TOOL STEELS FOR HOT STAMPING OF HIGH STRENGTH AUTOMOTIVE BODY PARTS

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## ABSTRACT

Hot stamping of high strength automotive body parts is a key technology to fulfill safety requirements and $CO_2$-emmision limit values which are made by the EU. In the last ten years, high effort was made to improve the hot stamping process. Besides optimizing workflow and heating of the sheet metal blanks, new tools steel grades were developed which show beneficial properties with respect to hot stamping and hard cutting of high strength body parts. Furthermore, engineering of cooling systems results in different cooling strategies which all shall improve the cooling efficiency of hot stamping tools. In combination, these improvements lead to a reduction of cycle time and maintenance work and therefore increases productivity of hot stamping processes. This paper gives a short summary of the latest developments with respect to tool steels for hot stamping and hard cutting tools including concepts for active cooled hot stamping tools.

## KEYWORDS

High strength steels, hot stamping, hard cutting, tool steels, cooling concepts

## 1. INTRODUCTION

The demand of high strength steels for automotive body parts increased continuously in the last 30 years (Fig. 1 a). One reason is the increasing safety standard for passengers. As it can be seen in Fig. 1 b, the passenger cab of the VW Golf VII is made of high strength steels which shall protected the passenger in case of accident.

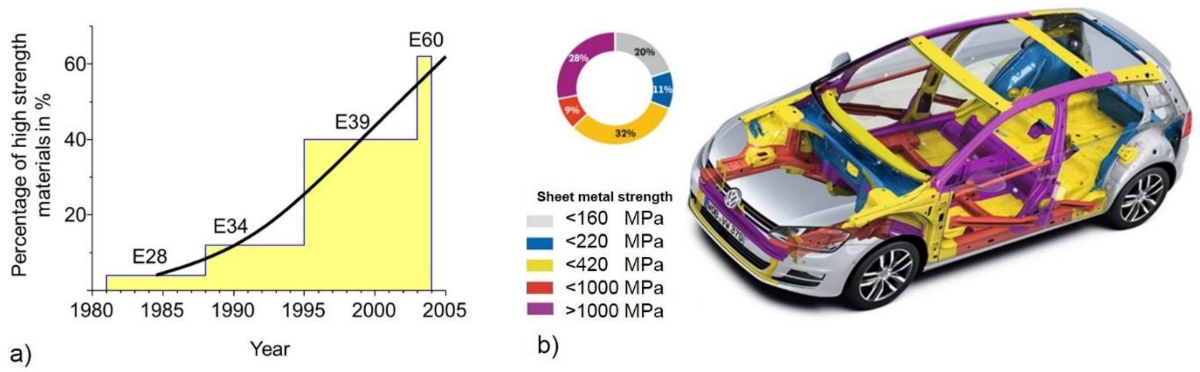


*Fig. 1: a) Increasing demand of high strength material for automotive body parts; b) Sheet metals used for automotive body parts for the VW Golf VII [1].*

Another driving forces are the CO2-emission limit values for the automobile industry. One strategy to fulfill these requirements is the reduction of weight and therefore the reduction of petrol consumption [2]. As an example, the autobody weight of the new VW Golf VII was reduced by 23 kg just by including a higher amount of high strength steels [1]. Therefore, the use of high strength steels for automotive body parts has two big benefits. However, the production of high strength body parts is not easy. Cold forming of high strength steels has many disadvantages. Besides high deformations forces and mechanical loads on the cold forming tools, the spring back and the risk of cracking of the deformed parts is very high. Therefore, engineers reused a production method which was developed in the seventies of the last century and was first used to produce high strength body parts in the year 1987 [3, 4]. It is called hot stamping – sometimes also hot forming or press hardening – and it evolved to a key technology with respect to the production of automotive body parts. As it is shown in Fig. 2, the demand on hot stamped body parts has been increasing continuously since the beginning in 1984 and it was suggested that it achieves 350 million parts in 2015.

