Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 645-654
doi:10.4028/p-5kczh8

Submitted: 2021-11-28
Revised: 2022-01-31
Accepted: 2022-02-08
Online: 2022-07-22

Influence of Conformal Cooling Channel Parameters on Hot Stamping Tool and Press-Hardening Process

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Keywords: Hot stamping tool, Conformal cooling channel, design optimization, Finite Element analysis

Abstract. Press hardening is a technology increasingly used in the automotive industries to produce high-strength structural parts in boron steel. The part strengthening is due to a martensitic microstructure, which is obtained during the quenching phase of the process by imposing cooling rates typically higher than 27 K/s. To improve cooling efficiency, conformal cooling channels (CCC) are increasingly adopting thanks to opportunities offered by additive manufacturing (AM) technologies in combination with the development of powders with high thermal conductivity.
In this work a methodology for the design of CCC inside hot stamping tools is presented and the press hardening of an automotive B-Pillar in 22MnB5 has been used as case study. The proposed methodology provides for an optimization of the distance between the cooling channels (p) and distance between the tool surface and the cooling channel center (d).

Introduction

Press-Hardening process is a technology increasingly used in the automotive industries to produce high-strength structural parts in Advanced High Strength Steels (AHSS). During this technological process the blanks are initially heated above the complete austenitization temperature Ac_3, then the blanks are formed and cooled in closed tools to quench the material [1]. The high mechanical strength of the part is guaranteed thanks to the quenching phase during which a martensitic transformation occurs. However, the fully martensitic microstructure is obtained for cooling rate greater than 27 K/s approximately and for a tool temperature below 200 °C [1-3]. To attain this, a production of tools with cooling system is required. In general, the cooling system consist of drilled channels in which water circulates [2,4]. An efficient design of the cooling system is desired in order to reduce the cooling time of the process and allow a uniform distribution of cooling. In fact, reducing the cooling time by means of an increase of the cooling rate, the total cycle time is reduced [5]. Moreover, the need to have a uniformly cooled part arises from the need to avoid dimensional discrepancies [6-7]. To meet these requirements, most of scientific works are mainly focused on optimizing cooling channel diameter, the distance between channels and the distance between tool surface and channel. Shan et al. [8] showed that the depth from the die surface to the cooling channels has the biggest impact on the cooling rate and uniformity of the workpiece. Moreover, they discovered that augmenting the cooling channel diameter near the inlet improved the water flow uniformity. Lin et al. [9] showed that the distance between the cooling channels and the distance between the cooling channel and the tools surface have significant influence on the quenching effect; in particular better quenching effect can be achieved with the shorter distance from the tool surface and with smaller distance between cooling channels. Furthermore, thermal expansion proved to be the main reason for deformation of the hot forming tools, which causes the distortion of the cooling channels, and the stress concentration at corner of the cooling channels. Recently, Hung et al. [10] stated that the blank thickness, the distance from the tool surface to the cooling channel edge, and distance between cooling channel edges are the parameters that have marked effects on cooling performance. These studies mentioned so far are mainly focused on straight drilled channels, however to improve cooling efficiency, conformal cooling channels (CCC) are increasingly adopting thanks to opportunities offered by additive manufacturing (AM) technologies in combination with the development of powders with high thermal conductivity. Cortina et al. [11] investigated the design and manufacturing of conformal cooling ducts via additive manufacturing and they compared the conformal cooling conduits with the traditional straight channels. With regard to thermal results, a more homogeneous temperature distribution within the tool and the stamped part is attained with CCC, leading to the enhancement of the dimensional accuracy and features of the produced parts. Moreover, they stated that better temperature distribution also leads to the lowering of the process cycle times in hot stamping and the subsequent improvement of the efficiency of the process and reduction of the costs. Muvunzi et al. [12] proposed a method for designing hot stamping tools with conformal cooling channels. The suggested method involves the evaluation of the part to decide whether it is suitable for AM application, the definition of conformal cooling parameters and the design of alternative layouts. Vallas et al. [13] explored the increase of cooling capacity of tools by using the new high thermal conductivity tool steel powders FASTCOOL-50 and HTCS-230.

In this work, a methodology for the design of CCC inside hot stamping tools is presented and the Press Hardening of an automotive B-Pillar in 22MnB5 has been used as case study. By choosing a commercially available tool steel powder with high thermal conductivity, an optimization of the distance between the cooling channels (p) and distance between the tool surface and the cooling channel centre (d) has been performed. The design and the optimization phases for the investigated case involves, initially, the thermal analysis as a function of the geometric channels parameters on a simplified tool geometry with a flat surface and straight channels. Thereafter, with the aim to define an optimal channel configuration, the thermal analysis has been carried out on a real case study (an insert of the B-pillar with conformal cooling channels), varying the geometric channels parameters (d, p). The thermal cycles on the tools and on the formed part, the microstructural evolution of the formed part during the quenching phase and the presence of hot spots has been evaluated.

