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STUDY ON THERMOMECHANICAL BEHAVIOR OF COOLED DIE APPLIED TO HOT STAMPING PROCESS

Caio Henrique Grisotto
Gregory Bregion Daniel
School of Mechanical Engineering – University of Campinas, Mendeleyev Street, 200, Campinas - SP - 13083-860
caiohgrisotto@gmail.com; gbdaniel@fem.unicamp.br

Abstract. Automotive industries have assumed an increasingly competitive hole in relation to the development of new products. In addition, initiatives to ensure greater sustainability have been strongly adopted in this sector, mainly aiming to guarantee the manufacture of lighter and more efficient vehicles, without compromising the resistance, safety and comfort requirements safeguarded by normative entities. In this scenario, the hot stamping process is a powerful technology for manufacturing of automotive structural components, allowing to reduce the weight of structural components, increase the mechanical and fracture strength of the stamped components and guarantee the dimensional quality of the final products. In general, the increase of the mechanical strength of the stamped components is due to the martensitic microstructure, which is obtained in the cooling phase of the blank inside the closed die during the process. As blank cooling occurs inside the dies, an efficient design of the die and its cooling system is essential to increase tool life and ensure high mechanical strength in the stamped part. Thus, there are three main parameters that need to be studied in order to obtain a die design with good performance in your cooling system, namely: the distance from the cooling channel to the die's surface, the distance between neighbors cooling channels and the diameter of the cooling channel. Although hot stamping is currently a well-established process, the simulation of this process by Finite Element Method incorporating thermal and structural behaviors is still a challenge. Within the context, this work aims to simulate the hot stamping process by Finite Element Method, in order to evaluate the thermomechanical effects both in the stamped part and in the tools (die and punch). The results obtained through these thermomechanical analyses provide important contributions related to the effects of positioning, quantity and geometry of the cooling channels in relation to the temperature distributions in the components involved in the process. This way, possible improvements can be established to the die design, in order to guarantee better production quality and mechanical strength for manufacturing of stamped parts. From the analyzes carried out, it can be concluded that among the geometric parameters of the cooling system of the dies, the distance from the centers of the channels to the forming surface of the tools was the parameter that best played a role in reducing the peak temperature both of the punch and the die. The number of channels and the placement of the channels in relation to their neighbors play an important role in homogeneously cooling the tools and preventing the minimum temperature increase and its interior.

Keywords: Hot Stamping; Finite Element Method; Cooling Channels, Die Design

1. INTRODUCTION

Fuel consumption and the consequent emission of harmful gases into the atmosphere is one of the main sources of impact on the environment by cars during their useful life. The car's fuel consumption is directly related to the performance of its propulsion/transmission system, its own weight, and its aerodynamics. Although fuel consumption is mainly influenced by the propulsion/transmission system, aerodynamics has a secondary role in this task. Moreover, it is possible to reduce the vehicle's fuel consumption by reducing the weight of its bodywork and its equipment, since the bodywork weight is equivalent to approximately ¼ of the total weight of the vehicle (Diogo, Cruz, & Morais, 2014).

Within the current context, the growing demand in the automotive industry for lighter vehicles has promoted and driven the development of hot stamping technology. The main objective of this technology is to increase the mechanical strength of stamped automotive components by obtaining a predominantly martensitic microstructure that makes it possible to reduce the thickness of the component and consequently its weight, without compromising its mechanical performance.

In a hot stamping process, ultra-high strength steel blanks such as 22MnB5 are initially austenitized in temperatures between 900 °C and 950 °C during a time interval of 5 to 10 min. Then, after leaving the oven, the blank is transferred to a press where it is hot formed, and respectively tempered through cooled dies through cooling channels. For a good quality of the final product, the blank must present an austenitic microstructure throughout the conformation stage, thus making it necessary for the blank to finish this stage at a temperature above the temperature at which the martensite formation starts of the steel used (Diogo, Cruz, & Morais, 2014).

In the final step of the operation, the blank inside the dies is simultaneously tempered, with the dies acting as a tempering medium for the process, enabling the microstructure of the blank to be transformed from austenite to martensite. However, this microstructural change is only achieved when the cooling rate is above a critical value, which depends on the alloy. If the cooling rate is below this critical value, the final microstructure of the stamped product will consist of a mixture of bainite and ferrite phases, thus considerably affecting the final mechanical properties of the stamped part (Chantzis, et al., 2020).

For 22MnB5 high strength steel, a cooling rate of at least 27 °C/s must be provided by the tools on request to obtain a stamped component with a predominantly martensitic microstructure, providing a resistance limit of up to 1500 MPa at the end of the process. This cooling rate can be obtained by changing the geometric parameters of the die cooling system, namely: the distance between the centers of the channels, the distance between the channels and the tool's work surface and the diameter of the channels. In addition, the efficiency of the tool cooling system also depends on the temperature gradient and the geometry of the part to be stamped (Mace, Lin, & Min, 2012).

During the series production of parts using hot stamping technology, it is necessary to maintain the surface temperature of the tools below 200 ºC, in order to guarantee the cooling of the blank and to extend the useful life of the tools. (He, Ying, Li, & Hu, 2016).