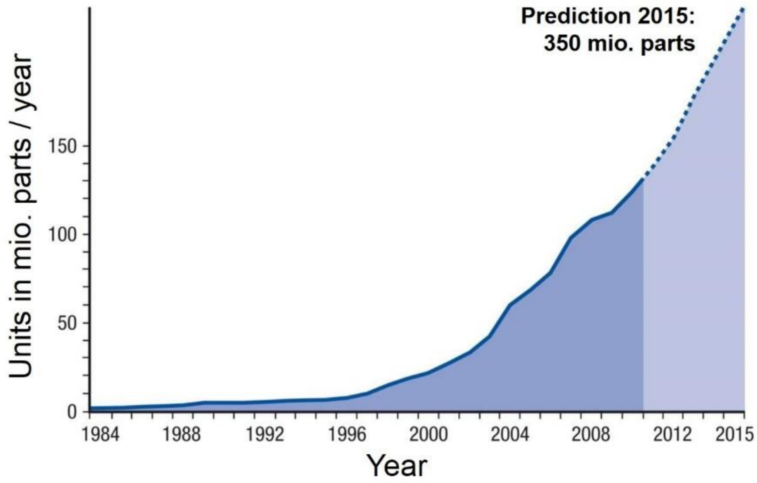


*Fig. 2: Demand on hot stamped body parts in the automotive industry [5].*

There are two different hot stamping processes which have to be distinguished (Fig. 3). Using the direct hot stamping process, a sheet metal blank is directly formed and quenched in a single hot stamping tool. In comparison, using the indirect process, forming and quenching is done in two separate tools. In the first tool, the blank is preformed. In the second tool, the preformed parts is quenched and calibrated after austenitization [4]. Due to the long process chain of the indirect hot stamping, it is not widely used in the automotive industry. Most assembly lines work according to the direct method.

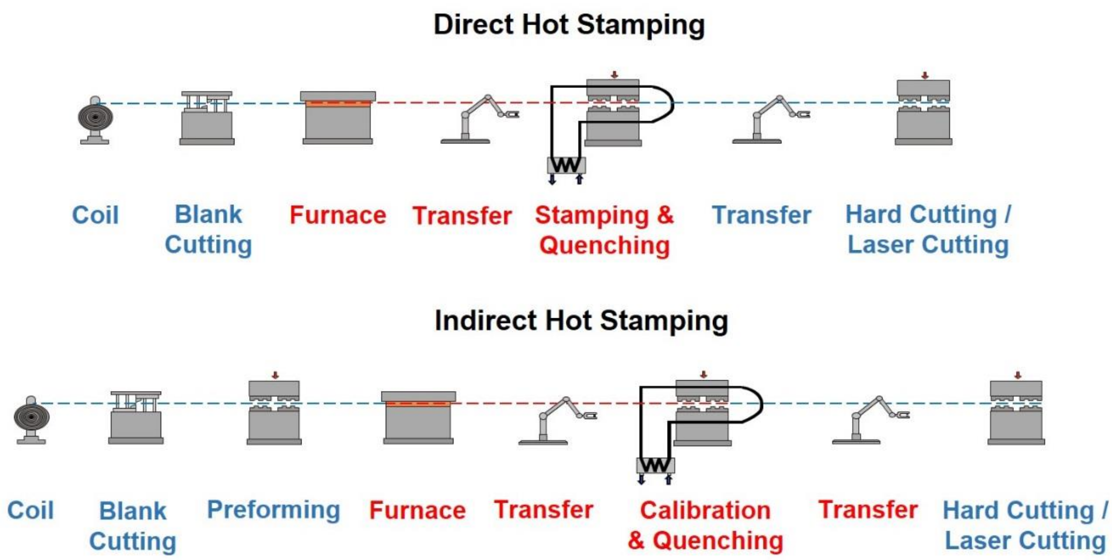


*Fig. 3: Process flow of the direct and indirect hot stamping.*

However, using the direct hot stamping process, there is a significant higher impact on the hot stamping tool. The major failure is abrasive and adhesive wear which is caused by sliding of the sheet metal against the tool surface [6]. It is also influenced by sheet metal coating which is usually used to protect the blank against oxidization during austenitizing [7]. Furthermore, during forming of the sheet metal blank, high mechanical loads are induced which might lead to deformation or cracking of the tool. In addition, inserting a hot sheet metal blank into the tool results in additional thermal loads which will add to the mechanical loads [8].