Material and Method

The case study shown in this work to explain a method for designing the conformal cooling channels is the Press-Hardening of an automotive B-Pillar in 22MnB5 advanced high-strength boron steel, known as USIBOR®1500, that is the registered trademark of the steel producer ArcelorMittal.

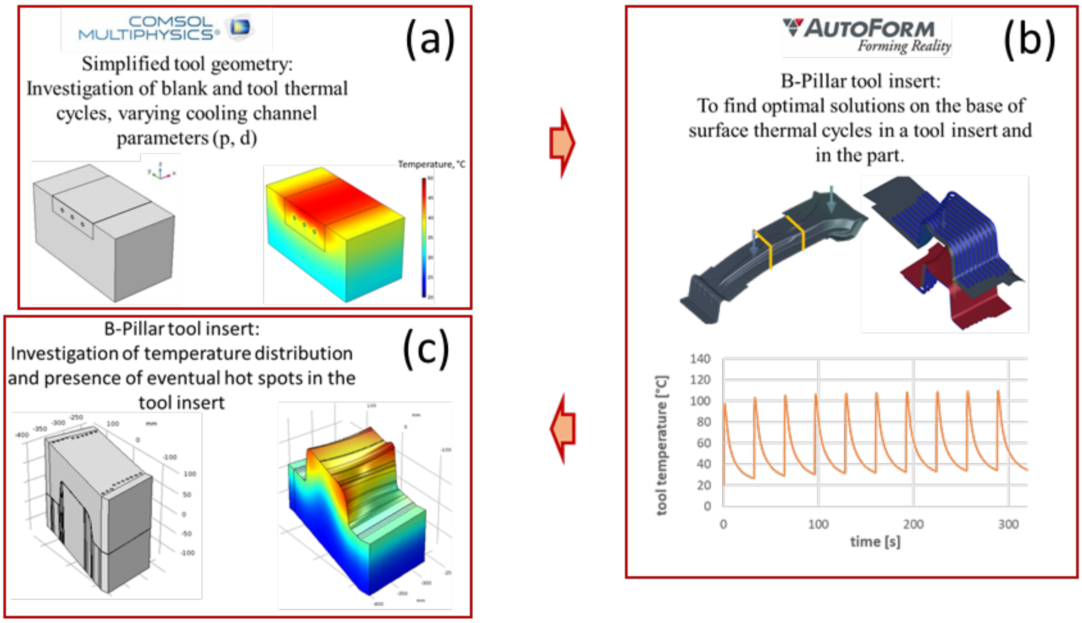

Fig. 1: Scheme of adopted procedure

The high strength of this material is reached thanks to the quenching phase in the water-cooled stamping tools. Therefore, cooling channels inside hot stamping tools play an important role in the temperature uniformity of tools, in the cooling efficiency and in the microstructural evolution in the stamped part. In this work, a methodology to optimize the cooling system characterized by CCC is proposed. The procedure is illustrated in Figure 1.

Specifically: (i) in the first phase (Fig. 1a), using a 3D transient Finite Element (FE) thermal model developed in Comsol Multiphysics, a preliminary investigation of tool thermal cycles, varying the distance between the cooling channels (p) and distance between the tool surface and the cooling channel center (d) has been carried out. For this model, a simplified tool geometry with a flat surface and straight channels has been used. (ii) The modelling of conformal cooling channels the hot stamping tools has been performed through a CAD modelling software. Each configuration has been imported in the AutoForm FE code and the Press-Hardening process has been numerically simulated (Fig. 1b). On the base of thermal cycles on surface of tool insert and in the part, an optimal solution have been chosen, by evaluating the value of peak temperature, the tool temperature at the beginning of the next stamping cycle and the number of cycle needed to reach the steady state condition. (iii) In correspondence with the identified optimal solutions the temperature distribution and presence of eventual hot spots in the tool insert have been investigated with a 3D FE thermal model developed in Comsol Multiphysics (Fig. 1c).

Investigation of the temperature distribution using a simplified tool geometry

A transient 3D thermal model has been developed using Comsol Multiphysics FE software. The model simulates the quenching and the cooling in air phases during several stamping cycle in a press-hardening process. A simplified tool geometry with a flat surface and straight channels has been used and, with the aim of reducing the number of element and the iteration time, only the lower tool and half thickness of the blank have been modelled. Figure 2 shows a scheme of the model geometry and the cooling channels parameters, i.e. the distance between the cooling channels (p) and the distance between the tool surface and the cooling channel centre (d). The thermal analysis has been carried out as a function of geometrical parameters p and d. Table 1 repots the investigated values of p and d parameters.

