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Impact of Flow Conditions in Cooling Channels on Thermal Cycling

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Abstract. In order to improve the set-up of industrial press hardening processes, companies and researchers are spending considerable efforts in the design and positioning of cooling channels. Following the increasing demands for modelling options, FEA software vendors have implemented corresponding features in their codes. Modeling cooling channels in FEA simulation facilitates a more accurate prediction of the location and dimensions of hot spots on the tool surface.

The present simulation case study is based on a complete tool set up for a typical part. The FE-model of tool set-up, including a suitable cooling channel design, has been utilized for a study on press hardening of 22MnB5. The effectiveness of cooling channel design is determined by the flow conditions of the cooling media - here water. The flow rate and cooling media temperatures are the parameters with most influence on the thermal behavior of the tool. The impact of variations in these parameters on the final surface temperature distribution on tools, and the ramp-up of this distribution to thermal steady state, are the subject of this study. Beyond tool temperature distribution, the impact of the above parameters on the quality of produced parts is assessed by evaluating typical part quality metrics: hardness, martensite volume fraction in the part`s microstructure, and thermal distortion.

It is observed that due to the complexity of the press hardening process, the details of cooling channel flow conditions do not carry a direct and proportional impact on part quality outcomes. This observation clearly indicates that engineers can derive descriptions of the cooling channel flow conditions from easy-to-use analysis tools that are fully integrated with the simulation of the forming process, rather than resort to extended, time consuming “offline” flow computations. An analytical method for calculation of cooling channel flow conditions is also introduced by the authors.

1. Introduction

In order to fulfil emerging requirements for the design of more energy efficient and safe vehicles, car body designs have undergone numerous assessments regarding potential for further simultaneous performance enhancement and weight reduction. Material-based lightweight design approaches have been manifold; one particular focus using steel has offered the application of the 22MnB5-grade, providing substantial benefits in terms of strength-to-weight ratio and impact resistance, as well as and energy absorption to weight ratio when combined with different strategies for tailoring of final part properties. Since this material is easy to integrate into existing production technologies, not least due to their good compatibility with thermal joining techniques, more efforts in production are justified. Nowadays, the press hardening technology has reached a remarkable level of maturity and acceptance in the market.

Nevertheless, there are still enough opportunities for improvement dealing with lean and efficient product and process design concepts. Extensive use of finite elements based virtualized solutions plays a crucial role in the development and validation of product and process. Therefore there needs to be a clear understanding of the importance, or lack thereof, of all the component models and features of these virtual engineering tools [1]. Unnecessary functionality, overly complex functionality, and complicated methods of application of these tools run the risk of driving up engineering lead times and costs.

A very important extension that has recently become available is the ability to integrate cooling channels in the design of tools; through fully coupled thermo-mechanical simulations that model their effectiveness and influence, it is now possible to identify hot spots on tool surfaces – and therefore to countermeasure these. This extended capability also enables the engineer to further investigate the opportunities and limitations of the influence of flow conditions inside the cooling channels. This paper addresses the level of sensitivity accompanying varying flow conditions in a practically proven tool and PHS process set-up.

2. State of the Art Press Hardening Tool

Valuable results in experiments can be obtained best by applying a proven prototype tool set and appropriate process parameters as input for all kind of virtualization, modelling and simulation. The considered forming process is proven multiple times to be stable and reliable in terms of the quality of the outcome. The blank used is of typical dimensions - 700 x 230 mm^2, thickness of 1.6 mm. Since the virtual experiment deals dominantly with thermally induced effects, the mechanical material model employs a regular Hill-based yield surface and does not handle with temperature depended r-values even though possible in the code. Apart from the material model, the code is linked to a hardness prediction routine which refers to a Dynamic TTT. Based on this input data - the CAD data and the process parameter provided - a generic reference model was created (Figure 1).