To resist wear, mechanical, and thermal impact, tool steels have to fulfill several requirements when used for hot stamping tools. They should offer a high hardness and tensile strength to withstand thermal and mechanical stresses and to increase wear resistance. However, they also should offer a sufficient toughness to avoid spontaneous cracking. Furthermore, they should exhibit a high thermal conductivity to reduce thermal stresses which are caused by internal thermal gradients. Additionally, a high thermal conductivity also improves product quality and the productivity of the hot stamping process because heat can be transferred much faster from the sheet metal into the tool. Therefore, the risk of bainitic or pearlitic transformation is reduced and the hot formed body part can be removed much faster from the tool which increases the number of hot stamped parts per hour.

However, after hot stamping, the high strength body parts have to be hard cut. In this case, thermal conductivity is less important whereas the demand on hardness, wear resistance, and toughness increases. Therefore, hot stamping and hard cutting of high strength automotive body parts require special tool steel material properties which have to be ensured by using different tool steel grades or by performing special heat treatments for each application.

The present article gives a concise overview of the state of the art with respect to hot stamping and hard cutting tool steels. It is shown that during the last 15 years many different tool steel grades were developed which already established in practice.

## 2. GENERAL CLASSIFICATION

As it is shown in Fig. 4, tool steels used for hot stamping and hard cutting of automotive body parts can be divided into three groups. Steels in group 1 show a good toughness and resistance against thermal fatigue. Steels in group 2 achieve a higher hardness and therefore offer a higher wear resistance. Steels in group 3 have a high carbide volume fraction. They can be heat treated to a very high hardness and exhibit a very high wear resistance.

*Tab. 1: Tool steels used for hot stamping and hard cutting of high strength body parts.*

| **Group** | **Material** | **Nominal Chemical Composition in wt.%** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **C** | **Si** | **Cr** | **Mo** | **V** | **W** |
| **1.** | X38CrMoV5-3 | 0,38 | 0,40 | 5,00 | 3,00 | 0,50 | - |
| | X40CrMoV5-1 | 0,40 | 1,00 | 5,30 | 1,40 | 1,00 | - |
| | WP7V | 0,50 | 0,90 | 7,80 | 1,50 | 1,50 | - |
| **2.** | AMO / GAMO | 0,60 | 0,35 | 4,50 | 0,50 | 0,20 | - |
| | CP4M® / GP4M® | 0,60 | 1,00 | 5,00 | + | + | - |
| | CP2M® / GP2M® | 0,65 | 0,20 | 2,00 | + | + | + |
| **3.** | CPOH | 1,00 | 1,10 | 8,00 | 2,50 | 0,30 | - |
| | CPR | 1,20 | 0,25 | 12,00 | 1,40 | 1,70 | 2,50 |
| | X153CrMoV12 | 1,55 | 0,35 | 12,00 | 0,80 | 0,90 | - |

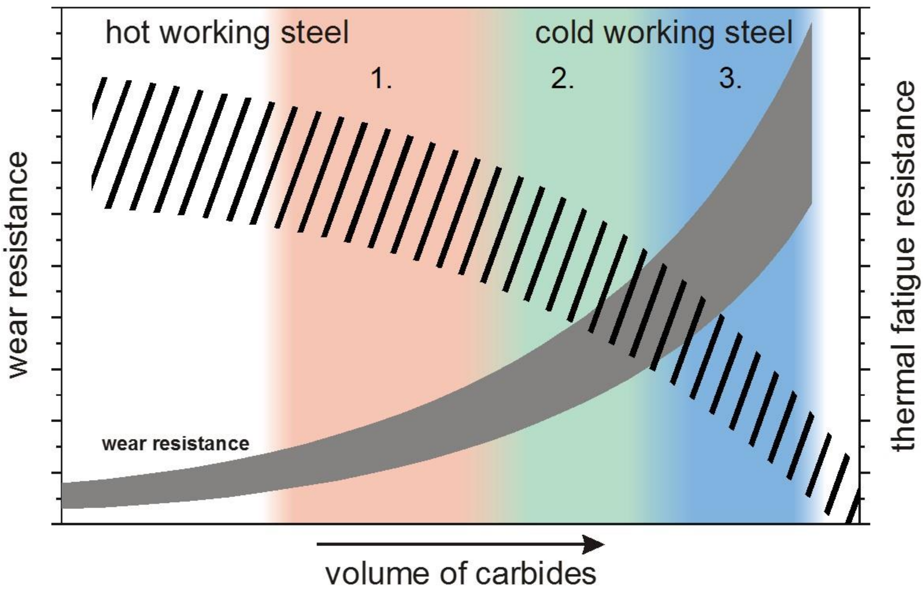


*Fig. 4: Classification of tool steels used for hot stamping and hard cutting of high strength body parts.*