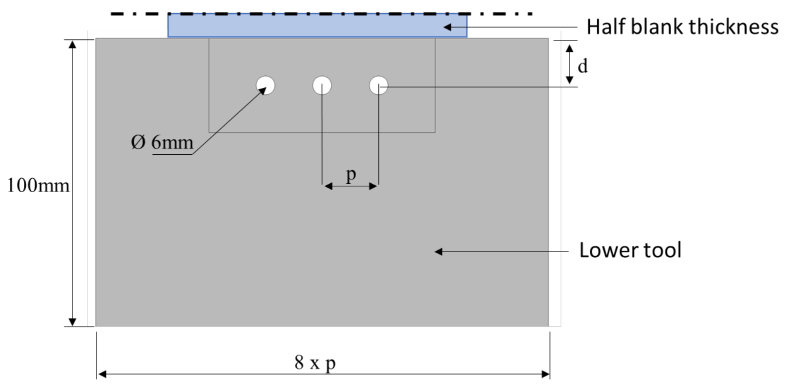

Fig. 2: Scheme of simplified FE model s

Table 1: Values investigated for geometrical parameters of cooling channels

p (mm)	d (mm)
12	9
18	15
24	21

Table 2a: Values of tool parameters

Tool parameters	
Thermal conductivity (W/m·K)	54
Heat capacity (J/kg·K)	480
Density (kg/m^3)	8040
Young’s modulus (GPa)	210
Poisson ratio	0.3

Table 2b: Values of blank parameters

Blank parameters	
Thickness (mm)	1.7
Thermal conductivity (W/m·K)	32
Heat capacity (J/kg·K)	470
Density (kg/m^3)	7800
Young’s modulus (GPa)	210
Poisson ratio	0.3

For the thermal analysis the initial temperature of the tool and the Heat Transfer Coefficient (HTC) have been set respectively equal to 20 °C and 3000 W/(m^2 K). The HTC parameter has been assumed to be constant. For the choice of the value of the HTC between tool surface and blank, the work of Lechler et al. [17] has been considered as reference. Moreover, a Reynolds number equal to 4000 has been imposed, in order to obtain a turbulent water flow. The initial blank temperature at the beginning of the quenching phase and the quenching time have been set respectively equal to 650 °C and 18 s. The cooling in air time have been set equal to 14s. Tool and blank parameters are specified respectively in Table 2a and in Table 2b. The properties of the tools shown in Table 2a are characteristics of commercially available powders (HTCS1) with high thermal conductivity that are used to manufacture tools with the L-PBF (Laser Powder Bed Fusion) technique.

Having assumed the manufacturing of cooling channel by means a L-PBF technique, the diameter of the channels has been set at 6 mm. Beyond this value, in fact, it is necessary to use internal supports that cannot be removed after manufacturing the tool. The presence of such supports is not recommended as it can adversely affect the flow conditions inside the channels [18].

Investigation of the temperature distribution of the tool surface

The press-hardening process of a B-Pillar has been modelled in AutoForm FE software, using the Conformal Cooling Channels corresponding to the p and d parameters reported in Table 1. Each of the nine thermo-mechanical simulations has been performed to analyse twenty consecutive hot stamping cycles. Figure 3 shows the tools modelled in AutoForm (Fig. 3a) and a detail of the insert with conformal cooling channels (Fig. 3b).

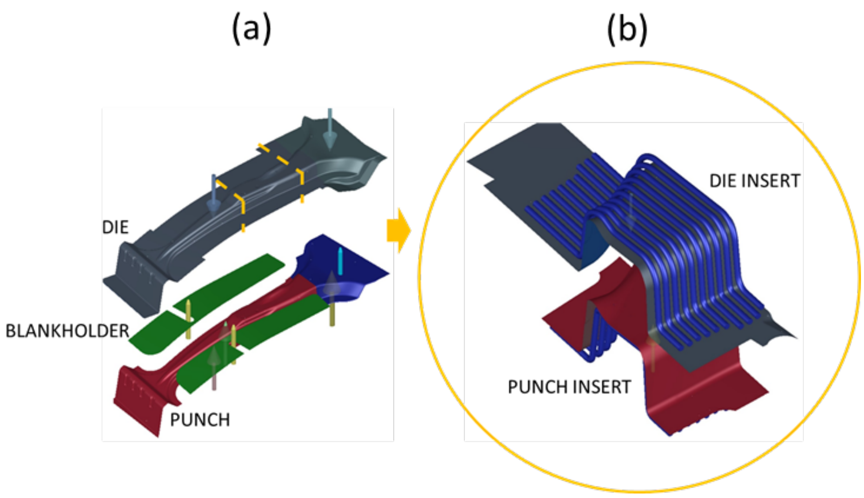

Fig.3: Tools of investigated B-Pillar (a) and detail of tool insert (b)