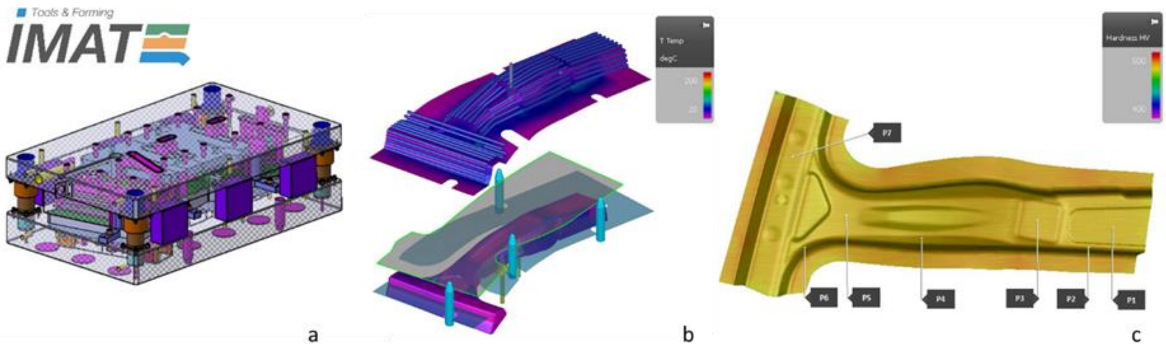

Figure 1. (a) tool geometry, (b) FE-model, (c) reference part results

The discretization for the input of the implicit solver was done automatically in form of a triangle mesh. The element section is an elastic-plastic-shell with 11 integration points - as typically used for final validation cycles. Thus, the initial maximum element size assigned the blank geometries mesh is 20 mm, refinement upon contact was enabled. For the rigid tools a maximum element size of 5 mm was determined. The thermal contact conditions between the rigid tools and the blank mesh are represented by an advanced gap and pressure dependent heat transfer formulation. The heat transfer conditions at the interface were ideally adapted - as typical for productive tool sets.

Characteristic measures can be derived from the given data and enable a better understanding regarding in particular the thermal conditions during the forming and quenching operation (Table 1). Chosen average parameters describing a typical forming cycle were considered for the model generation such as a handling time of the blank - which has been initially heated to 930 °C - of 5 seconds, a waiting time in the open tool set of 5 seconds and a quenching force of 1,000 kN for also 5 seconds before releasing the final part. In our model we were able to generate a perfect parameter set by using Systematic Process Improvement functionality which is not commented in detail.

Table 1. Characteristic measures of the reference tool geometry.

	Die	**Punch**	**Binder**
Volume [m^3]	0.048	0.014	0.048
Length - cooling channels [m]	13,450	8,120	-
Diameter - cooling channels [m]	0.008		-

It turns out that under the initial reference conditions - referring to the default heat transfer coefficient (HTC) of 10.0 mW/mm^2K at the interface between cooling channel and the tools - a good quality part can be obtained through simulation. The hardness is nearly evenly distributed all over the surface area. No critical hotspot could be detected. Furthermore, no potential issues are formed in terms of splits and wrinkles. As typical for press hardening processes, thermal distortion is less critical. During modelling the contact area between the tool surfaces and the blank was defined as ideally adapted. This can be considered as an elegant option to represent perfectly spotted dies. Gap and pressure dependent formulation of the HTC implemented in the software leads to more realistic results as long as efforts in spotting activities are considered, tracked and documented. To a certain extent this is a regular use case that is also beneficial for further explanations.

3. Cooling channel flow conditions

The impact of the position of the cooling channels embedded in the tool on final part quality has been the focus in recent publications. It has been shown that even though an intentionally bad distribution of cooling channels in the tool bodies can lead to a pronounced inhomogeneity of the temperature field at the surface area of the tools - hotspots - under regular process conditions, such inhomogeneity produces only limited influence on the quality of the final part [2]. This is valid in particular for the hardness. It seems that the order of heat conduction in the tool and the sheet itself, combined with damping effects of the heat transfer at the contact interfaces form a stable thermal system.