It is obvious that steels in group 1 show advantages with respect to hot stamping whereas steels in group 3 have benefits in case of hard cutting. Steels in group 2 exhibit advantages for both applications. However, as it was already mentioned, lifetime of tools used for hot stamping and hard cutting is not just a question of wear resistance and resistance to thermal fatigue. There are much more requirements which have to be fulfilled and which change from tool to tool.

## 3. TOOL STEELS USED FOR HOT STAMPING TOOLS

Tool steels used for hot stamping tools should offer a high hardness and good wear resistance to withstand tribological attack during service time. However, they should also have a sufficient toughness to avoid cracking due to thermal and mechanical overloads. A high thermal conductivity is beneficial to reduce thermal gradients inside tools which produce high thermal loads. Furthermore, using tool steels with high thermal conductivities, there is a faster heat transfer from the hot blank into the tool which reduces closing times and increases productivity of the hot stamping process. Additionally, tool steels should also show a good tempering resistance, especially with respect to tailored tempering applications. However, the materials should also have a good machinability and they should be nitridable and coatable to increase wear resistance.

In the past, many different tool steel grades were developed which show some advantages with respect to hot stamping applications. As it is shown in Fig. 5, the standard grade X38CrMoV5-3 (1.2367) has advantages with respect to toughness and machinability. However, its wear resistance and thermal conductivity is low compared to other tool steels. X38CrMoV5-3 is widely-used for hot stamping tools and it is sometimes taken as a reference material when new tool steel grades are tested.

The special steel WP7V is an 8%-chromium steel which shows a low thermal conductivity. However, it has a good toughness and sufficient wear resistance which can be increased by nitriding of the surface. WP7V is also widely-used for hot stamping tools and it shows very good results with respect to wear and lifetime.

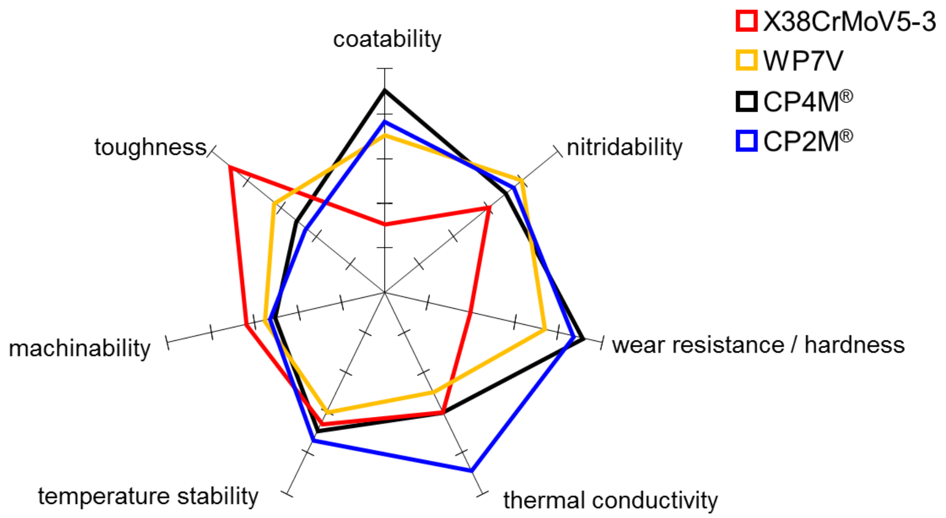


*Fig. 5: Comparison of the properties of steels X38CrMoV5-3, WP7V, CP4M®, and CP2M® which are used for hot stamping tools.*

CP4M® was developed for high wear impact. Its wear resistance can be enhanced by nitriding and coating. However, its toughness is lower compared to X38CrMoV5-3 and WP7V. In case of hot stamping tools, it is recommended to use CP4M® quenched and tempered to a hardness of 56-58 HRC.