Table 3: Process parameter for hot stamping FE simulation in AutoForm environment

Process parameters	Values
Blank heating temperature (°C)	950
Transport time (s)	5
Positioning and drawing time (s)	7
Quenching time (s)	18
Cooling water temperature (°C)	20
Quenching force (ton)	400

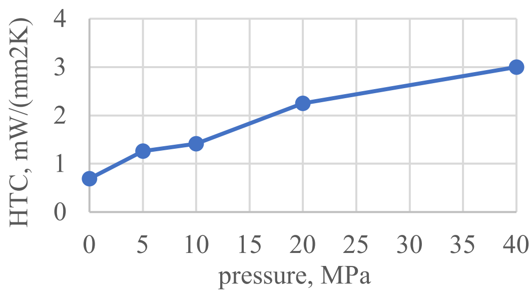

Fig. 4: Pressure dependent HTC

The process parameters adopted for the numerical simulations of the hot stamping process in the AutoForm environment are shown in Table 3. The model simulates the transport phase of the sheet from the furnace into the press and the cooling in air phase of the component as well as the drawing and quenching phases. Some blank and tools parameters are reported in Tables 2a and 2b. The HTC coefficient has been defined as a function of gap and contact pressure between sheet and tool. The gap change the contact conditions and it can occur due to the sheet thinning. Figure 4 shows the influence of contact pressure on HTC coefficient. Scale factor for the variation of HTC coefficient as a function of the contact pressure and the value of the gap for which the HTC is halved have been chosen referring to the work of Lechler et al. [17].

Investigation of the temperature distribution in the tool insert

With the aim to analyse the temperature distribution in the tool insert highlighted in Figure 3, a transient 3-D thermal model has been developed using Comsol Multiphysics FE software. The model simulates the quenching and the cooling in air phases during several stamping cycle in a press-hardening process. The formed part and tool parameters are the same as entered in Tables 3a and 3b, while the process parameters are the same as described in section 1.1.

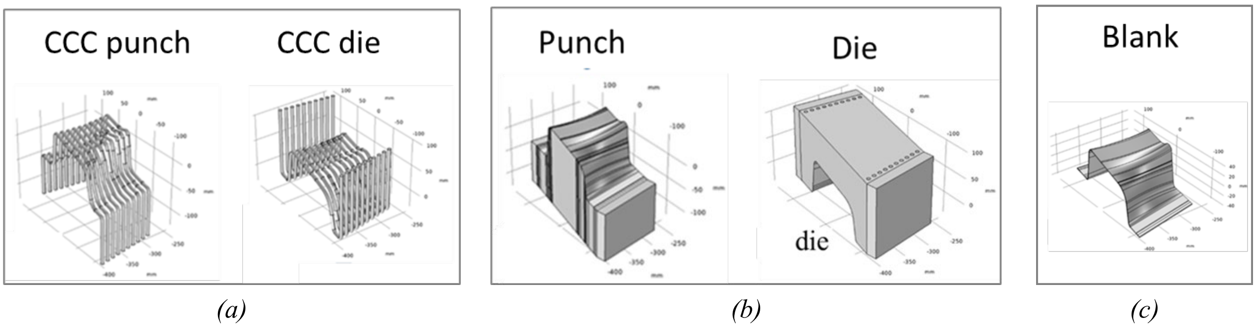

Fig. 4: Geometric model of the conformal cooling channels(a), the die and the punch (b) and the blank(c)

Figure 4 shows the geometric model of the conformal cooling channels (Fig. 4a), the die and the punch (Fig. 4b) and the blank (Fig. 4c). An unstructured tetrahedral mesh has been chosen for the numerical simulations.

Results and Discussion

Thermal analysis on simplified FE-model

The simplified FE-model has been used to investigate the effect of cooling channel parameters (p, d) on tool temperature distribution. The range shown in Table 1 has been selected on the base of surface temperature uniformity that decreases with the increase of the distance between channels (p) and the reduction of distance between the cooling channel centres (d). The result analysis focused on the comparison of thermal cycles on the tool surface in the central point. For all investigated channel configurations, the tool peak temperature, the tool temperature at the beginning of the next stamping cycle and the number of cycles needed to reach the steady state condition have been evaluated.