In addition to having a direct influence on the final mechanical properties of the stamped product, the cooling system of the dies also has a significant effect on the useful life of the tools and on the process cycle, being the blank cooling stage one of the main process bottlenecks. Therefore, this work aims to evaluate the effects of the geometric parameters of the cooling system on the peak temperature and temperature distribution in several tool models. For this, thermomechanical simulations were performed by ANSYS MECHANICAL 2020 – COUPLED FIELD TRANSIENT software. The following geometric parameters of the cooling systems of the hot stamping tools were considered in this study: the diameters of the channels, distance between the centers of the neighboring channels, distance from the centers of the channels to the forming surface of the dies and number of channels of cooling. The results obtained in this study show which are the most influential parameters in the resulting temperature distribution of the stamped part, thus indicating the best layout for the cooled die.

2. TEXT FORMAT

The strength of the stamped product by hot stamping process is achieved and influenced by the performance of the cooling system of the stamping dies. Therefore, the cooling channels of the tools play a crucial role in the microstructural evolution of the blank, in the process cycle time, in the useful life of the tools, in the minimization of the peak temperature of the tools and in the temperature distribution of both the blank and the tools.

In this work, a 3D CAD model of a set of hot stamping tools was idealized, with the objective of numerically simulating a hot stamping process through coupled thermomechanical analysis. Changing the geometric parameters of the channels resulted in a total of 10 different 3D CAD models that were incorporated into the ANSYS MECHANICAL 2020 software in order to have a perception of the influence of the cooling channels on the peak temperature of the tooling and on the temperature distribution of the tooling. As it was an idealized model just to have a perspective of the behavior of the process and the responses of the geometric parameters of the channels in the performance of the cooling system, the material used for both the tools and the blank was a structural steel from the library itself provided by the ANSYS software, with the appropriate mechanical and thermal properties varying with temperature and necessary to simulate this type of process in a coupled thermomechanical way.

2.1 Simplified models of hot stamping tools

In order to investigate and evaluate the influence of the geometric parameters of the cooling system of the dies on the peak temperature and on the temperature distribution in the tools, a simplified 3D CAD model of hot stamping tools with some channels was idealized, as represented by figure 1.

In terms of dimensions, the width and length of the tools are respectively 204 mm x 210 mm for both the punch and the die. The blank has a width and length of 180 mm x 200 mm, respectively. Regarding the thickness of the blank, it is worth mentioning that several literatures indicate a recommended diameter range for the cooling channels depending on the thickness of the blank to be stamped. In this work, a thickness of 5 mm was adopted for the blank, which is outside the recommended range for the diameters of the channels adopted. The choice of a thicker blank for its recommended diameter range was due to the need to identify the influence of geometric parameters of the cooling system from the first cycle of coupled thermomechanical simulation of the hot stamping process, reducing the computational costs of these simulations. Figure 2 illustrates the geometric parameters of the cooling die.

From the standard tools model represented in figures 1 and 2, the geometric parameters of the cooling system were changed, generating others 9 CAD models, which were submitted to coupled thermo-mechanical simulations of the hot stamping process by Finite Element Method. Figure 3 illustrates the 10 models simulated by ANSYS.
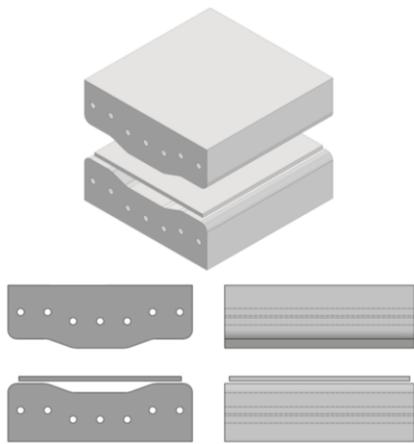
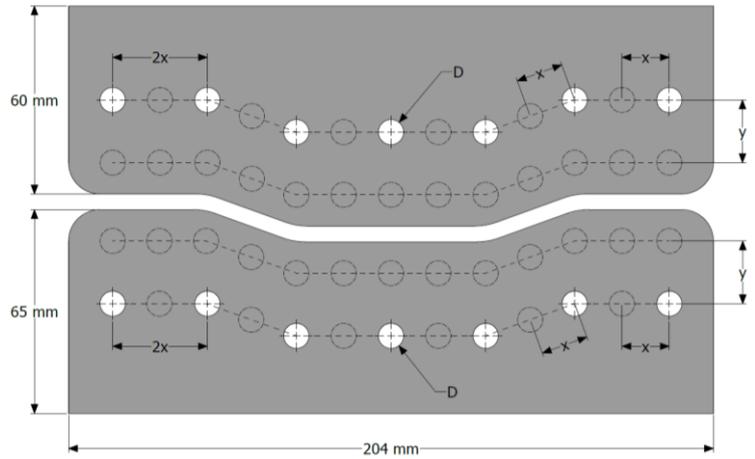Figure 1. Simplified tool used in the simulations