The new special steel CP2M® was particularly developed for hot stamping tools [9]. Besides a high thermal conductivity it also offers a high wear resistance and temperature stability. As it shown in Fig. 6, CP2M® can be quenched and tempered to high hardness which is comparable to CP4M®. However, at lower hardness it achieves significant higher thermal conductivities than CP4M®. In these conditions it is comparable to the high conductive steel 30MoW33-7. In comparison to the standard grade X38CrMoV5-3, CP2M® shows always a better performance with respect to hardness and thermal conductivity. The wear resistance of steel CP2M® was investigated according to ASTM G 65 (rubber wheel). The results are shown in Fig. 7. Here, CP2M® was tested in comparison to the standard grade X38CrMoV5-3 and the high conductive steel 30MoW33-7, all quenched and tempered to a hardness of 50-52 HRC. As one can see, CP2M® shows a significant lower wear loss and therefore a higher wear resistance.

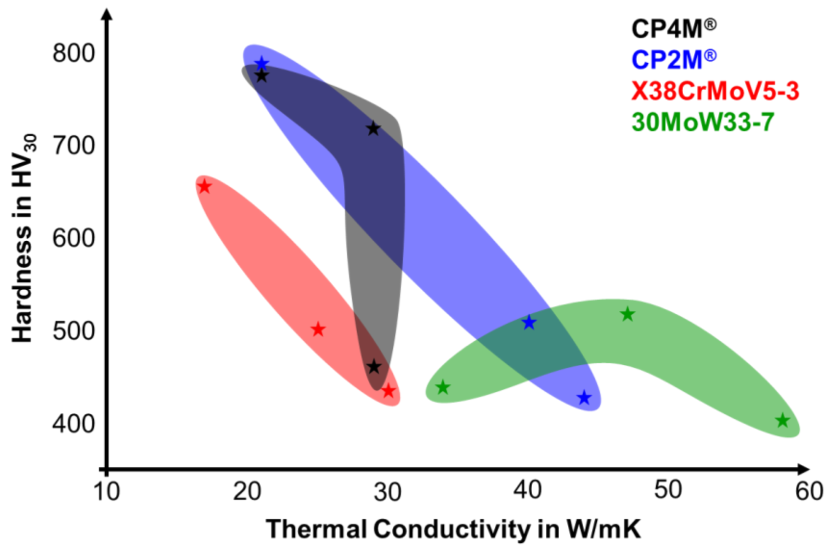


*Fig. 6: Thermal conductivities of the special steels CP4M® and CP2M® in comparison to the standard grade X38CrMoV5-3 and the high conductive steel 30MoW33-7 after quenching and tempering to working hardness.*

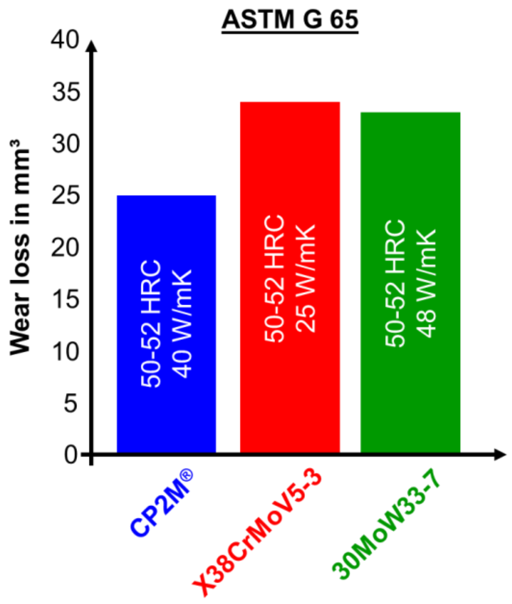


*Fig. 7: Results of wear test according to a) ASTM G 65 and b) ASTM G 75 for steels CP2M®, X38CrMoV5-3, and 30MoW33-7.*

First practice with CP2M® confirms that it shows a better wear resistance than other steels used for hot stamping tools. Trials were made for segments used in a bumper tool for the Golf VII. The segments were quenched and tempered to 58-60 HRC and plasma-nitrided and the drawing radius was measured continuously during service time. Using the standard steel grade X38CrMoV5-3 (52-54 HRC, plasma-nitrided) the tool have to be changed after 120,000 to 150,000 parts. With CP2M® wear was reduced and lifetime was enhanced up to 200,000 parts which is 25-67% longer service time of the tools.