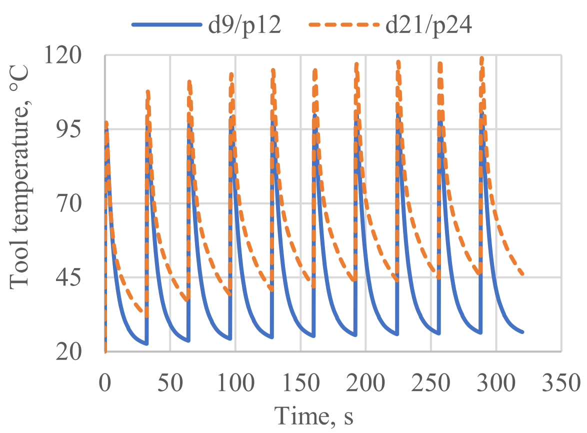

Fig. 5: Thermal cycles on tool surface with cooling channels in two geometric configuration

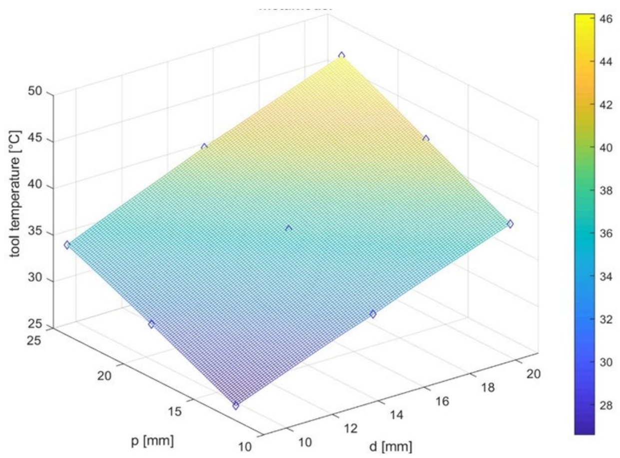

Fig.6: Metamodel for the evaluation of the tool temperature at the end of the stamping cycle

Figure 5 shows the extreme thermal cycles, obtained using the following cooling channels configurations: (i) Minimum values of d and p parameters (d = 9 mm and p = 12 mm). (ii) Maximum values of d and p parameters (d = 21 mm and p = 24 mm). The other cooling channels configurations show thermal cycles between curves drawn in Figure 5. Results show that minimum value of tool peak temperature and tool temperature at the end of the hot stamping cycle is obtained with the lowest value of d and p parameter investigated (d = 9 mm and p = 12 mm). Moreover, tool peak temperature varies in the range 100 °C - 118 °C, tool temperature at the end of the hot stamping cycle varies in the range 27 °C - 46 °C, while stationnary conditions are reached after about 10 cycles. Using Kriging technique, the tool temperature at the end of the stamping cycle in the steady state condition has been modelled as a function of d and p parameters. The obtained metamodel (Fig. 6), highlights the effect that an increase of both d and p parameters have on the increasing of the tool temperature at the end of the stamping cycle.

Thermal analysis on FE-model with B-Pillar insert in AutoForm environment

Press-hardening process of a B-Pillar has been simulated with AutoForm software using CCC with the cooling channel parameters reported in Table 1. In post-processing phase, temperatures on the central points of tools surfaces (punch and die) have been analysed observing twenty hot stamping cycles, for all the CCC configurations.

Figure 7 shows the punch thermal cycles corresponding to the extreme configurations. These results confirm that an increase in d and/or p parameter leads to an increase both of the tool peak temperature and of tool temperature at the end of the stamping cycle. To better evaluate after how many hot stamping cycles the steady state condition is reached, the punch temperature difference between two consecutive hot stamping cycles at the end of quenching phase has been calculated (Fig. 8). It is possible to state that in the configuration with the cooling channels closest to the tool surface and closest to each other, the temperature stabilizes already starting from the sixth cycle (temperature difference equal to zero). For the configuration with cooling channels at maximum distance from the punch surface and at maximum centre distance, the temperature difference is below 1 °C starting from the seventh cycle, but the temperature difference decreases to zero in the twelfth cycle. Therefore, the twelfth cycle can be considered as the steady state condition for all the geometric configurations of the CCC.

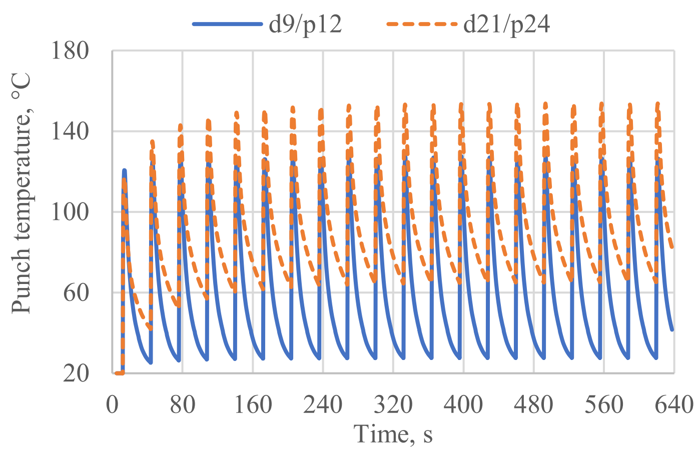

Fig. 7: Thermal cycles on punch surface with cooling channels in two configuration

