New approaches to thermal tool performance, cooling and machining strategy: the strongly correlated triple that determines the cost effectiveness of the process

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Abstract. The mechanism of the cooling, including its intensity and distribution, of hot stamped components is the most important factor that determines not only the cost effectiveness of the process, but also the formability of the new ultra-high strength sheets and of more complex component geometries. The parameters that determine the cooling mechanism are: contact condition between the tool and stamped parts, initial tool temperature, thermal properties of the tool material and hence the tool, and the cooling system configuration and performance. Once the blank-tool contact conditions have been optimized in terms of applied pressures, contact surface adjustments, roughness and eventually interstitial material, the remaining most important parameters to be optimized are the tool material’s thermal properties, cooling strategy and initial tool temperature. These parameters are strongly related as the heat must be extracted through the tool material before it is evacuated through the cooling channels, and because the cooling rate determines the initial tool temperature. The distance and the diameters of the cooling lines from the surface also depend on the tool material strength. The thermal properties of tool steels may decrease when the strength of the same increase. However, the cooling channels cannot be brought too close to the active tool surface because of the risk of premature tool cracking, nor can the cooling lines be adapted to conform with the tool cavity due to conventional machining limitations. This work explains the increase of the cooling capacity of tools by using the new cost effective high thermal conductivity tool materials FASTCOOL-50 and HTCS-230, which differ from other high thermal conductivity grades by easy machining and hardening processes, as well as a homogeneous distribution of material properties along the different tool sections. Also, the usage of the high thermal conductivity tool steel powder for cavity conformal cooling channels, especially for complex geometries, will be presented by semi industrial pilot tests.

1. Introduction
The automotive industry is facing the challenge to reduce CO₂ emissions respecting different international and national regulations and agreements. It is estimated that reducing car weight by 10% reduces emissions by 6.9%, which translates into a reduction of 11.71g of CO₂ per Km [1]. The automotive industry is exploring all technological possibilities in order to reduce the car weight without jeopardizing quality requirements and passenger security. Also, for electrical vehicles weight reduction is one of the most important challenges to tackle for their large-scale viability, as associated weight increments counter the potentially beneficial effect of electric engines.

For a passenger car, the body-in-white (BIW) structure represents approximately 30% of the vehicle’s total weight. The replacement of thick cold stamped steel by thinner and lighter hot stamped High Strength Steel has been showing an exponential increase in the last few years, proportionally to
the increasing pressure on the automotive industry to reduce weight. The number of lighter high strength parts in the BIW structure has increased from 8 million/year in 1997 to 700 million/year in 2017 [2]. Nowadays, many components of the car structure are produced with hot stamping.

The hot stamping (HS) process combines the forming of the components at high temperature, where the high strength steels are formable, and then quenching the formed components in one step. The process starts by pre-heating boron alloyed steel sheet “blanks” to approximately 900°C in adequate furnaces to austenitize the entire microstructure and reach good formability. The heated blanks are then transferred and positioned in water-cooled tools, where stamping takes place in order to form and quench the final part.

To reach the high strength demanded from hot stamped components, the cooling rate of the blank is a central process parameter. According to the continuous cooling transformation (CCT) diagram for 22MnB5 steel (most used type of blank), the minimum cooling rate required to fully transform austenite to martensite and obtain a good mechanical resistance is 27°C/s [3]. It has also become clear that the zones of the component are subject to deformation and the sliding movements need even higher cooling rates in order for this transformation to occur.

2. Mechanism of the blank cooling rate and its impact on the cost effectiveness of the process

The blank cooling rate at a given point, during the stamping process, is governed by the intensity of the heat transfer at the blank-tool interface. The interfacial heat flux is characterized by the following equation

\[ q = h \Delta T \]  

where \( q \) in W/m² represents the local heat flux density, \( h \) is the interfacial heat transfer coefficient (IHTC) in W/m²·K and \( \Delta T \) is the temperature difference between the blank and the tool surface. Then the two governing parameters of the interfacial heat flux density that determine the intensity of the cooling rate are IHTC and \( \Delta T \). IHTC depends on several parameters, in particular surface topography and roughness of the blank and the tool surface, contact pressure, blank and tool thermal properties, etc.

The heat transfer between the blank and the tool in HS processes has already been investigated by a number or researchers. Experimental IHTC values for hot stamping with low temperature tools (water-cooled) were studied by Salomonsson et al [4-5], Merklein and Lechler [6] investigated the IHTC for given contact pressure and temperature, Bosetti et al. [7], Abdhulhay et al. [8] and Ping et al. [9] showed that increasing the pressure from 5-10 MPa to 40-45 MPa results in increasing the IHTC from 2500 W/m²·K to 5000 W/m²·K. Zhang et al. [10] showed that increasing the temperature difference between the blank and the tool surface from 110°C to 525°C will increase the IHTC from around 2000 W/m²·K to 4500 W/m²·K.