While on the one hand there is the opinion that there is almost no influence of the flow conditions in the cooling channels, some consider flow condition control as a vital prerequisite to achieving high quality parts. The latter consider that extensive CFD studies towards accurate prediction of tool surface temperature distribution is crucial to predicting final part quality outcomes from forming simulation. This is naturally linked to remarkable additional efforts spent in terms of installing equipment, modelling and computation.

By means of an "upper bound – lower bound" approach, the influence of the flow condition for the given real geometry can be tested. In order to create a worst case scenario one can integrally increase the HTC at the interface between the cooling medium and the tool. This means that the cooling channels are not even segmentally designed with varying HTCs assigned to several segment groups for channel center lines describing arches or edges. This leads to less effort for such experiments and additionally pronounces the results. So, the idea is to generate a set of integral flow characteristics that finally results in reasonable HTC as widely occurring in real tools. The proposed set of parameters and how they translate into fluid flow control measures is displayed in Table 2.

Table 2. Assigned cooling channel flow condition for simulation experiments.

Run	**1**	**2**	**3**	**4**
Current assumption		turbulent		
Reynolds number []	5,250	8,500	12,000	15,700
Average flow rate [m/s]	0.590	0.949	1.340	1.753
HTC [W/m^{2}K]	4,000	6,000	8,000	10,000
HTC [mW/mm^{2}K]	4.000	6.000	8.000	10.000

3.1. *Variation of temperature distribution in tools*

Introducing the mentioned HTC-values in the models, keeping remaining parameters constant, the thermal behavior was successively influenced. The temperature values were extracted at the punch surface at the defined measurement points in Figure 1c. The punch is the most affected tool since contact times are highest compared to the other tool components. Due to the typical cyclic behavior of the temperature in the tool components the time-step at the end of quenching has been selected for all considerations. The observed evolution of temperature is displayed in Figure 2.