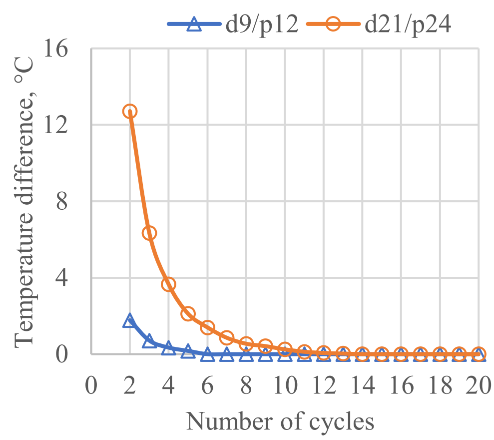

Fig.8: Punch temperature difference between two consecutive hot stamping cycles

Figure 9 shows the steady-state thermal cycles in the two extreme conditions and the respective temperature distributions in the tool. The results show that as the geometric parameters of the cooling channels vary, the peak temperature of the tool varies in the range 126 °C - 154 °C, while the tool temperature at the end of the hot stamping cycle varies in the range 42 °C - 82 °C. The lower values of these ranges are obtained using d = 9 mm and p = 12 mm and for this configuration it is possible to reach the steady state condition first, already from the sixth stamping cycle. In the steady state condition, all the CCC configurations investigated assure in the quenching phase cooling rate in the formed part higher than 50 K/s; therefore the complete martensitic transformation is guaranteed.

Taking as reference the less severe channels configuration (d = 21 mm and p =24 mm), in the Figure 10 is shown the time evolution of the martensitic transformation on the blank during the quenching phase. This result highlights that just three seconds from the start of the quenching phase, greatest part of the formed part has a completely martensitic microstructure, while after 14 s, the formed part is fully martensitic.

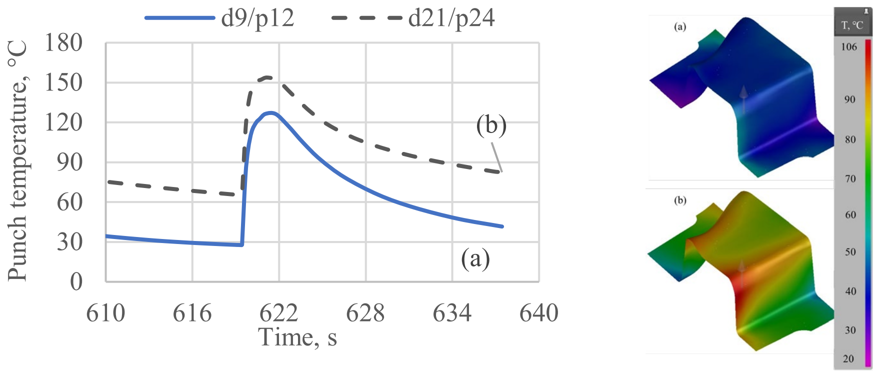

Fig. 9: Thermal cycles in the steady state condition for the two most extreme condition and the respective temperature distribution on the punch

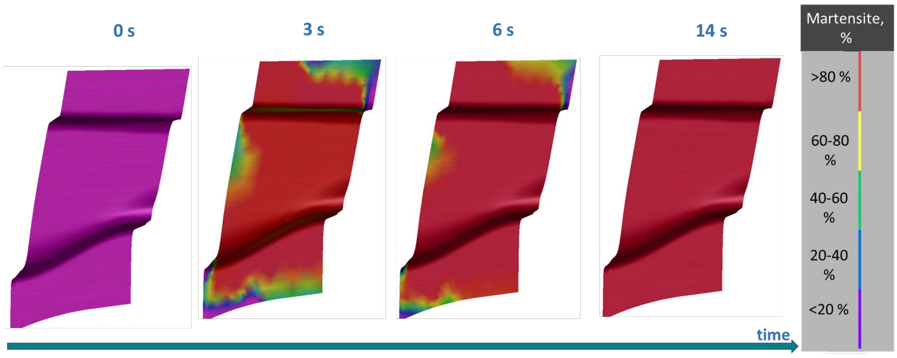

Fig.10: Martensite history during quenching phase (d = 21 mm, p = 24 mm)