The mechanism of the cooling rate impacts directly on the cost-effectiveness of the process. On the one hand, the intensity of the cooling rate determines the closing die time, which is an important contributor in the overall cycle time to form a component and to the production cost of each component. On the other hand the intensity of the cooling rate determines the resulting mechanical properties of the component. If the minimum cooling rate for 22MnB5 type blank can be reached with the actual hot stamping technology. The industry is facing the challenge to reduce this cooling time in order to reduce the production cost and to obtain a homogenous cooling rate over all zones of the components to obtain the expected homogenous properties. However, nowadays, due to the limited thermal conductivity of used standard tool steels and the limitations of the cooling line configuration, especially in terms of the distance to the tool surface and adopting the form of the die cavity, hot stamping dies are subject to the generation of hot spots and stamped components suffer an inhomogeneous hardness distribution, especially for complex component geometries, towards which the future of hot stamped components must go to tackle the weight problem of transport vehicles.

3. Impact of the tool material’s thermal properties on the cooling rate

The thermal properties of the tool are of major importance during the forming and quenching step.
The thermal diffusivity of the material is related to the material density \( \rho \), thermal conductivity \( \lambda \), and specific heat capacity \( C_p \) by the equation (2). These parameters allow defining the thermal diffusivity used to express the capacity of temperature tending to balance.

\[
\lambda = \alpha \rho C_p
\]  

(2)

The higher thermal conductivity leads to a higher heat transfer rate from the tool surface to the cooling medium. Consequently the holding time for the same blank opening temperature is shorter for higher thermal conductivity tools. This has been demonstrated in the work of reference [11] where high thermal conductivity tool steel material HTCS\(^\circ\)-150 has been compared to the standard tool steel 1.2343 (AISI H11, JIS SKD61). The higher diffusion of the heat through the higher thermal conductivity tool implies a lower temperature on the tool surface during the steady state production conditions for a given tool and blank. Figure 1 shows the tool surface temperature variation of the high thermal conductivity die made with HTCS\(^\circ\)-150, which features a thermal conductivity around 60 W/m-K, and a die made of standard tool steel 1.2344 (AISI H11, JIS SKD61) that has a thermal conductivity of order 24-26 W/m-K according to the reference. Further tests have been carried out on a U-shaped component, in semi-industrial production conditions, where the half of the die was built of a very low thermal conductivity material of ROVALMA known as GTCS\(^\circ\)-550 and the high thermal conductivity tool steels known as HTCS\(^\circ\)-130DC. The results of the temperature measurements at 1 millimetre below the tool surface is shown in the Figure 2. One can observe that on the side of the low thermal conductivity material the temperature increases progressively to be stabilised at over 150°C, and after each stamping, the surface temperature of the tool reaches to around 230°C. On the high thermal conductivity side on the other hand, the surface temperature is stabilised at almost room temperature and the temperature increase remains below 50°C. It is worth noticing that for this try-out, the low thermal conductivity side is not cooled and the high thermal conductivity side is cooled with water at room temperature. From this experience, one can note that the \( \Delta T \) is increased by more than 30\% compared to the low thermal conductivity side. Taking the equation (1), the heat flux will increase proportionally. In fact, the impact of the tool material’s thermal conductivity is not only on the blank cooling rate, but also on the tool cooling rate when the tool is opened to remove the stamped components. Hence, the tool surface temperature is always lower compared to the lower thermal conductivity tool. Taking advantage of this impact, many hot stampers have been able to improve the cost-effectiveness of their processes by using high thermal conductivity tool material.

**Figure 1.** Comparison of tool cooling performance between HTCS\(^\circ\)-150 and tool steel 1.2344 [11]
4. Cost-effective die materials for hot stamping processes

In view of the above, high thermal conductivity tool steels help in improving the cost effectiveness of the process. Furthermore, due to the relative movements during the forming process and the high applied pressure, tool materials for hot stamping must also withstand high adhesive and abrasive wear loading, therefore, a tool that combines high thermal conductivity with very high resistance to wear is required. For hot work tool steels, the level of hardness is often used as an indicator of wear resistance. For this reason, for direct hot stamping processes, a surface hardness of ≥ 50 HRc is commonly employed, in order to ensure an acceptable tool durability. Given this requirement, standard hot work tool steels like EN/DIN 1.2343 (AISI H11, SKD6) and DIN 1.2344 (AISI H13, SKD61), DIN 1.2367 or derivatives thereof, are often used by hot stampers. However, these tool steels feature low levels of the thermal conductivities that remain between of 25-30 W/m-K.

