High Thermal Conductivity and High Wear Resistance Tool Steels for cost-effective Hot Stamping Tools

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Abstract. In hot stamping/press hardening, in addition to its shaping function, the tool controls the cycle time, the quality of the stamped components through determining the cooling rate of the stamped blank, the production costs and the feasibility frontier for stamping a given component. During the stamping, heat is extracted from the stamped blank and transported through the tool to the cooling medium in the cooling lines. Hence, the tool’s thermal properties determine the cooling rate of the blank, the heat transport mechanism, stamping times and temperature distribution. The tool’s surface resistance to adhesive and abrasive wear is also an important cost factor, as it determines the tool durability and maintenance costs. Wear is influenced by many tool material parameters, such as the microstructure, composition, hardness level and distribution of strengthening phases, as well as the tool’s working temperature. A decade ago, Rovalma developed a hot work tool steel for hot stamping that features a thermal conductivity of more than double that of any conventional hot work tool steel. Since that time, many complimentary grades have been developed in order to provide tailored material solutions as a function of the production volume, degree of blank cooling and wear resistance requirements, tool geometries, tool manufacturing method, type and thickness of the blank material, etc. Recently, Rovalma has developed a new generation of high thermal conductivity, high wear resistance tool steel grades that enable the manufacture of cost effective tools for hot stamping to increase process productivity and reduce tool manufacturing costs and lead times. Both of these novel grades feature high wear resistance and high thermal conductivity to enhance tool durability and cut cycle times in the production process of hot stamped components. Furthermore, one of these new grades reduces tool manufacturing costs through low tool material cost and hardening through readily available gas-quenching, whereas the other new grade enables a faster manufacturing of the tool at reduced cost by eliminating the time and money consuming high temperature hardening altogether. The latter newly developed grade can be hardened from a soft delivery state for easy machining to 52 HRc by way of a simple low temperature precipitation hardening. In this work, these new grades and the role of the tool material’s thermal, mechanical and tribological properties as well as their processing features will be discussed in light of enabling the manufacture of intelligent hot stamping tools.

1. Introduction
The globalisation of the market and the increasing environmental targets, in particular for reducing the CO₂ emissions (COP21 agreement), for increasing energy efficiency and reducing raw material consumption, have put the topics of competitiveness and technological requirements at a highly challenging level, especially for the automobile industries. It is estimated that a reduction of 10% of the vehicle weight allows reducing CO₂ emissions by about 6.9% (11.71g of CO₂ per Km) [1,2]. To achieve this target, the automotive industry has been continuously looking for replacing the different components by lighter ones, without compromising the security of the passengers, and in a cost-
effective way to keep competitive advantages. The same applies to the aeronautic industry. Moreover, the tendency in the appliances industry is to make more functional and smaller structures, while reducing production times and costs.

The material forming processes are directly affected by this global trend for lighter, functional and more complex components. Nowadays, composite forming, Plastic Injection Moulding (PIM), Die Casting of light alloys (DC), Press hardening / Hot Stamping (HS) of Ultra and Advanced High Strength Steels (UHSS and AHSS), represent the major material forming processes, with which the light components are produced and which have the potential to tackle this challenge. It has therefore become a survival issue for these industrial sectors, to develop and acquire the technologies that allow producing lighter, cheaper, complex and more functional components at a competitive cost.

In the press hardening process, the tooling is one of the principal technologies that directly contributes to tackle the mentioned challenges. In terms of production cost, the tooling is one of the principal cost factors that can make up to 20% of the final cost of the produced components [3]. This impact is not only related to the costs associated to the design conceptions, tool material cost and processing (hardening, machining) and maintenance. It is also related to the fact that in press hardening, tooling is a functional element of the process that not only determines the required cycle time to make a specific component, but also affects the quality standard for acceptable components as the cooling rate of the shaped sheet depends on the properties of the tool [4].

In HS, the preheated blanks need to be cooled down rapidly to produce the martensitic transformation of the shaped components. Therefore, the tool material functions as a heat transfer bridge between the working surface of the tool and the cooling medium. However, the cooling conception has its limitations because cooling channels cannot be brought too close to the working surface of the tool due to the risk of cracking induced by the thermomechanical loading on the working surface during the forming process. A distance of 10-15mm should be respected depending on the process configuration and cavity geometry [5]. Furthermore, with conventional machining, EDM or/and high speed machining, the possibility to adapt the cooling line conception to the cavity shapes is technically limited. Because of this, the tool material’s thermal properties determine the heat transfer, which in turn determines the cooling rates at different spots of the components and the temperature distribution over the tool surface.