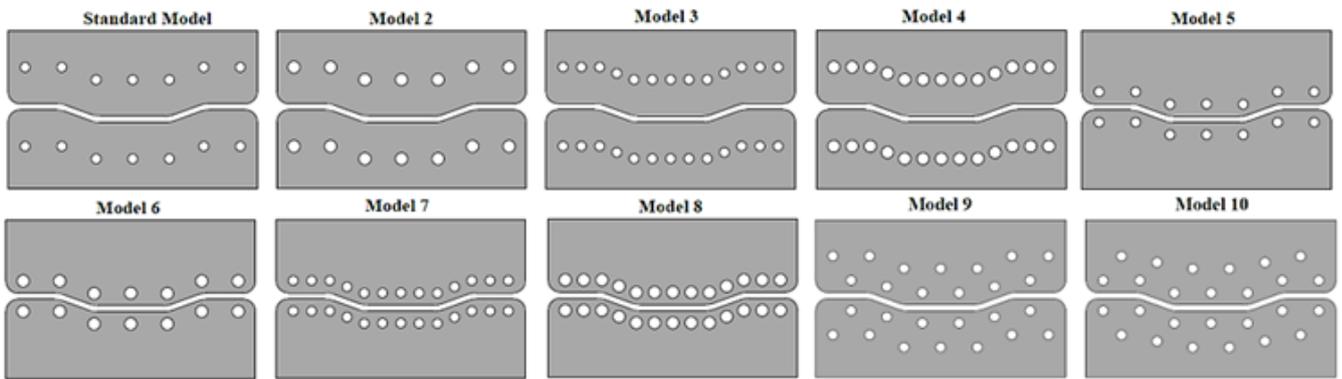Figure 2. Geometric parameters of the cooling system

Figure 3. CAD models simulated by ANSYS.

As can be seen in figure 3, in all models the channels are longitudinal, however, with changes in their geometric arrangements and diameters. Table 1 shows the parameters that were changed in the cooling system for each model shown in figure 3.

Table 1. Parameters changed in each model.

Models	Parameters			Total Number of Channels
	D	x	y	
Standard Model	8 mm	15 mm	0 mm	14
Model 2	10 mm	15 mm	0 mm	14
Model 3	8 mm	15 mm	0 mm	26
Model 4	10 mm	15 mm	0 mm	26
Model 5	8 mm	15 mm	20 mm	14
Model 6	10 mm	15 mm	20 mm	14
Model 7	8 mm	15 mm	20 mm	26
Model 8	10 mm	15 mm	20 mm	26
Model 9	8 mm	15 mm	0 and 20 mm	26
Model 10	8 mm	15 mm	0 and 20 mm	26

2.2 Convection in the Tool Cooling Channels

The tempering of the blank and the cooling of the tools are achieved through the forced convection of the cooling fluid (water) that flows through the cooling channels of the dies, in which this phenomenon is characterized by a convection heat transfer coefficient (CHTC). According to (Fernández, González, Artola, Lacalle, & Angulo, 2019), the convective heat transfer coefficient in the channels can be estimated by:

$$CHTC = \frac{Nu \cdot k}{\emptyset}, \tag{1}$$

being the Prandtl number (Pr):

$$Pr = \frac{\mu \cdot Cp_w}{k}, \tag{2}$$

Reynolds number (Re):

$$Re = \frac{\rho_w \cdot \upsilon \cdot \emptyset}{\mu}, \tag{3}$$

Nusselt number (Nu):

$$Nu = 0.023 \cdot Re^{\frac{4}{5}} \cdot Pr^{\frac{3}{10}}, \tag{4}$$

in which μ is the dynamic viscosity of water in Pa.s, k is the thermal conductivity of water in W/m.ºC, Cp_w is the heat capacity of water in J/Kg.ºC, ρ_w is the water density, $\emptyset$ is the diameter of the die cooling channel in m and υ is the average flow velocity in m/s. In this study, the water temperature during the process cycle was assumed to be constant and equal to 22 °C, therefore, was employed a CHTC = 15000 W/m².ºC for each cooling channel.

2.3 Heat Transfer between Tools and Blank

The heat transfer between the dies and the blank is characterized by the interfacial heat transfer coefficient (IHTC), which is highly dependent on the contact pressure during the stamping process, the surface conditions of the tool and the temperature of the system (Arrizubietaa, Cortina, Ostalaza, Ruiz, & Lamikiz, 2019). In this study, the IHTC was assumed to be constant equal to 2.5 W/m².ºC from the establishment/closing of the contact between the tool surfaces and the blank during simulations via FEM (Gap = 0 mm).

2.4 Finite Element Models

Due to the high computational cost and processing time required for numerical simulations of a hot stamping process via FEM, due to the high sources of nonlinearities and the complexities involved, such as: contact problem, large deformations, large deflections, plasticity, rigid body motion, mechanical and thermal properties of the material varying with temperature, microstructural changes, friction and among other factors, the following simplifications were adopted in the numerical analyses carried out in this study:
- The 10 models were simulated with ¼ symmetry;
- A reduction scale of 1:10 was applied to all models to simulate them via MEF;
- It was not considering the microstructural change and evolution of the blank;
- Only 1 stamping cycle was simulated for the 10 models; IHTC and CHTC were assumed to be constant during all analyses;
- For both channel diameter values adopted, the same CHTC value was assumed; It was not considered heat exchange by natural convection from the tools and the blank to the environment;
- It was not considered the heat loss by thermal radiation by the tools and by the blank;
- The friction model adopted is the Coulomb model with μ = 0.15 and constant throughout the analysis;
- The Bilinear Isotropic Hardening model was adopted for the blank.