About a decade ago, ROVALMA managed to solve this dilemma for hot work tool steels through the invention of tool steels that combine high thermal conductivity with high hardenability by way of a new hot work tool steel design and production methodology resulting in hot work tool steels that feature up to 60 W/m-K of thermal conductivity and hardenability of > 54 HRc. Since then, many different grades of this high thermal conductivity tool steel family have been introduced into the hot stamping industries to cover different technical specification requirements, such as tools for direct and indirect hot stamping, prototyping, small, middle and large production series, very high quenching requirements, tool construction time, blank type, etc. Furthermore, HTCS-230/233 for tooling of hot stamping is a revolutionary tool steel that can be hardened up to 50-52 HRc by a simple, low temperature precipitation hardening (aging), which allows to considerably cut down the lead time for die construction and to enhance tool durability through a homogeneous distribution of the tool properties along the different tool sections. Also the production costs of high thermal conductivity tools steels have been optimized progressively and have nowadays reached a level comparable, or even lower than that of standard hot work tool steels. Table 1 shows essential properties of high thermal conductivity tool steels available for tooling of hot stamping in comparison to conventional hot work tool steels.
High thermal conductivity tool steels offer a unique solution package to fight against thermally related problems associated to standard hot work tool steels, in particular, against long cycle time, slow quenching rate, hot spots, fast wear and premature-cracking, and related quality and process problems. The wearing of the tool is also related to the working temperature of the tool. For the same level of hardness, high thermal conductivity tool steels feature higher wear resistance because the working temperature of the tool is generally around 50-100°C lower than when using conventional tool steels with lower thermal conductivity, as can be seen from the case study graphic illustrated below for different cycles for the hot stamping of a USIBOR® 1500 blank from ArcelorMittal. Considering the different technical requirements of a specific hot stamping process, the optimal tool material solution for a given hot stamping application should be customized not only in terms of tool steel choice, but also in terms of hardening options and machining and cooling design strategies.

Table 1. General comparison table between standard hot work tool steels and high thermal conductivity tool steels developed by ROVALMA.

| Material       | Thermal Conductivity | Wear Resistance | Max. Hardness | Heat Treatment       |
|----------------|----------------------|-----------------|---------------|---------------------|
| 1.2344 (H13)   | +++                  | +++             | 54 HRc        | Harden +Temper      |
| 1.2343 (H11)   | +                    | +++             | 54 HRc        | Harden +Temper      |
| HTCS®-130 WU   | ++++++               | +++             | 52 HRc        | Harden + Temper     |
| HTCS®-230/233  | ++++                 | +++             | 50/52 HRc     | Aging               |
| FASTCOOL-50    | +++++++              | +++++           | 50-54 HRc     | Harden + Temper     |
| FASTCOOL-70    | ++++++++             | ++++++          | 50-54 HRc     | Aging               |

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), have proven to bring significant advantages to the production process of hot stamped parts when compared to traditionally used standard hot work tool steels, as is elaborated in the following sections, and it has thereby created important opportunities to manufacture intelligent hot stamping tools.

5. Main advantages of high thermal conductivity tool steels for hot stamping
By using high thermal conductivity tool steels, significant reductions in close and open die time can be achieved when compared to tooling made of standard hot work tool steels. Figure 3 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°C for the HTCS®-130 WU tool, while the tool made of EN/DIN 1.2344 presented a heating trend from 75°C to 100°C. 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°C for the HTCS®-130 WU tool compared to about 145°C for the EN/DIN 1.2344 tool.

On the other hand, the high thermal conductivity means high thermal diffusivity. Therefore, the diffusion of the thermal energy is much faster, which brings another advantage of having a significantly more homogenous temperature distribution over the tool surface before each stamping in addition to lower tool surface temperature. The lower tool surface temperature ensures a higher cooling rate that translates to a higher mechanical resistance obtained in the produced component. The faster diffusion of the heat through the dies prevents the development of the hot spots in the ill posed zones of the tool surface, hence increasing the homogeneity of the quality distribution in the produced component.
In terms of durability, it’s known that the abrasive wear resistance decreases when the surface temperature of the steel increases [12]. As the surface temperatures of high thermal conductivity tools are lower, it is expected that the abrasive wear resistance is higher for a high thermal conductivity tool at the same hardness.

