Virtual method for the determination of an optimum thermal design of hot stamping tools

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Abstract. This work presents a new virtual method for the optimised thermal design of hot stamping tools. It provides optimal positions of the tool’s tempering ducts with respect to the average working temperature and its homogeneous distribution on the surface of a tool. It consists of a specific procedure for hot stamping tool design and a software framework in order to interconnect three domains: (I) a parametrised CAD tool model, (II) a linear thermal solver using a fast boundary element method and (III) an optimisation algorithm. This enables the automated set-up, simulation and optimisation of a duct topology. The boundary conditions for the simulations are derived from a reduced model of the thermal loading of the tool. The virtual method proposed is demonstrated on simplified tool segment geometries. The results are transferred to complex tool designs used in industry. For a selected use case, the number of ducts could be reduced by 50% through the application of the proposed method. These results are validated virtually based on an existing design. Hence, the new virtual method contributes to a CAE-driven tool design and a more efficient tool manufacturing.

1. Introduction

The process of hot stamping is a wide-spread process for the manufacturing of ultra-high strength steel (UHSS) parts in the automotive industry. Since its first applications in the mid-1980s the number of press hardened components in car bodies continuously increased to a level beyond 500 million parts per year. This evolution was accompanied by the development of enhanced simulation models in order to capture the complex thermo-mechanical-metallurgical process for the purpose of virtual process and component design. The phase transformation of the steel grade 22MnB5, commonly used for hot stamping applications, was in the special focus of the scientific community during the last 10 years (refer to [1]). Also aspects of tribology (e.g. [2], [3]) and tool wear (e.g. [4], [5]) have been addressed extensively in order to accurately describe the forming and quenching process of the blank. Many of these scientific developments are available in commercial simulation codes. The consideration of the stamping tools as elastic solid bodies with thermal conduction rather than shell surfaces with constant temperature further contributes to accurate descriptions of the stamping and quenching process. Therefore the quality of the stamped components in terms of mechanical and geometrical properties can be predicted with good approximation to reality. These detailed simulations require complex model set-up and expert knowledge on both the stamping process and the FEM-software (refer to [6] for further details on forming process simulation). Further, these detailed stamping simulations rely on tool designs and duct layout concepts that are normally not available in early design phases of the
stamping process. So an iterative procedure becomes necessary for the design of an optimal duct layout. This is true for both cooled and heated stamping tool segments, often referred to as “soft zone” tools (see figure 1).

![Diagram of a segmented lower hot stamping tool with one soft-zone segment and 5 cooled segments](image)

**Figure 1.** Tempering duct design of a segmented lower hot stamping tool with one soft-zone segment and 5 cooled segments; (a) heating ducts, (b) air cooling ducts; (c) water cooling ducts. *source: weba GmbH*

2. Tool Design

The design of a tool and its specific duct layout is performed on individual standards and knowledge of tool making companies. There exists no single, optimal tool design but there are a multitude of feasible tool designs possible. Normally, the stamping process claims homogeneous quenching of the full component in order to reach the desired high strength properties. This standard process requires a tool surface temperature lower than 200°C [7], evenly distributed over the surface of the tool. High contact pressure enables good contact for adequate heat transfer between blank and tool, leading to a homogeneous quenching process. Whereas the contact pressure is mainly influenced by the spot-grinding process during run-in and the capacity of the press, the working temperature of the tool mainly is determined by process parameters (e.g. cycle time, blank’s initial temperature, tool cooling performance, heat losses to environment) and by the tool design regarding the duct layout. Since the process parameters are fixed for a given series process, the duct layout remains as the most critical parameter for the tool’s average working temperature.

There are several designs of a cooling duct layout in stamping tools described in [8], e.g. straight, transversal, parallel, serpentine. Regarding the manufacturing of these layouts there are three common possibilities: (i) drilling of cooling bores, (ii) cast-in pipes and (iii) near-surface milling of shells (refer to [9]). Additive manufactured tools with arbitrary near-surface duct layouts are possible too and also discussed in the stamping community [10], although this type of production process is mainly applied with injection moulding and related processes [11]. The most common solution for hot stamping tools is the drilling of straight cooling ducts into the tool body (see figure 1), which is widely applied among the tooling industry.

For the standard process of cooled segments, the duct layout is mainly determined by a maximum density of bores to reach maximum cooling at minimum cycle times in series processes. This is achieved through the specific expertise of the CAD engineer who designs the duct layout, the inlets and outlets and the flow path based on experience and company standards. At early design phases, the design engineer has no feedback on the effects of the duct layout regarding the thermal status of the tool during the series process. This leads to trial and error loops between the design and the simulation process. For more complex stamping tools with e.g. soft-zones with different average temperature levels at different segments, these iterative loops become even more important since the temperature level of the tool is not determined by maximum cooling any more. A combination of integrated heating elements, mainly to heat up the segment at start-up, and cooling ducts to maintain the segment’s nominal temperature during the series process becomes necessary. Through this, a different
duct layout design is required due to the different tempering strategy of soft-zone segments. Within this work, a virtual tool design method and an optimisation framework are presented for the efficient design of duct layouts for hot stamping tools.