For the 10 models analyzed numerically via FEM, the initial temperature of the blank and the tools were established at 900 ºC and 22 ºC, respectively. Figure 4 shows the visual representation of the standard model with ¼ symmetry in reduction scale (1:10) as mentioned before.

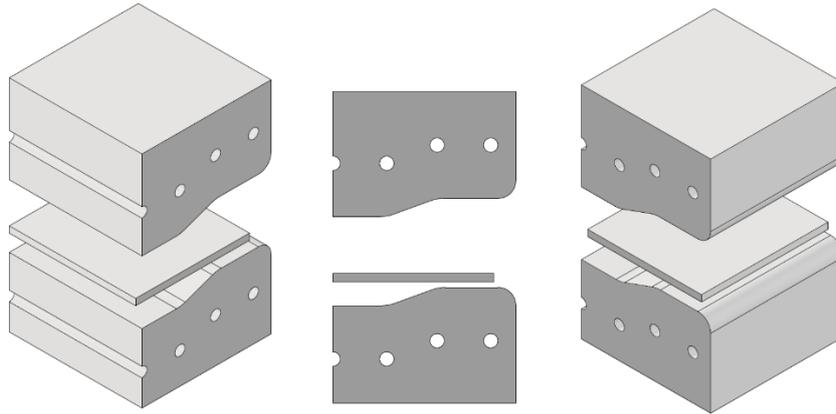Figure 4. Standard model with ¼ symmetry and reduction scale.

Regarding the mesh, dies were discretized with tetrahedral elements. Due to the absence of shell elements that account for the thermal and structural degrees of freedom simultaneously, the blank was discretized with linear hexahedral elements and, in addition, the size of the elements was kept the same for all 10 analyzed models. On the surfaces of both the tools and the blank that contained the symmetry planes that divided the tool in 1/4, using the symmetry tool (ANSYS environment) and creating an adequate coordinate system, the necessary restrictions and definitions were applied that provided the symmetry, thus numerically accounting for the effects of the missing parts for all models studied. To complete the initial boundary conditions of the model, the degrees of freedom were blocked in the vertical direction of the lower surface of the die (tool lower than the blank shown in figure 4) and on the upper surface of the punch (tool higher than the blank shown in figure 4) a displacement was applied in order to simulate the conformation of the blank. In the 10 numerical analyses, a conformation time (closing of the tools) of 3 seconds was considered, adding more 7 seconds in which the dies were kept closed, implying a cycle of 10 s.

3. RESULTS AND DISCUSSIONS

3.1. Peak temperature in the punches

For the 10 numerically simulated models, it was noted that the punch reached a given peak temperature on its forming surface. As previously mentioned, one of the design requirements for hot stamping dies is that the temperature of the work surfaces remains below 200 ºC throughout the working cycles, as a guarantee for the cooling of the blank and also to prolong tool life. Although this study addressed only one stamping cycle for the 10 analyzed models, it is necessary to investigate the peak temperature on the tool surfaces already in a first stamping cycle, since in a real application the tools tend to reach a steady state, therefore, they will tend to suffer an increase in peak temperature over the course of the cycles to reach this state. Obtaining a steady state on the part of the tools ensures a lower tendency for variability in microstructural terms, and consequently, of the mechanical properties of the stamped parts. Table 2 shows the peak temperature values on the punch surface for the 10 models.

Table 2. Peak temperatures in the punches.

Models	Peak Temperature
Standard Model	136.20 ºC
Model 2	135.95 ºC
Model 3	135.50 ºC
Model 4	131.85 ºC
Model 5	106.40 ºC
Model 6	102.30 ºC
Model 7	94.65 ºC
Model 8	90.42 ºC
Model 9	119.30 ºC
Model 10	106.30 ºC