![Figure 3. Example of the die surface temperature captured by thermographic camera.](image)

### 6. Tool construction strategy

The tool construction strategy does not only matter because of the high costs associated to the machining, but also because of the effectiveness of the die design, especially how the cooling channels are introduced into the dies, and how the die is hardened. For conventional machining of the cooling lines, the number and location of the cooling channels must be defined and their distance from the surface must be fixed considering the tool material’s range of stress allowance to prevent tool surface deformation and cracking, either during the hardening process, or during the production cycles. When the cooling lines are near to each other and densely distributed, the fast quenching during the hardening of the tool implies risks because of the stress generated during quenching and the volume change during the transformation of the microstructure to martensitic. To overcome these risks, ROVALMA has developed high thermal conductivity tool steels that do not require the aggressive quenching step during the hardening of the tool. Instead, the tool hardness can be increased after machining by applying only a tempering cycle at a low temperature around 600°C to reach the hardness level of up to 50/52 HRc. This innovative characteristic makes these tool steels easy to process and allows reducing both, tool manufacturing costs and lead times. During precipitation hardening, the new HTCS®-2-series grades grow in an isotropic reproducible manner and to a very small extent by about 0.07 - 0.09%, which allows die manufacturers to take this growth into account during the tool design and avoid hard machining.

Nowadays, additive manufacturing (AM) technologies present a potential to overcome the limitations related to the conventional machining of cooling lines and to adapt the former to complex cavity geometries. The usage of these technologies is still under investigation and has not yet been introduced to the scale of industrial series production. At laboratory and semi-industrial tryout scales, the results suggest that the impact of additively manufactured cooling lines will be limited, if the thermal conductivity of the AM material layer is not high. This is because, due to the induced stress on the tool surface and to reach an acceptable tool durability for such high cost tools during stamping, enough distance of the cooling lines from the tool surface should be respected. Thus, even if the pattern of the cooling and the temperature distribution over the tool surface will be improved by the usage of AM technologies, the risk of hot spot generation will continue to exist, and the cycle time will not be impacted on significantly, when using standard tool steel powders because their thermal conductivities...
are too low. The potential advantages of using high thermal conductivity tool steel powder in combination with AM technology have been further investigated in a part of a B-Pillar tool with conformal cooling design. The previously mentioned part has been manufactured by 3D printing using high thermal conductivity tool steel powder of ROVALMA. This part had been chosen for the try-out, as it has previously been suffering from inhomogeneous and low hardness distribution when made by way of conventional machining technology. With the conformal cooling using high thermal conductivity powder these problems have been resolved. Figure 4 shows images of the conformal cooling design of the B-Pillar tool, the produced components and the hardness distribution over the components. Within this project, which has been co-financed by the Spanish Centre for the Development of Industrial Technology (CDTI) and the South-Korean Institute for Advancement of Technology (KIAT), high thermal conductivity powder of ROVALMA has been optimized for 3D-printing and successfully been applied to make additively manufacture inserts for the B-Pillar tool.

![Figure 4. a) Introducing the principle of conformal cooling using high thermal conductivity powder for additive manufacturing of the tool, and b) the stamped components and the hardness distribution.](image)

7. Conclusions

Thermal conductivity of the tool material is one of the main parameters that control the blank cooling rate and the cycle time in hot stamping processes in addition to the applied pressure and contact features between the blank and the tool surface. When the cooling design is optimized, by simulations, brazing or even additive manufacturing and pressure distribution, the remaining limiting factor will be the thermal conductivity of the zone between the cooling line surfaces and the working surface of the tool. Hence, for the optimization of hot stamping processes in terms of reducing the cycle time, achieving homogeneous properties and improving the hardness level and distribution in the produced components, high thermal conductivity tool steels are providing an effective solution. The diversified range of high thermal conductivity tool steels in the market covers the requirements of different production series configurations from prototyping to large production series, and which feature thermal conductivities of up to twice as much compared to standard hot work tool steels at the same hardness level. ROVALMA has furthermore developed high thermal conductivity steel powders for the additive manufacturing of tools and components.

Acknowledgements

The project leading to the up-scaling of the new hot stamping steels presented in this article has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 726558. The development and testing of new materials to increase the cost-efficiency of hot stamping in combination with AM technologies has received funding under the EUROSTARS project COHFTOOL E!9120, co-funded by CDTI within the framework of the EUROSTARS-2 program. ROVALMA thanks its Korean Partners for the successful cooperation within the project and
for providing the images included in this publication, in Figure 4. The sole responsibility of this publication lies with the authors. The European Union and CDTI are not responsible for any use that may be made of the information contained therein.

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