of the pin surface roughness, where Ra⊥ and Ra// are the linear roughness values perpendicular and parallel to the sliding direction, respectively.

Table 2. Values of the roughness in the sliding direction and perpendicular to the sliding direction.

| Grade  | S_a [µm] | R_a⊥ [µm] | R_a// [µm] |
|--------|----------|-----------|-----------|
| HTCS3  | 0.896± 0.045 | 1.079± 0.098 | 1.035± 0.103 |

The machining parameters used to realize the testing samples were chosen according to the industrial practice for the manufacturing of stamping dies.

3. Hot Wear and Friction Tests (HW&FTs)
Hot Wear and Friction Tests (HWTs) based on a pin-on-disk configuration are used to investigate the wear mechanisms and friction behaviour at high temperatures for HTCS3 alloyed steel against 22MnB5 steel coated with Al-Si coating. To this aim, the Bruker® UMT-3 tribometer equipped with the furnace described in [15] was modified with a specifically designed cooling apparatus to replicate the thermomechanical cycles of the hot stamping dies, Figure 3(a).

In accordance with the industrial process, before starting the Hot Wear Test, the sheet disks positioned in the furnace are heated above the austenitization temperature by adopting a heating rate of 0.43 °C/s and a soaking time of 180.0 (±0.1) s and then are cooled down to the target test temperature with a constant cooling rate equal to 0.33 °C/s. At this point, with the sheet disk maintained at the target constant temperature, at the beginning of each cycle, the cold pin is moved into the furnace and then is...
pushed against the rotating hot disk for a fixed time, which was evaluated to be representative of the actual contact-time between the blank and the dies in typical hot stamping processes. At that time, both thermal and mechanical loads are simultaneously applied to the pin surface, and the pin temperature rises up as the dies in the industrial process. When the pin is moved away from the hot disk, the mechanical loads are completely removed while surface thermal stresses are induced since it is cooled down by a forced air flow just outside the hot chamber. The above-described cycle can be repeated several times and figure 3(b) shows a schematic representation of the cyclic thermal-mechanical loads applied to the pins and metal disk. Strain-gauge sensors perform simultaneous measurements of the normal load and the torque, in order to calculate the friction coefficient during the test in accordance with the Coulomb’s law.

The pin temperature is monitored by a type K thermocouple spot-welded at the bottom of an axial hole inside the pin, with a diameter of 2 mm and a depth of 7.5 mm, Figure 3(c).

The final temperature of the pin and the cooling rate are adjusted through a manometer in a range of pressure from 0 to 8 (±0.1) bar.

The characteristics of the Al-Si coating of the blank in the wear track were preliminary checked, and after every 100 cycles a new wear track was selected to continue the test, although the coating was almost undamaged on the disk surface. An acquisition frequency of 10 Hz was assumed during the tests. The wear test parameters are given in table 3. The tests were stopped at 200, 600, 1200 and 2000 cycles to analyse the pin and metal sheet surfaces, and evaluate the wear mechanisms.

### Table 3. Plan of the HWTs.

| Pin steel grade | Sheet temperature (°C) | Normal pressure (MPa) | Sliding speed (mm/s) | Sliding distance per cycle (mm) | Pin cooling time (s) | Test duration (cycles) |
|----------------|------------------------|-----------------------|---------------------|---------------------------|-------------------|---------------------|
| HTCS3          | 600, 700, 800 (±1%)     | 10 (±0.1)             | 15 (±1)             | 75                        | 15                | 2000                |

### 4. Results

#### 4.1. Coefficient of Friction results

The stability of the mechanical condition at the interface between the pin and the dies was controlled by monitoring the friction coefficient during the tests; Figure 4(a) shows the average coefficient of friction calculated during the 2000 cycles for the different test temperatures, while Figure 4(b) shows an example of friction coefficient monitored in a single cycle, in the case of temperature at 700°C.

**Figure 4.** (a) Average of the coefficient of friction calculated during the 2000 cycles; (b) example of friction coefficient registered in a single cycle at 700 °C.
The steel grade presents high stability as proved by the low scattering of the data. The highest values are observed at the lowest temperature, while a decrease is detected increasing the testing temperature. At the lowest tested temperature of 600 °C the Al-Si coating shows a slight increase of friction coefficient, probably due to the higher shear strength of the coating with, lowering the temperature. Such behaviour, higher temperature lower COF, already observed and explained in [16], is due to the decrease of the coating shear strength and the activation of an intra-film lubrication mechanism so to accommodate the relative displacements of the two surfaces. As a consequence, when the pin slides over the coated surface, the asperities are more easily deformed provoking a decrease of the friction coefficient.