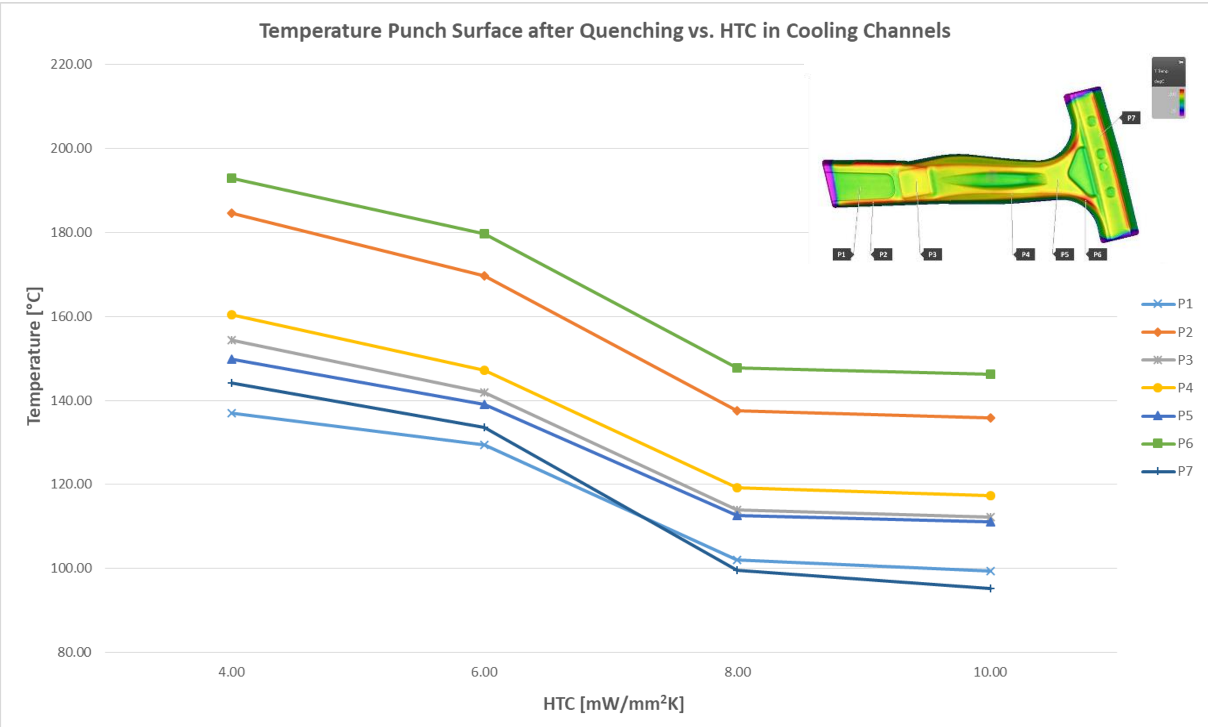

Figure 2. Temperature evolution in punch surface.

It can be pointed out that there is a clear effect generated. Between the extreme cases the surface temperatures vary on average around 25%, which is clearly sufficient to be further investigated in terms of the influence on the peak temperatures on the part at the end of the quenching stage. Thus, the impact of the assumed damping effect of the interface layer between the tool and the sheet can be quantified. This is to examine the validity of the hypothesis mentioned above, that only minor impact is expected in the final part quality even though the surface temperature distributions shows clear evidence of being affected by the thermal equilibrium in the tools.

3.2. Variation of temperature distribution in quenched part

The experimental set up did not change. All measures are taken from same models und current controls settings. Nevertheless, there are already remarkable differences that are obvious. The temperature distribution on the sheet after quenching is far more moderate: at the end of the quenching stage, the range of predicted temperatures at any of the observed points on the sheet, over the applied HTC range of 4 to 10 mW/mm^{2}K, are observed to be within a 5% range - as shown in Figure 3. This indicates that the evolution of the ***cyclic*** (steady state) temperature fields is also not affected in a way that could lead to remarkably higher or lower cooling rates in the sheet material. Based on the given tool design this can be easily proven. Since we are assessing this effect entirely virtually, these effects can be investigated further with ease.