Traditional hot work tool steels of type EN-DIN 1.2344 (AISI H13, JIS SKD 61), or EN-DIN 1.2343 (AISI H11, JIS SKD 6), and some other derivatives of such conventional tool steels have been generally used because of their good properties at high temperature, especially mechanical strength, fatigue resistance and dimensional stability, which are indispensable for having an acceptable tool life time. However, both the wear resistance and the thermal conductivity of these tool steels (25-30 W/m-K) are moderate [6,7]. Other conventional tool steels with somewhat higher wear resistance like EN-DIN 1.2360 are also employed but the higher wear resistance comes along with a lower thermal conductivity (around 20 W/m-K) and considerably higher propensity to cracking at the cooling channels.

During the last decade the high thermal conductivity HTCS®-grades, developed by Rovalma and which feature thermal conductivity levels up to 62 W/m-K, have been progressively used and further adapted for press hardening tooling. These new tool steels have been opening new possibilities to this process toward the realization of making much higher strength and thinner components, more complex geometries and to reduce the production cost. The present work resumes the features of high thermal conductivity, high wear resistance tool steels, including some application examples, and the latest developments related to these advanced tooling materials with their advantages for manufacturing intelligent tools for hot stamping. Those new tool steels have also been optimized for additive manufacturing and hybrid additive manufacturing with the particle size distribution in powder format required for the additive manufacturing technology selected and also in thin wire form.

2. Short overview on the technology behind high thermal conductivity tool steels
Tool steels are metal matrix composites with ceramic particles and/or intermetallic elements. The overall thermal conductivity of steels depends on the phonon and electron conductivities of both, the
metallic matrix and the hardening phases and their surface and volume fractions. Conductivities of both carrier types in the different phases will depend on the density of states, Fermi energy levels, phonon spectra and scattering. Besides the phonon-electron scattering, other scattering mechanisms are related to the lack of regularity in the crystalline structure, the most significant being due to impurity or point defect lattice distortion. Rovalma invented a method and the related technology in order to adjust the mentioned parameters with the objective of increasing the thermal conductivity, while keeping the alloying elements that provide high mechanical strength and fatigue resistance, along with other required properties, such as dimensional stability, tribological properties, machinability, etc. The invented tool steel grades (HTCS®) are capable of featuring a thermal conductivity over 60 W/m·K, and even get to more than 70 W/m·K. The first grade of HTCS grades was developed a decade ago for hot stamping processes. Progressively different grades of these tool steels have been developed for different applications, production configurations and processes. There are several already awarded patents and patent pending applications relating to the these advanced tool steels. In the following sections, the features of different grades of high thermal conductivity tool steel grades for press hardening applications and their benefits for manufacturing intelligent tools for hot stamping are elaborated.

3. High thermal conductivity tool steels for press hardening/ hot stamping

Hot stamping of Advanced High Strength steel (AHHS) and Ultra High Strength Steel (UHSS) is one of the important material forming processes to make light structural parts for the automotive industry, which in turn allows a lower fuel consumption and a decrease in CO₂ emissions. To achieve a significant weight reduction of vehicles, without compromising the mechanical performance of the components, is one of the main objectives of the hot stamping process. The process consists of austenizing the UHHS blanks in a furnace, the blank is then transferred to the tool with the required shape geometry and subsequently stamped and cooled down as fast as possible to allow the microstructure to undergo a martensitic transformation that results in high strength components. The stamping of the hot blanks results in the heating up of the tool surface. To ensure steady state production conditions at a cost-effective cycle time, the tool should cool down to 50 -100 °C before the next part is stamped.

Table 1. Comparison of relevant properties and features of high thermal conductivity tool steels for hot stamping tools with conventional hot work grades in terms of typical thermal conductivity, maximum achievable hardness and heat treatment method.

| Material                  | Typical Thermal Conductivity (W/m·K, at RT, at 44 HRC) | Wear Resistance (at working hardness) | Max. Hardness (HRc) | Hardening |
|---------------------------|--------------------------------------------------------|---------------------------------------|---------------------|-----------|
| EN/DIN 1.2344/ 1.2343     | 26 / 27                                                | ++                                  | 54                  | Q+T³       |
| HTCS®-150                 | 60                                                    | +++                                  | 54                  | Q+T³       |
| HTCS®-130 WU              | 58                                                    | +++                                  | 52                  | Q+T³       |
| HTCS®-117                 | 40                                                    | ++                                   | 46                  | PH²       |
| HTCS®-230 (new, reduced tool cost) | 47                                           | +++                                  | 50                  | Aging²     |
| FASTCOOL-50 (new, reduced tool cost) | 50                                         | +++++++++++++                        | 54                  | Q+T³       |

³ Q+T: High temperature austenization, quenching and tempering.
² PH: Pre-heat treated, no further heat treatment is needed.
² Aging: precipitation hardening to high hardness though low-temperature heat treatment (around 600 °C).