Observing table 2, it is noted that the maximum peak temperature was observed in the standard model and the lowest peak temperature was observed in the model 8. Figures 5 and 6 illustrate the peak temperatures in the punch for the standard model and model 8, respectively.
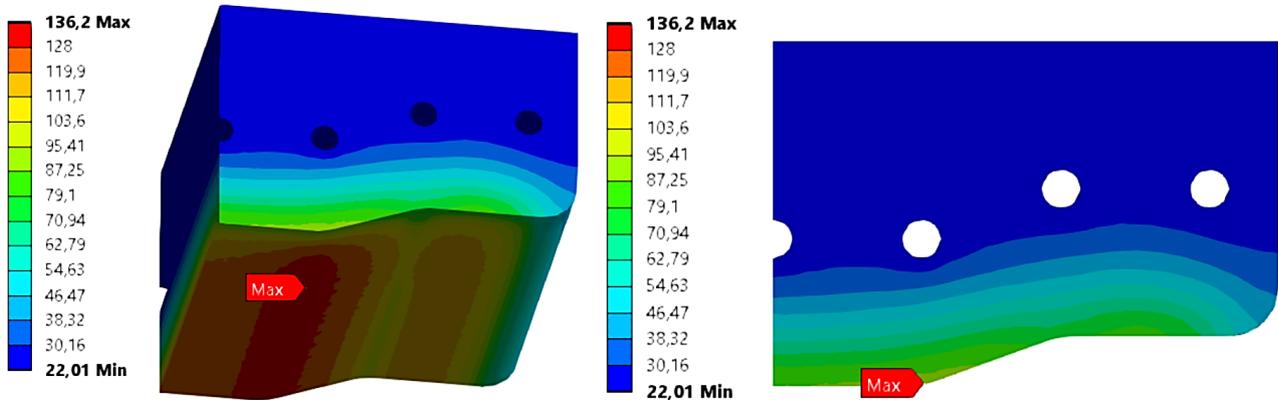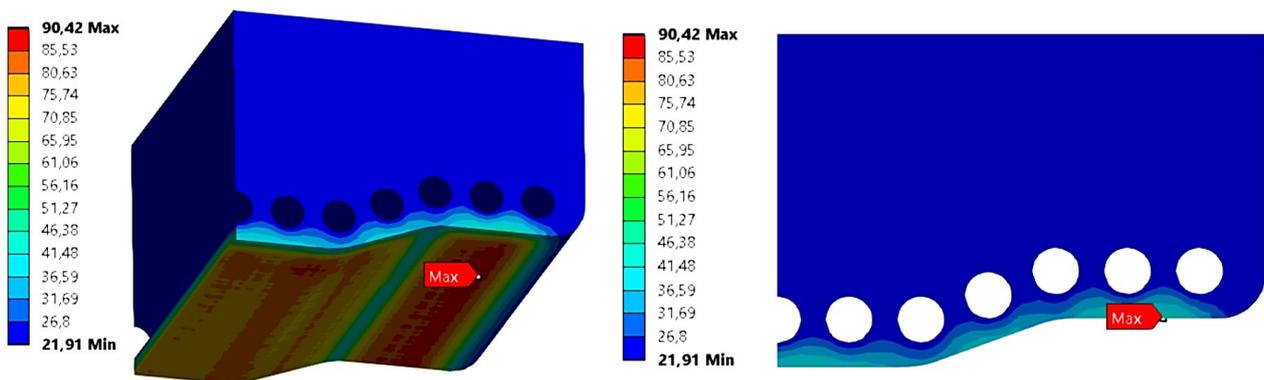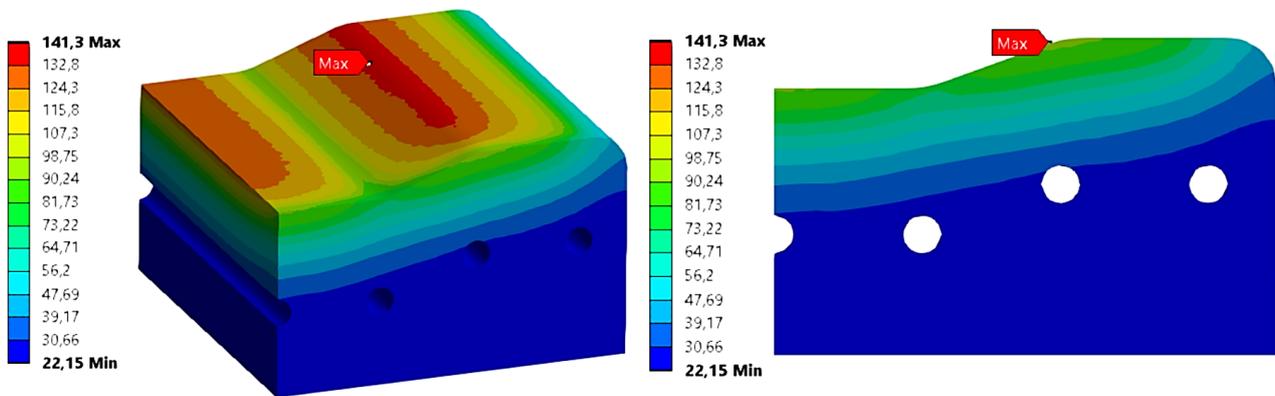

Figure 5. Peak temperature in the standard model.

Figure 6. Peak temperature in model 8.

Based on Figures 5 and 6 and Table 2, the approximation of the channel centers to regions closer to the forming surface of the tools plays a more significant role for reducing the peak temperature in the punch. Being the model corresponding to tools with channels diameter of 8 mm in full scale, model 7 performed a good reduction in the peak temperature in the punch. As previously mentioned, the CHTC for both the smaller diameter tools and the larger diameter tools were assumed to be equal. It is worth mentioning that in a real application, the coolant flow should be to adjust through the channels of the tools to have this equivalence. The idea of maintaining the same CHTC value aimed to identify whether the increase of the channel's diameter would provide greater gains in relation to the reduction in the peak temperature of the tools. As can be seen in Table 2, the increase in diameter did not represent very significant effects in this task.