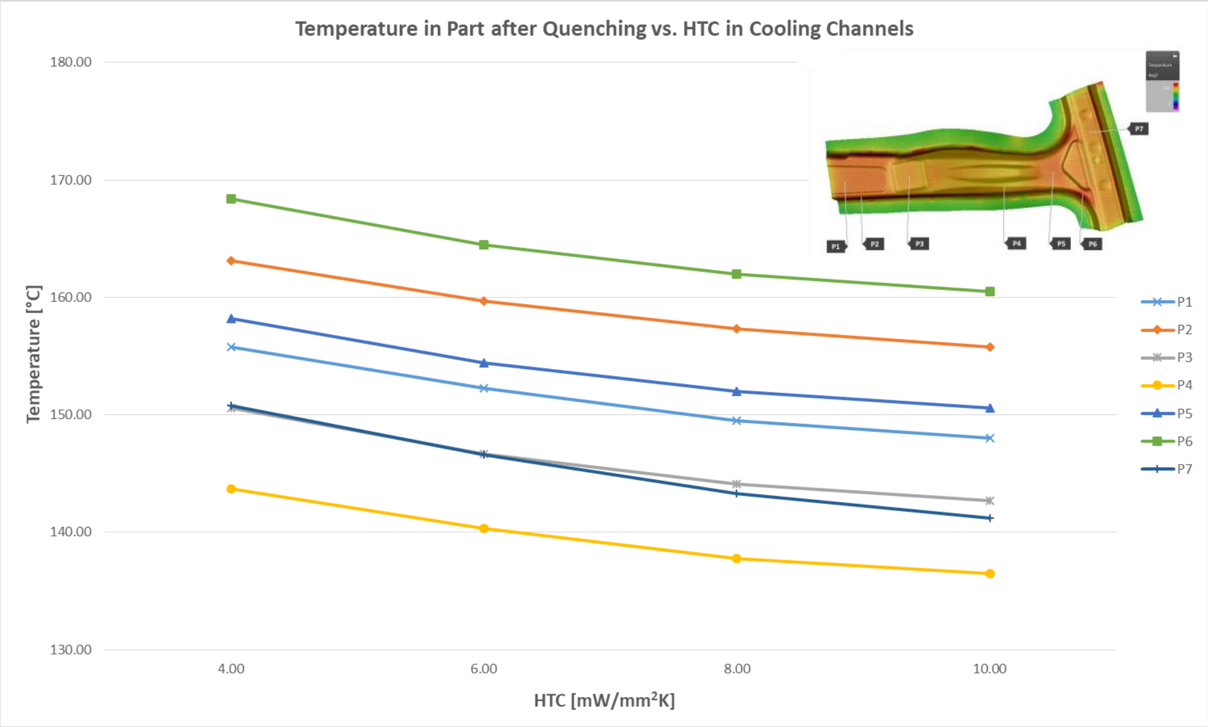

Figure 3. Temperature evolution in part.

3.3. Evolution of hardness in part

As mentioned, the described effects translate only in slightly affected cooling rates at the selected points. It becomes clear, that the generated hardness values cannot be strongly controlled by modifying the heat transfer coefficient. Since the HTC is the result of the current conditions which have been assumed to be integrally changing, this leads to the observation that there is almost no practical way to significantly affect the part quality outcome just by flow rate control. This may also help answer the question of how local inconsistencies of flow conditions in certain areas of the tool design can influence the distribution of temperatures in the contact areas. It seems to be more than unlikely that major effects can result from HTC variations in a reasonable range. The considered tool set is clearly not sensitive to integral changes of flow conditions (Figure 4). Hardness values are predicted to only be moderately affected. This means that the detailed design of cooling channels can lead only to minor order impacts. In other words, for a given design of channels in a tool, varying flow rates and flow conditions does not provide a good handle to actively influence part quality outcomes for hot forming processes.

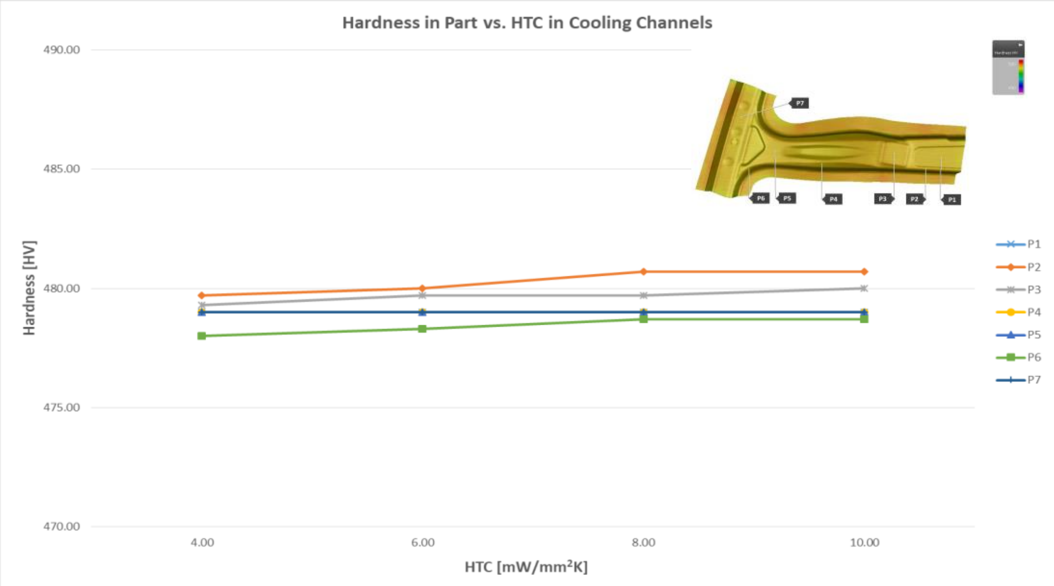

Figure 4. Hardness distribution on part.