Hence, the cooling rate determines the output of the process in terms of component quality and cycle time. Several factors are influencing the cooling rate, including temperature difference between part
and tool, pressure, surface roughness (which determines the contact conditions between tool and blank), thermal properties of the tool, design of the cooling system, etc.. For tooling in hot stamping, conventional hot work tool steels type EN/DIN 1.2344/ 1.2343 and its derivative has been used. In Table 1, the main relevant properties and features for making high productivity tools of different grades of high thermal conductivity steels, including the recently developed grades, are compared to conventional the tool steels.

4. Main advantages of high thermal conductivity tool steels for hot stamping

The much higher thermal conductivities of HTCS® and FASTCOOL hot works tool steels, especially at the working hardness of the tools (generally around 50 HRc or higher), has proven to bring significant advantages to the production process of hot stamped parts when compared to conventionally used hot work tool steels, as is elaborated in the following sections, and it has thereby created important opportunities to manufacture intelligent hot stamping tools.

4.1. Cycle time

For the same blank type, tool geometry and production configuration, high thermal conductivity tool steels allow for faster cooling rates and shorter cycle times thanks to the fact that the diffusion of the heat from the tool’s working surface to the cooling channel is higher. Hence, both the die and the components cool down much faster as a function of the degree of thermal conductivity of the used tool material, for the same interface tool/component conditions such as pressure, surface roughness and cleaning. In hot stamping applications, depending on the degree of thermal conductivity, significant reductions in close and open die time can be achieved when compared to tooling made of conventional hot work tool steels. Figure 1 shows an example of the die surface temperature vs the cycle time for the forming of a bumper beam made of USIBOR® 1500 blank, having 2.3 mm of thickness. With the same cooling water temperature, the steady state initial temperature (before each cycle) was constantly below 40 ºC for the HTCS®-130 WU tool, while the tool made of EN/DIN 1.2344 presented a heating trend from 75 ºC to 100 ºC. Thanks to this faster cooling of the die, in this application, and for the same tool working hardness level, the cycle time was reduced by 35-45% for the HTCS®-130 tool, having a blank temperature at tool opening of about 130 ºC for the HTCS®-130 WU tool compared to about 145 ºC for the EN/DIN 1.2344 tool.

4.2. Component quality

Generally, the higher cooling rate obtained with HTCS® and FASTCOOL dies ensures higher hardness in the produced components due to a full martensitic transformation. In addition to that, the temperature distribution of the tool surface before each forming cycle is more homogeneous, preventing hot spot formation, as can be seen in Figure 2. The image shows the tool surface temperature distribution of a hot stamping tool built with HTCS®-230 compared to one made with a conventional tool steel, for the same hardness level (50 HRc). This effect results in a homogenous hardness distribution of the produced components. In Figure 2, a comparison of the blank temperature at the same closed die time is displayed. For the same tools, the blank temperature is around 40 ºC to
50 °C lower in the tool build with HTCS®-230. The closed die time could be reduced by 33% for this application. Also, the lower surface temperature of the tool provides better wear resistance at the same hardness, compared to conventional tool steels.

Figure 2. The image of the tool surface temperature distribution of a hot stamping tool built with HTCS®-230 compared to one made with a conventional tool steel.

5. Latest developments in high thermal conductivity tool steels

5.1. HTCS®-2-series

Considering current mould making trends, Rovalma S.A. developed and launched the new generation of precipitation hardening high thermal conductivity grades, the HTCS®-2-series. Out of this new series, table 1 further above shows the properties and features of the recently developed HTCS®-230 grade compared to conventional hot work and other high thermal conductivity steels used for the application area of hot stamping and plastic injection. The innovative features of the HTCS®-2-series grades are the combination of high thermal conductivity and high mechanical properties with a fast and more economic mould manufacturing compared to tooling making with conventional tool steels. The HTCS®-2-series is supplied in solubilized microstructural state at a hardness level that enables easy machining (see comparison further below). Contrary to hot work tool steels in general, the new HTCS®-2-series does not need the time and money consuming hardening & tempering cycles for full hardening. Instead, the tool hardness can be increased after machining by applying only a tempering cycle at a low temperature around 600 °C to reach to the hardness level of up to 50-52 HRc. This innovative characteristic makes them easy to process and reduce both, tool manufacturing costs and lead times. As illustrated in the Figure 3, around two weeks can often be saved when compared to tool manufacture with conventional tool steels.