3.2. Peak Temperature in the Dies

Analogously to what happened to the punches, the dies also reached a peak temperature on their forming surfaces. Table 3 shows the peak temperature values in the dies for the 10 analyzed models.

Table 3. Peak temperature in the dies.

Models	Peak Temperature

Standard Model	141.30 ºC
Model 2	141.09 ºC
Model 3	141.05 ºC
Model 4	139.48 ºC
Model 5	127.25 ºC
Model 6	125.90 ºC
Model 7	125.11 ºC
Model 8	124.10 ºC
Model 9	135.40 ºC
Model 10	128.10 ºC

Observing table 3, it is noted that the maximum peak temperature was observed in the standard model and the lowest peak temperature was observed in model 8. Figures 7 and 8 illustrate the peak temperatures in the dies of the standard model and model 8, respectively.
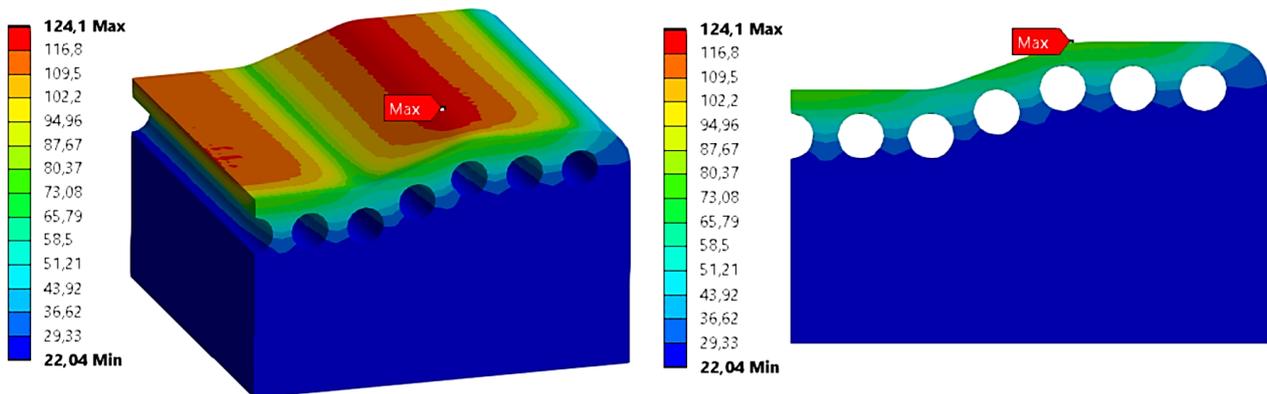

Figure 7. Peak temperature in the standard model.

Figure 8. Peak temperature in model 8.

Analyzing Tables 2 and 3, with the approximation of the channels to regions closer to the forming surface of the tools, a more significant effect is observed in the reduction of the peak temperature for the punch than for the die. For constructive reasons, the surfaces of both the punch and the die have different dimensions to provide adequate closure of the tools, and consequently, the conformation of the blank. As tried to maintain the same pattern in the distribution of channels for both the punch and the die, some channels were positioned closer to the peak temperature region of the punches (their variants) and in on the other hand, some channels were further away from the peak temperature region of the dies (their variants). These questions caused a not so significant change in the peak temperature for the dies studied. Another fact that also contributes to this mentioned phenomenon is the kinematics of the tools, where:

- The blank first comes into contact with the punch;
- The punch in contact with the blank travels through a certain displacement until contacting the die;
- The contact area of the blank's first touch with the punch is greater than the area of the die's first touch with the blank, which resulted in a greater initial heat distribution to the punch;
- Until the tools closed, the blank touched them in different and opposite regions.

All these characteristics indicate that in a real application, the design of the geometric parameters of the cooling system for both the die and the punch must be analyzed and carried out separately. Thus, it is possible to identify the regions where the peak temperatures occur on the tools using computational simulations and, consequently, to adopt an adequate arrangement of channels to minimize this temperature for each tool (die and punch) individually.