3.4. *Variation of temperature distribution in quenched part*

Another interesting aspect is total energy balance of the tool components. This can be observed in the cyclic behavior of the temperatures in the tool components. Exemplarily, the punch has been analyzed. From available options for the computation of these effects, the Real Cycling mode was applied in order to figure out how long it takes to achieve the thermal steady-state. The two extreme cases - HTC 10 mW/mm^{2}K and 4 mW/mm^{2}K respectively - are compared (Figure 5).

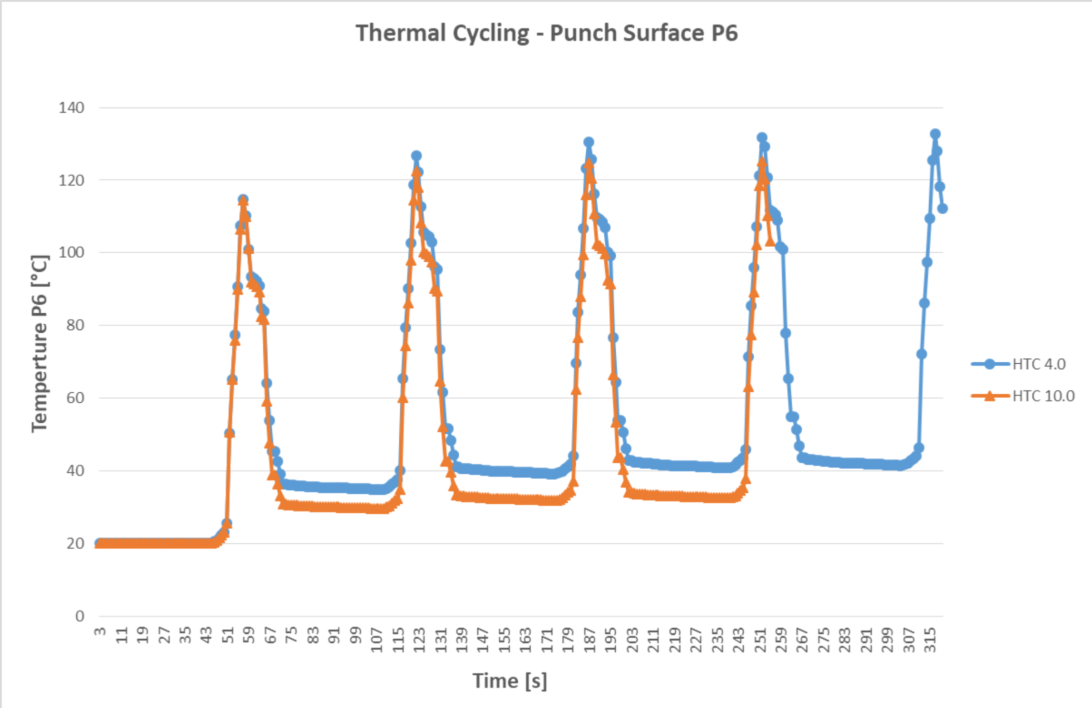

Figure 5. Process ramp-up cyclic behavior.

There is a noticeable difference in peak temperatures at the selected point (point 6) over the cyclic ramp-up to steady state conditions. There however is only a one-cycle difference between the two HTC extremes in how quickly steady state is achieved: 5 cycles for HTC 10.0 versus 4 cycles for HTC 4.0. This seems to be a negligible effect that does not need any further attention.