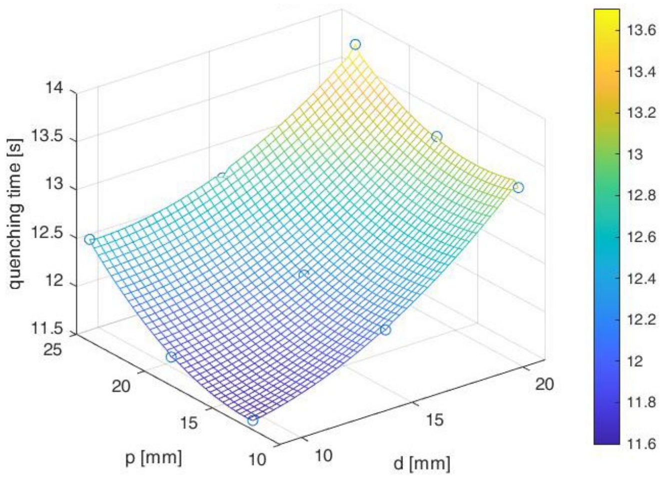

Fig. 11: Metamodel related to the quenching time that guarantees the complete martensitic transformation as p and d vary

Therefore it can be considered that the additive manufacturing approach that ensure conformal cooling channels production and the use of materials with high thermal conductivity allows the complete martensitic transformation of the component in approximately 14 s during quenching phase, less than the 18 s imposed. By tracking the temporal evolution of the martensitic transformation during the quenching phase for all the conformal cooling channels geometric configurations, the metamodel in Figure 11 can be obtained. It can be observed that as the parameters p and d are reduced, the quenching time necessary to guarantee the complete martensitic transformation is reduced. This suggests as optimal channel configuration, that obtained with d = 9 mm and p = 12mm.

Thermal analysis on FE-model with B-Pillar insert in Comsol Multiphysics environment

The optimal channel configuration highlighted in section 2.2 (d = 12 mm and d = 9 mm) has been investigated with the transient 3D FE thermal model described in section 1.3. This model allows to evaluate the temperature distribution not only on the tool surface but also on the entire tool volume.

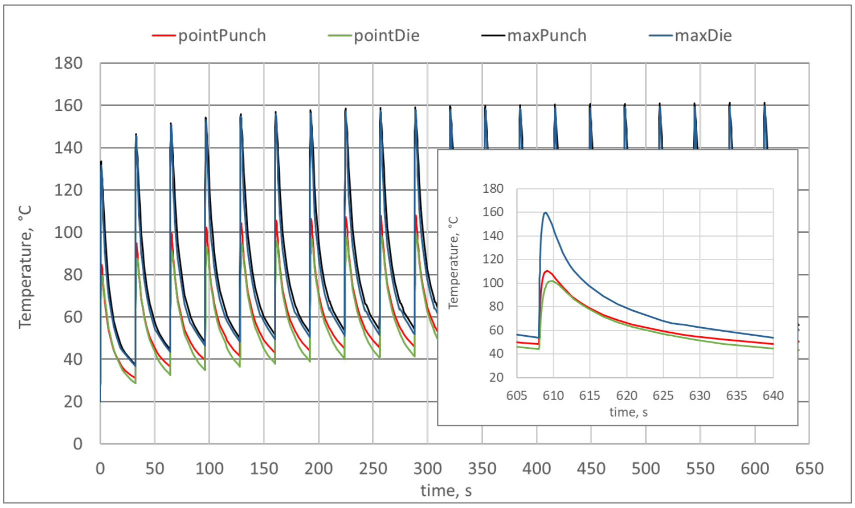

Fig. 12: Thermal cycles recorded during 20 hot stamping cycles at 30 mm from the punch and die surfaces and on the punch and die surfaces

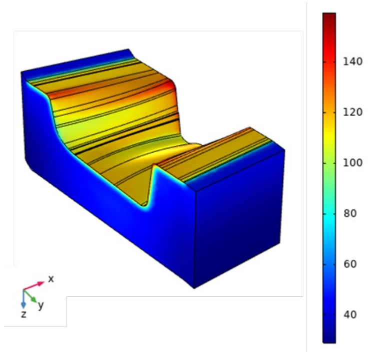

Fig.13a:Die temperature distribution in the steady condition at the time corresponding to the peak temperature

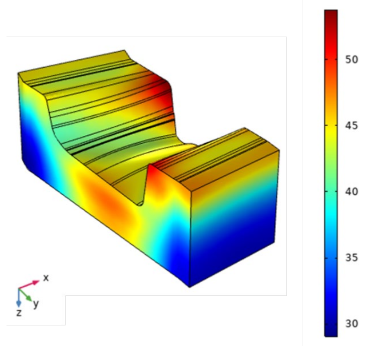

Fig.13b: Die temperature distribution in the steady condition at the time corresponding to the end of the hot stamping cycle