3.3. Distribution of temperature in the punches

Figure 9 illustrates the distribution of temperature in the punches for the 10 models analyzed at t = 5.40 s of each hot stamping cycle.
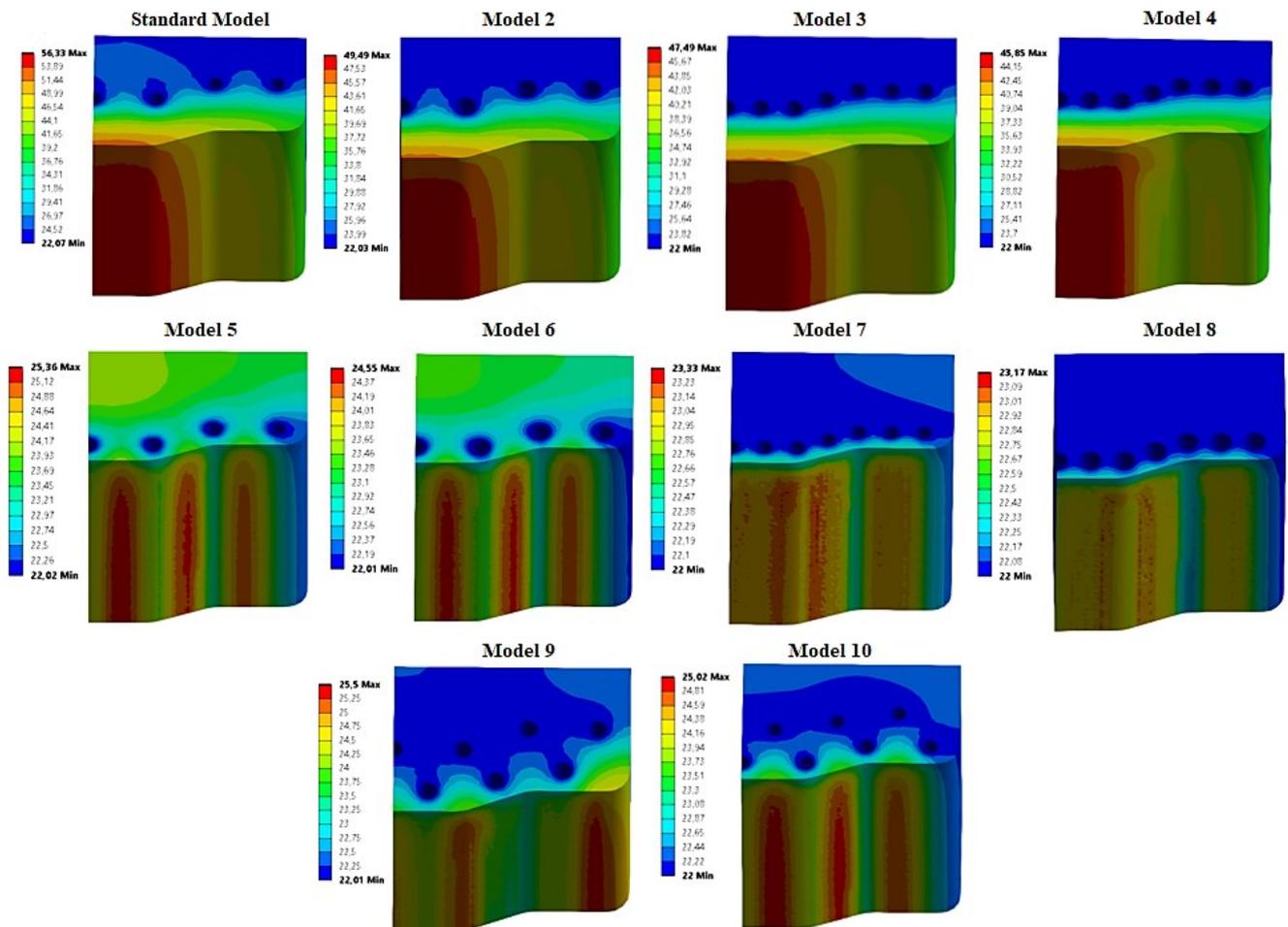

Figure 9. Distribution of temperature in the punches.

As reported in table 2, the models with cooling channels positioned closer to the work surface have a significant effect in the reduction of the peak temperature of the punch. However, comparing the distribution of temperature in the 10 punches shown in figure 9, it is noted that in the models with smaller number of channels, there is a greater tendency for heat to spread to the core, causing an increase of minimum punch temperature over cycles in a real application. Thus, a greater number of channels tends to minimize the heating of the punch and provide a more homogeneous cooling, both in the tool and the blank, mainly for tools with channels closer to the forming surface.