Figure 3. Diagram of the indicative time saving for tool manufacturing operations, using the new HTCS®-2-series compared to conventional steel requiring quenching and tempering strategies for hardening.
During precipitation hardening, the new HTCS®-2-series grades grow in an isotropic reproducible manner and to a very small extent, which allows die manufacturers to take this growth into account during the tool design and avoid hard machining. As an example, multiple blocks of the grade HTCS®-230 were heat treated and scanned at different installations and the resulting dimensional change was reproduced in all cases. The tool presented in the Figure 4 is one of the samples studied. It represents a tool for a hot stamping process with the corresponding cooling lines and surface configuration. This tool was machined and hardened from solubilized state to 50-52 HRc following a single tempering cycle around 600 ºC. As can be seen from the Figure 4, the overall change in all directions was between 0.06 -0.07% in a homogenous manner that could be taken into account during the tool design to avoid the time and money consuming hard machining. According to the experience reported by numerous mould makers, the machining cost and time of HTCS®-230 before precipitation hardening is comparable to that of conventional hot work steel in annealed state. Significant reductions in mould-making lead times of ≥ 2 weeks and machining costs in the range of 15-25% could however be achieved through the exceptional dimensional stability of the HTCS®-2-series during precipitation hardening, whereby finish machining in hardened state can be avoided. This way of hardening is especially advantageous for big section tools, since the way of hardening is independent of the section, contrary to the quench plus tempering tool steels, in which the obtained mechanical properties decrease when the section increases.

Figure 4. 3D scan of the part built in HTCS®-230, Study provided by SMP Société Mécanique de Précision, France.

5.2. FASTCOOL-50

FASTCOOL-50 is a newly developed harden + temper hot work tool steel. It has been developed with the objective to provide a high thermal conductivity, high wear resistant tool steel at reduced cost and to facilitate the hardening process, especially for big inserts, with high hardenability requirements. FASTCOOL-50 can be gas-quenched to a high hardness level of up to 54 HRc. Its thermal conductivity can achieve almost double that of conventional hot work tool steels at the same hardness level. It has been mainly designed for applications, in which wear is the main mode of the tool damage mechanism, and for configurations, in which the tool requires high thermal conductivity at high hardness. The relative wear resistance, thermal conductivity and maximum hardness levels are presented and compared to other hot work tool steels in the Table 1. The main mechanical and physical properties of this new tool steel are shown in Table 2. FASTCOOL-50 also enables very high polishability levels (mirror and superior), which are required in certain plastic injection moulding applications.
Table 2. Typical mechanical, physical and thermal properties of FASTCOOL-50, at 44 HRc, evaluated on specimens taken from the mid-radius of a 660x430 mm section bar.

| Density (g/cm³) | Yield strength (MPa) 0.2% | Mechanical resistance (MPa) | Elongation (%) | Specific heat capacity (J/g·K) | Thermal diffusivity (mm²/s) | Thermal conductivity (W/m·K) |
|----------------|---------------------------|-----------------------------|----------------|-------------------------------|----------------------------|----------------------------|
| 7.81           | 1070                      | 1400                        | 17             | 0.47                          | 13.5                       | 50                         |

6. Conclusions
High Thermal Conductivity HTCS® and FASTCOOL tool steels grades are unique hot work tool steels that combine high mechanical properties with very high thermal conductivity. Their thermal conductivity reaches up to 62 W/m·K, which is more than double that of conventional hot work tool steels like EN/DIN 1.2343/1.2344 (AISI H13/AISI H11) at the different hardness ranges. The different application specifications in hot stamping processes, such as production volumes, geometry of the components, type and thickness of the blank to be hot stamped amongst others, require different tool properties not only in terms of tribological, mechanical and thermal properties, but also in terms of hardness level and hardening method.

To cover the large number of tooling configurations of hot stamping, for which the high thermal conductivity of the tool is always primordial, different grades of HTCS® and FASTCOOL with different hardness levels and hardening methods have been developed and launched in the market. HTCS® and FASTCOOL tools steel grades provide great opportunities for cost savings in the production line as well as in tool manufacture. At the same time, they facilitate the production of light components or complex geometries, as well as the improvement of part quality. As elaborated in the application examples above, these innovative tools steel grades allow to strongly increase the process productivity and tackle many other production problems, which are related to the generation of hot/cold spots and poor surface temperature distribution, low hardness and bad hardness distribution over the surface of the hot stamped components.

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