4. Analytical HTC calculations for modelling

The results discussed indicate that an easy approach for the determination of the HTC is possible. Since the necessary geometric definition of cooling channels is directly linked to the heat transfer conditions between the channels surfaces and the tool material, it is useful to do some preliminary calculations regarding various flow conditions of the cooling media from the fluid mechanics point of view prior setting up highly sophisticated models in FEA-models. Although there are many descriptions and formulations of heat transfer from cooling fluids toward surrounding material in a tubular shape, in our further explanations we refer to most basic knowledge. This easily showcases the process of defining appropriate parameters for modelling and computation. This basic approach can be expanded by taking into account many other influential variables such as pressure for instance.
The preliminary calculation also distinguishes between different states of flow in the cooling channel, which directly affect the heat transfer coefficient between the cooling channel surface and the tool material: the laminar and the turbulent current state. Hereby a highly turbulent state is the most desirable one in terms of high heat transfer rates although it creates a need for more powerful pumping equipment. For laminar flow, the constraint of a Reynolds number Re below 2,350 - 4,000 under a cooling channel diameter d of 8 mm must be fulfilled [3]. Furthermore, the length of the cooling channels is measured individually for the punch and the die, the diameter of the cooling channels will be constant and equal to 8 mm. One should recall that in the case of specific heat transfer rates - as typical for certain flow conditions and geometric dimension of the cooling channels - the necessary length/diameter ratio can be roughly calculated by balancing incoming energy amounts with the extracted heat amounts by means of water cooling to be designed.

Literature indicates how the relationship between the diameter of the cooling channels and the corresponding flow rate can govern the Reynolds number as a measure for the cooling medium's flow state (1).

$$v = \frac{Re\,\nu}{d} \tag{1}$$

The Nußelt number - as a measure for heat transfer conditions – is derived from the Péclet number (2).

$$Pe = Pr\,Re \tag{2}$$

The Nußelt number has been calculated for the less desired laminar state of the current in a straight tube (3), and the Prandtl number Pr is equal to 7.

$$Nu = \left[3.65 + \frac{0.0668 Ped/l}{1+0.045(Ped/l)^{2/3}}\right]\left(\frac{\eta_t}{\eta_w}\right)^{0.14} \tag{3}$$

For the recommended turbulent states, Equation 4 applies.

$$Nu = 0.04\,Pe\,\frac{Re^{-1/4}}{1+1.5Re^{-1/8}Pr^{-1/6}(Pr-1)} \tag{4}$$

The relationship between the relevant heat transfer coefficient and the Nußelt number is formulated as given in **Error! Reference source not found.**.

$$Nu = \alpha l_0/\lambda \tag{5}$$

Under given conditions, the corresponding heat transfer coefficients are easily calculated and can be modified as a characteristic parameter in models deploying cooling channels.

5. Conclusions

How much early effort, in detailed design of cooling channels, is really necessary for meaningful outcomes in terms of final part quality? This paper attempts to answer this question, based on data available from physical panel measurements. The variation of the flow conditions - represented for instance by the cooling media flow rate - gives the opportunity to the engineer to virtually assess common effects by means of FE-code. It has been shown that a reduction of the flow rate - still in reasonable limits - can lead to a pronounced increase of peak temperatures at the tool surfaces after quenching. But, it has been also shown that this does not directly translate into noticeably higher peak temperatures in the part – which indicated almost no effect on cooling rates and hardness. Overall, the process – based on a realistic tool geometry - can be considered as a less sensitive one. This subsequently leads to the conclusion that generic formula-based approaches can sufficiently serve for the layout tasks of the cooling channel current conditions. One more or less simplified set of formulas for such purpose - neglecting the local pressure distribution in the cooling channels - has been introduced.

List of Symbols

v	average flow rate fluid	[m/s]
Re	Reynolds number	[]
d, l_0	diameter / characteristic length	[m]
ν	kinematic viscosity fluid	[m^2/s]
Pe	Péclet number	[]
Pr	Prandtl number	[]
Nu	Nußelt number	[]
α	heat transfer coefficient	[W/m^2K]
λ	heat conductivity fluid	[W/mK]

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