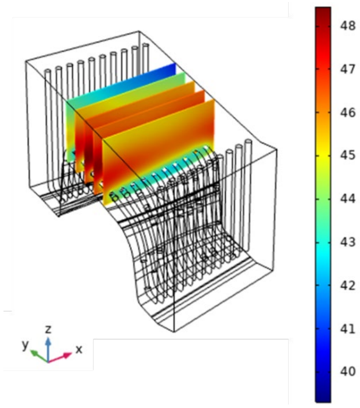

Fig.13c: Temperature distribution in the cross sections of the die at the end of the stamping cycle in the steady state condition.

Figure 12 shows the thermal cycles in the punch and in the die recorded both at 30 mm from the tool surface centre (pointPunch, pointDie) and in the point of the tool surface where are observed maximum temperatures (maxPunch, maxDie), during twenty hot stamping cycles. In addition, Figure 12 also shows the details of the thermal cycles at steady state. It can be seen that the peak temperatures recorded at 30 mm from the tool surface are about 33% lower than those obtained on the punch and die surfaces. Moreover, it is possible to observe that, while on the tool surface the thermal cycles of the die and the punch coincide, at 30 mm from the tool surface temperatures are lower in the die respect to those recorded in the punch because they depend from the tool shape. Finally, it can be highlighted that the steady state condition is reached starting from the tenth stamping cycle.

In Figure 13a and in Figure 13b, the die temperature distribution in the steady-state is shown at the time corresponding to the peak temperature and at the time corresponding to the end of the hot stamping cycle, respectively. On the other hand, Figure 13c shows the temperature distribution in the cross sections of the die at the end of the stamping cycle in the steady state condition. From Figure 13a it can be seen that the peak temperature of the die ranging between 100 °C and 160 °C on the surface, while in the remaining part of the die, not in direct contact with the hot blank, the temperature is about 40 °C. From Figure 13b, on the other hand, it is observed that the heat is distributed by conduction in the entire volume of the die. In particular, analyzing the temperature distribution in the cross sections of the die (Fig. 13c), it is observed that near the cooling channels the temperature is slightly higher than 40 °C while moving away from the cooling channels the maximum temperature recorded is 50 °C. From these figures, it emerges that although there are hot spots, in these points, compared to the remaining areas of the tool, the temperature increase of about 20 °C. This temperature increase is negligible, therefore the geometric solution for conformal cooling channels with p = 9 mm and d = 12 mm is actually an optimal solution.

Conclusion

In this work, a methodology has been presented for the optimization of the cooling system of the tools adopted for the Press-Hardening process to manufacture a B-Pillar in 22MnB5. The cooling system must be effective to ensure the complete martensitic transformation of the component, i.e. high mechanical resistance, to reach a steady state condition in a few cycles to give the stamped components constant microstructural characteristics for each stamping cycle and, finally, to avoid increasing operating temperatures to prolong the lifespan of the tools.

The optimization has been carried out by varying the parameters p and d, i.e., the distance between the cooling channels and the distance between the cooling channels centre and the tool surface.

With this aim, to reduce computational costs, a simplified model has been first developed with a tool flat surface and straight channels. The model made it possible to identify channel configurations of possible interest, the steady state condition (evaluated in about 10 stamping cycles), and the channel configuration with lower peak temperatures and temperatures at the end of the stamping cycle (d =12 mm and p =9 mm).

The model developed in AutoForm FE software was used to simulate several stamping cycles in the press-hardening process of a B-Pillar. Thermal results on the tool surface agree with those of the simplified model, allowing a more precise definition of: (i) the steady state condition (6 - 12 cycles switching from the most severe to the least severe channel configuration). (ii) The tool peak temperatures in the steady state condition, which vary between 126 °C and 154 °C. (iii) The tools temperatures at the end of the hot stamping cycle, which vary between 42 °C and 82 °C. The microstructure evaluation in the formed part showed a decrease of the quenching time needed for the complete martensitic transformation, passing from the less severe to the more severe channel configuration. The maximum quenching time simulated (14 s) is in any case less than that imposed in the simulation of the press-hardening process (18s). The configuration of the channel with the minimum hardening time (12), obtained with d = 9 mm and p = 12 mm, can be considered optimal because it reduces the cycle time. The analysis of the temperature distribution in the punch and die inserts with the optimal channel configuration, made using the transient 3D model developed with the Comsol Multiphysics software, did not highlight any criticality caused by the presence of hot spot.

Acknowledgments

The authors are grateful to thank MIUR (PICO&PRO project) for funding this research, AutoForm and Fiat Research Centre (CRF) for the technical support.

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