4.2. Wear results
The wear of the tool steel at varying number of cycles was evaluated by means of: (i) measurement of the pins weight variation at different number of cycles, (ii) SEM-EDX analysis to understand the material transferred from the metal sheet to the pin or vice-versa, if present, (iii) optical observations and measurements of the pins sliding surface through the SEM and 3D optical profilometer.

The steel grade was interested by abrasive and adhesive wear mechanisms, as shown in Figure 5(a) where the variations in weight of the pins are plotted versus the number of cycles. The temperature appears having the major influence on the phenomena: at 800 °C, which corresponds to the first contact between the blank and the dies at the beginning of the deformation in the industrial process, an average weight loss of about 0.11% was detected after 2000 cycles, while the lowest temperatures are interested mainly by adhesion. The change of wear mechanism from adhesion to abrasion can be explained with the fall of surface hardness that the steel grade present as the temperature increases. Figure 5(b) shows the HRC hardness of the steel grade measured before the Hot Wear Tests by means the Rockwell Hardness Tests at elevate temperature. In the case of the wear tests carried out at 700 °C, the temperature measured by the thermocouple embedded in the pin rises up to 180 °C (with an estimated temperature on the outer surface above 500 °C) with a consequent fall of the surface hardness that determines the abrasive mechanism.

The SEM images, carried on the pin surfaces, confirm the indications of the weight measurements, with large material transfer from the metal sheet to the pin surface at the lower temperatures, while abrasion takes place mainly at 800 °C. Such behaviour is supported also by the quantity of Al detected with the chemical analysis, which is part of the 22MnB5 coating to prevent the oxidation of the blank at elevated temperatures. Figure 6 shows the SEM-BSE and EDX of the pin surfaces and the weight percentage of the chemical components after 2000 cycles, in the case of HTCS3 steel grade, measured at the different test temperatures, respectively.
Figure 6. SEM-BSE and EDX analysis of the pins surface at (a) 600 °C (b) 700 °C (c) 800 °C.

On the base of test parameters listed in Table 3, Figure 7(a) shows a schematic representation of the pin temperature evolution during each cycle of the wear test as recorded by the embedded type K thermocouple, with the indication of the testing steps and their duration. It is possible to note that the total cycle time is 37 s, close to the one the forming dies are subjected to during the hot stamping process. Observing the temperature trend reported in Figure 7(a), it is possible to note that the maximum and minimum peak of temperature of the cycle were not reached when the pin moved out from the oven and at the end of the cooling phase, but subsequently. This was due to the delay in the response of the thermocouple being placed at a distance of 2 mm from the pin sliding surface, Figure 7(b), and to the pin thermal inertia.

Figure 7. (a) Schematic representation of the pin temperature evolution during each cycle of the wear test, (b) detail of thermocouple hole and (c) the average temperature measured by the thermocouple embedded in the pin along the 2000 cycles with a furnace temperature of 600 °C, 700 °C and 800 °C.

Figure 7(c) shows the average temperatures measured along the 2000 cycles by the thermocouple embedded inside the pin, respectively 98 (±2) °C, 117 (±2) °C and 141 (±2) °C for the testing temperatures of 600°C, 700°C and 800°C. It was noticed that increasing the testing temperature of 100°C determines an increase of about 22 (±2) °C of the average pin temperature.

5. Conclusions

The tribological behaviour of a new High Thermal Conductivity Steel grade for hot stamping tools has been investigated. The approach followed in the research is based on physical-simulation techniques to reproduce cyclic thermo-mechanical loads that are typical of the industrial conditions. A novel High Temperature Tribological testing procedure, as well as an experimental apparatus, were used to
investigate the tribological conditions of the dies material reproducing the thermo-mechanical cyclic loads in the temperature range from 600 °C up to 800 °C and pressures in the range of few tens of MPa. It was found that:

- the new steel grade shows a wear damage ruled by a combination of adhesion and abrasion based wear mechanisms. The coatings tend to adhere to the pin surface and scratches are also present due to oxides;
- the process temperature governs the wear damage: at 800°C the wear predominant mechanism is abrasion, while at the lower temperature it appears as a combination of abrasion and adhesion;
- wear debris formation may be attributed to the oxidation of the pin due to the longer permanence at high temperature;
- the results recorded in terms of friction highlight the stability in reproducing the testing protocol and the reliability of the testing set-up.

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