3.4. Distribution of temperature in the dies

Figure 10 illustrates the distribution of temperature in the dies for the 10 models analyzed at t = 4.0 s of each hot stamping cycle.
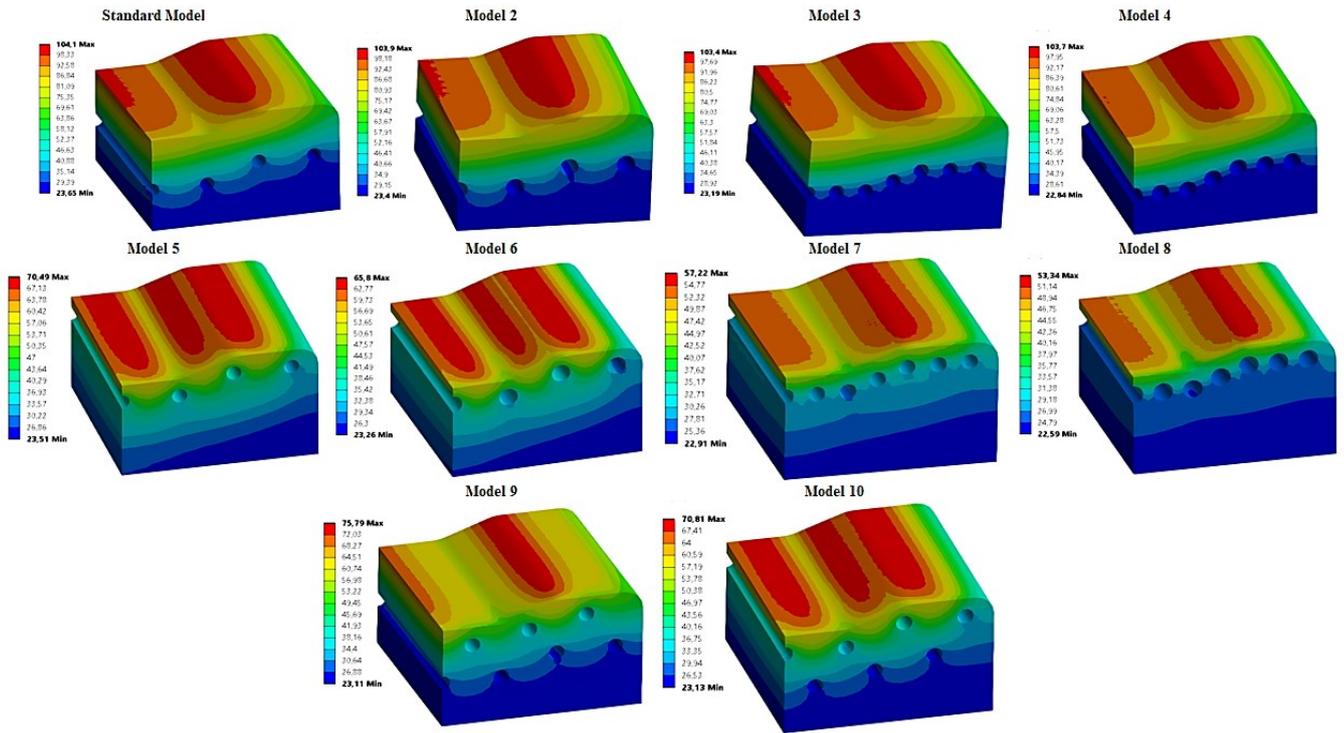
Figure 10. Distribution of temperature in the dies.

In a similar way to what was observed for the punches, the reduction of the number of channels in the dies tends to generate a greater diffusivity of heat towards the interior of the tool, causing its heating throughout of stamping cycles until reaching a steady state. In addition, this behavior tends to generate a more heterogeneous cooling in the die and the blank. Figure 11 represents the distribution of temperature in models 9 and 10 at t = 4.8 s.
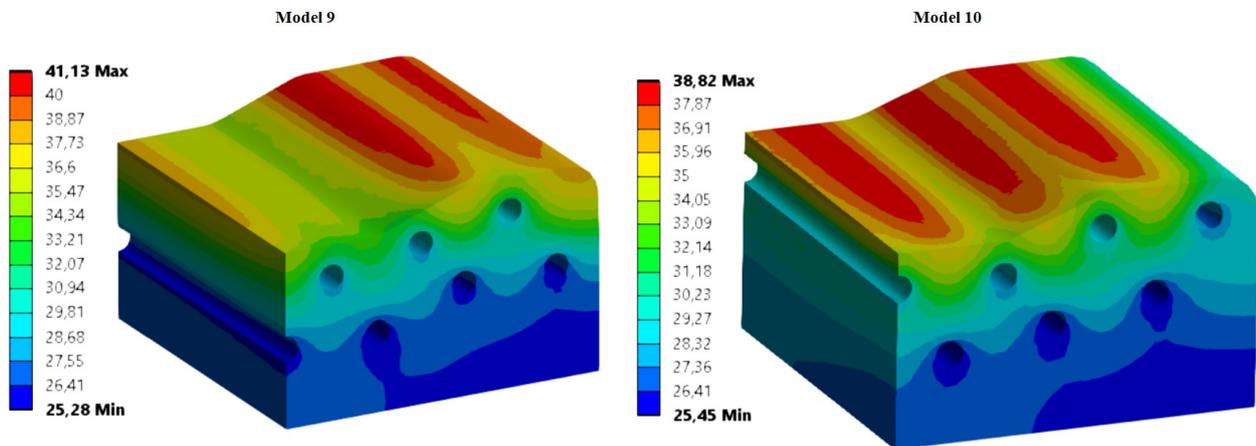

Figure 11. Distribution of temperature in models 9 and 10.

Models 9 and 10 present some channels with the same positions of the standard model and other channels with positions allocated to regions closer to the conformation surface. Although both models have the same number of channels as models 3, 4, 7 and 8, the fact that these channels are not aligned with their neighbors (like model 8 for example) tends to dissipate lower heat on the process, heating the interior and tip of the tools and causing high temperature gradients and high thermal stresses.

4. CONCLUSION

This work evaluated the effects of geometric parameters of the cooling system of hot stamping tools on their peak temperature and distribution of temperature. Based on the results presented, the main scientific contributions can be achieved:

1) The distance of the channel's centers in relation to the forming surface of the dies is the parameter that has the greatest effect in reducing the peak temperature of the tools;

2) Although some models with a smaller number of channels allocated to regions closer to the work surface of the tools have played a good role in reducing the peak temperature of the tools, a greater number of channels is necessary to ensure greater uniformity in cooling and minimize the heat that tends to diffuse into the tools' core.

3) In addition to a greater number of channels, more channels arranged side by side also tend to allow for more homogeneous cooling and prevent a greater amount of heat from diffusing into the interior of the tools (which ends up increasing the minimum temperature of the tools).

4. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE

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