To improve chilling by the hot stamping tools, most tool segments have internal cooling channels. Up to date there are three constructive ways for active cooled tools (Fig. 8). Most operators use drilled holes which have to be machined in the soft the soft annealed material. Although drilling is a well-known process, this production way shows many disadvantages. There are many machining operations which cost time and money. Furthermore, it is just possible to drill straight holes. Curved cooling channels are not possible although this would enhance cooling effect.

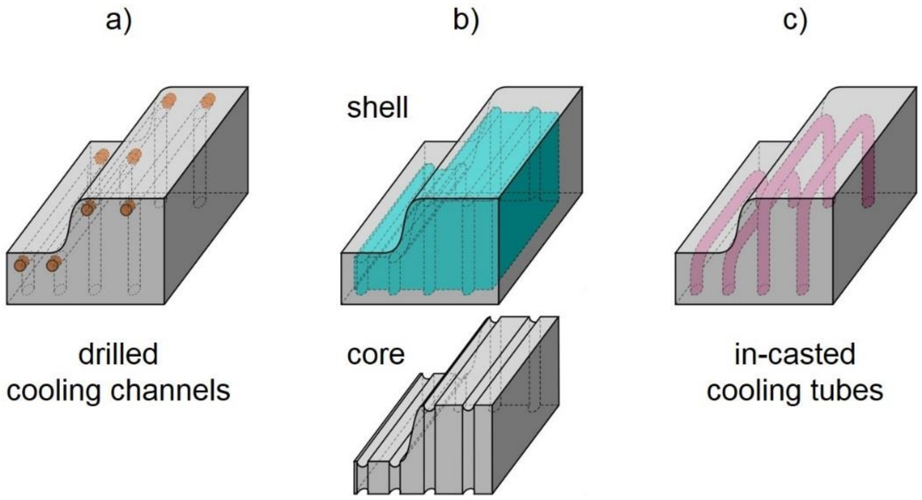


*Fig. 8: Cooling strategies for hot stamping tool: a) one-part with drilled cooling channels, b) two-parts with shell and core segment, c) one-part with in-casted cooling tubes.*

Another way is to use tools which are divided into an upper (shell) and a lower (core) part. In this case there is a higher degree of flexibility with respect to the cooling channel construction. However, there are still high machining cost and time consumption and one need a good sealing of the two parts to avoid leakage during service time.

The third way is to use in-casted cooling channels. In the past this was done by inserting tubes which were fixed in the sand mold [10]. However, fixing the tubes is very difficult and there is always a risk of melting when pouring the melt into the sand mold. A new approach is to use sand molds which were 3D-printed (Fig. 9). In this case, fixing the cooling channels is much easier and there is a big flexibility for cooling channel construction. However, casting is still very difficult.

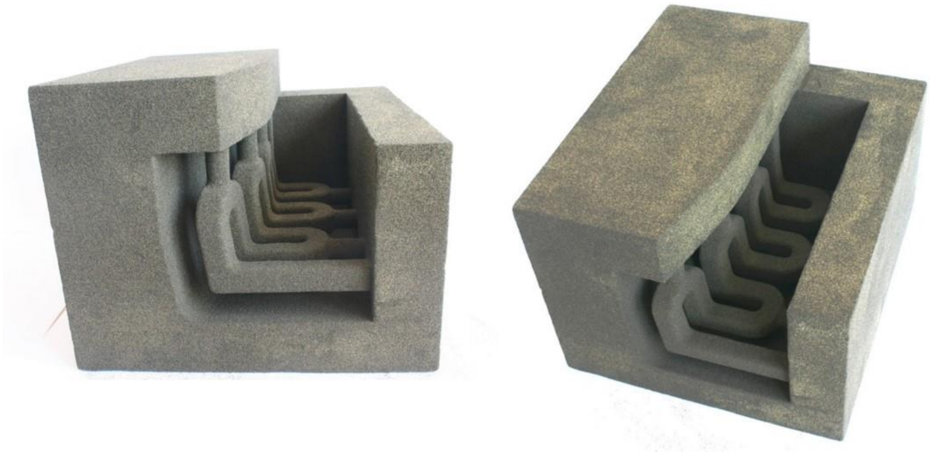

*Fig. 9: A printed sand mold with cavity and cores for cooling channels.*

Ongoing research projects are dealing with new processing technologies. In case of selective laser melting (SLM), a metal powder is used to build up a bulk material in layers. Every powder layer is melted using a special laser system. By means of SLM it is also possible to produce very complex cooling channels which is beneficial with respect to cooling efficiency. A related technology is called selective laser sintering (SLS) where the metal powder is not melted but sintered. Similar processes can also be done by electron beam which is then called electron beam melting (EBM). Another processes are build-up welding and cold spray deposition which are also used to build up 3D tools by processing metal powders.

## 4. TOOL STEELS USED FOR HARD CUTTING TOOLS

After hot stamping, automotive body parts have a high tensile strength and are in semifinish condition. They just need to be cut to bring them into final dimension. There are two ways to cut the high strength parts. Laser cutting is a very flexible and non-tool-dependent process. However, laser cutting is an energy and time consuming process [11]. Therefore, hard cutting is a common process to bring hot stamped body parts into final shape.

Hot stamped body parts normally have a tensile strength of about 1500 N/mm² (Fig. 10). Therefore, cutting tools need to have a high compressive strength and toughness. Furthermore, they should also offer a high working hardness and wear resistance. Due to sliding of the sheet metal against the tool surface there is a high friction and adhesive and abrasive wear.

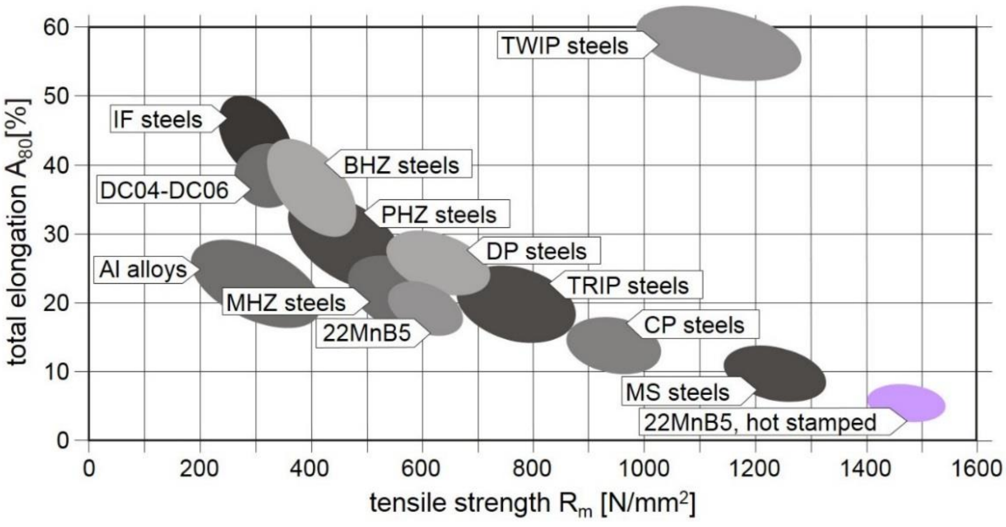


*Fig. 10: Total elongation vs. tensile strength of different steels used for automotive body parts.*

For hard cutting applications, hard and wear resistant steels show the best results. As it can be seen in Fig. 11, there are three types of steel which fulfill these requirements. For high wear resistance, cold work tool steels with a high carbide volume fraction are used which are quenched and tempered to a working hardness of 60-64 HRC. With increasing demand on toughness steels are used which show lower carbide volume fraction. Those steels are normally quenched and tempered to a working hardness of 58-62 HRC. If wear resistance and toughness are both of high importance it is also possible to use high speed steels like 1.3343 which can be heat treated to 60-64 HRC and still show a sufficient toughness. The third group of cold work tool steels show a low carbide volume fraction and therefore offer a higher toughness. However, they still reach a hardness between 56-60 HRC and provide a sufficient wear resistance.

For high demands on wear resistance and toughness there are two ways to ensure a good tool lifetime. The first way is to use powder metallurgical (PM) steels like CPOH$^{PLUS}$. According to the PM-processing route, these steels show a very fine microstructure although they exhibit a very high carbide volume fraction. These steels offer a very good wear resistance and toughness and are used for advance cutting applications. A second way is to use hard and tough steels which are nitrided and PVD-coated. In this case the base material still shows a sufficient toughness whereas the surface is covered with a very hard and wear resistant layer.

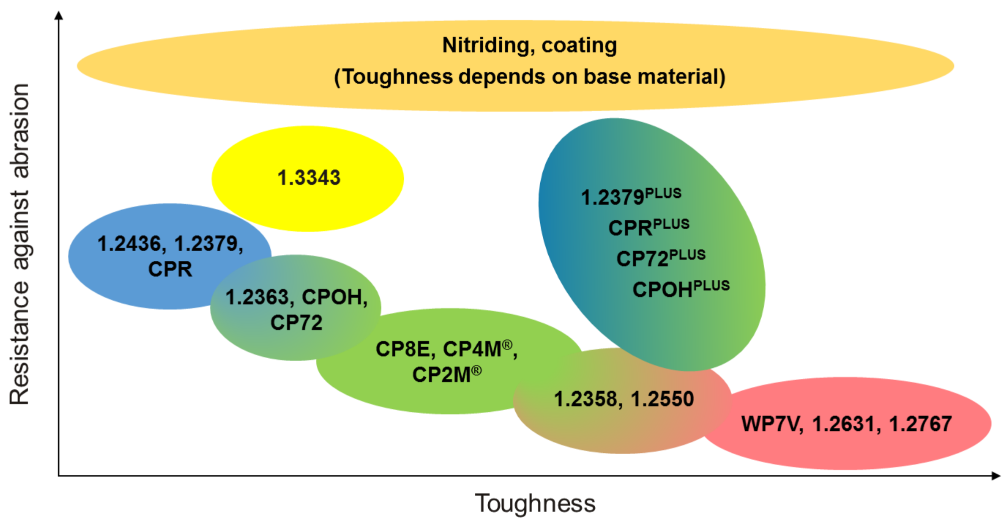


*Fig. 11: Wear resistance vs. toughness of tool steels used for cutting tools.*

Hot work tools steels and very tough cold work tool steels are normally not used for hard cutting applications. There is a too high risk of deformation and mechanical fatigue during service time. However, if sheet metal thickness increases the demand on toughness will increase in the same way. For these special applications it can be beneficial to use very tough tool steels to avoid cracking according to mechanical overload.

## 5. SUMMARY

During hot stamping, sheet metal blanks are hot stamped and afterwards hard cut. Both sub-processes require special tooling strategies. In case of hot stamping, a fast heat transfer from the hot blank into the tool is required. Furthermore, wear resistance, tempering resistance and resistance against thermal and mechanical loads are required. Therefore, hot stamping tools are normally made of hot working tool steels which exhibit a good tempering resistance and toughness. For higher wear resistance cold work tool steels are used which can be quenched and tempered to approximately 58-60 HRC and which still exhibit a good toughness. New steel grades were developed which offer higher thermal conductivities. One of these developments is the special steel CP2M® which achieves thermal conductivities between 30 and 45 W/mK in dependence of heat treatment condition. Practice shows that CP2M® additionally shows a high wear resistance which is significant higher than compared to X38CrMoV5-3.

To improve chilling of hot stamping tools, cooling channels are machined into the tools. The standard procedure is to drill bore holes into forged steel products. A second way is to use tools which are divided into a shell and a core segment. In both cases, there is a high machining effort which cost time and money. The third way is to use cast tools with in-casted cooling tubes. A new development is the 3D-printing of sand molds which improves the design of cooling channels. Future technologies are additive manufacturing processes like selective laser melting with which tools can be printed using metal powders.

For hard cutting applications, tools are exposed to high mechanical and tribological loads. They need to be hard, tough, and wear resistant. If wear resistance is of major importance, carbide containing cold work tool steels are normally used for hard cutting tool. With increasing demand on toughness hard cold work tool steel with lower carbide volume fraction are beneficial with respect to tool life time. For advanced cutting application it is favorable to use PM-tool steels or nitrided and coated cold work tool steels.

The aim of current developments is to combine the hot stamping and hard cutting process in one operations. This will affect the requirements of tool steels used for those tools because wear impact, mechanical and thermal loads will increase. Therefore, new advanced tool steels have to be developed with respect to these new requirements.

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