3. Virtual Tool Design Method
The virtual tool design method developed within this work utilises a generalised software framework developed at Virtual Vehicle Research Center (VIF Optimisation Framework) that interconnects (i) a CAD-software for duct layout design (e.g. CATIA®), (ii) a solver based on boundary element methods BEM (e.g. HyENA) and (iii) an optimisation algorithm (Particle Swarm Optimisation, PSO). The structure of this Virtual Tool Design Software Framework and its information flow is presented in figure 2, followed by a description of the single information paths.

![Figure 2. Structure of the Virtual Tool Design Software Framework.](image)

1 Schanz M 2016 Graz University of Technology HyENA - Hyperbolic and Elliptic Numerical Analysis Online: http://www.tugraz.at/en/institute/am-bm/forschung/software/
3.1. Determination of boundary conditions (BCs)

The boundary conditions for the simulation model are derived from analytical models of free convection (for the outside surfaces), forced convection (for the cooling duct surfaces) and radiation (for outside surfaces). The heat input from the blank is calculated from the transient results of a one-dimensional thermal Finite Difference model of the system blank-tool-duct. The blank thereby is reduced to a mixed boundary condition, representing the time-averaged heat flux into the active surface during a quasi-stationary series process. It is assumed, that the contact heat transfer between the blank and tool is homogeneous over the whole active surface, thus a one-dimensional model is applicable.

3.2. VIF Optimisation Framework

The solver, the optimisation algorithm and the design template are controlled by the VIF Optimisation Framework, a modular software prototype realised in Matlab®. It enables the set-up and control of the optimisation jobs within this work. Its graphical user interface enables the definition of an objective function OF, constraints and parameters based on the geometry and process parameter input of the underlying simulation model. The VIF Optimisation Framework uses Dynamic Link Libraries to enable a direct communication with the CAD software (CATIA®). Simulation jobs are started on a remote server using secure shell communication. Graphical job monitoring and basic error handling capabilities enable the design engineer to set up and supervise the optimisation run without specific expert knowledge.

3.3. Simulation (HyENA)

To provide information on the expected time-averaged working temperature of hot stamping tools in the series process, a simplified simulation method has been developed and validated in [9] and presented in [13]. This method uses the energy equilibrium at the stamping tool between the heat input from the blank and the heat withdrawal to the cooling fluid and the environment in order to simulate the time-averaged working temperature of a hot stamping tool. This simplified simulation method is useful to predict the temperature status of the stamping tool during a series production process already at a very early design phase. Besides the boundary conditions, the minimum input requirements are the active surface design model and the duct layout of the hot stamping tool (refer to [9], p.97). Through this, the effect of duct layout designs on the stamping tool temperature can be predicted. The main characteristic of the used simulation method is the utilization of a solver based on the Boundary Element Method (BEM) rather than on the Finite Element Method (FEM). This enables a simplified, automated model set-up due to the dimensional reduction from a volume model (FEM) to a surface model (BEM).

3.4. Duct layout design - CAD

The VIF Optimisation Framework offers two possibilities to consider geometric variations of the duct layout design in the optimisation procedure: (i) design templates and (ii) design variants, illustrated in figure 5.

3.4.1. Design templates

A general duct layout design as an input for the VIF Optimisation Framework is generated through a design template in CATIA® software. The design template represents a generic design of a stamping tool segment with bounding surfaces and basic geometric items for a parametric duct layout design. The parametric design rules are programmed in the CATScript®. Figure 3 shows the principle procedure of the parametric duct design and model development for a simple block-segment. First, a duct design is built up based on parameters controlling the distance to the active surface and the duct spacing. Second, the surface model of the duct design is exported and automatically meshed using the open source meshing surface Gmsh with a batch procedure. Third, the resulting mesh of the duct
design is merged with the boundary mesh of the design template. Figure 3 (right) shows one result of this procedure.

![Figure 3](image)

**Figure 3.** Principal procedure of the parametric duct design and model development: (a) parametric design of duct layout with geometric parameters $Q1$, $Q2$; (b) batch-meshing of duct layout; (c) merging of duct mesh with boundary mesh, (10)…active surface.

This model is then used for the optimisation of the tempering duct positions with respect to an average surface temperature of the active surface. The simple block-segment design is very efficient and enables the variation of the principal geometric model parameters. The design template can be modified to meet any demands of the user, depending on the complexity of the design rules.

### 3.4.2. Design variants

A second method of tool design is applicable within the workflow of the Virtual Tool Design Software Framework: the usage of arbitrary and highly complex duct layouts enables highest flexibility for the duct design. The design engineer can model various configurations of duct layouts, representing specific geometric inputs for the optimisation procedure. Examples of such design variants $V$ are shown in figure 4 for the use case stamping tool segment of this work. Inlet and outlet ducts are neglected because they do not contribute to the cooling of the segment.

Using arbitrary design variants affects the choice of the optimisation algorithm. As described in section 3.5, gradient based algorithms cannot be used for such problems.

![Figure 4](image)

**Figure 4.** Three different duct layout variants of the use case stamping tool segment: (a) $V=9$, (b) $V=5$, (c) $V=1$ according to table 2.

### 3.5. Optimisation algorithm (PSO)

The heart of an efficient optimisation set is an optimisation algorithm which is tailored to the problem and can be adapted in many ways. Many different algorithms are available and there is no overall general purpose algorithm which can be used in any case. The stated problem of stamping tool cooling uses duct layout design variants which need to be treated as discrete variables. Because of lacking a functional relationship between the duct designs, the designer has the freedom to rank them
differently. Therefore the structure and the appearance of the design space can change according to the ranking. That makes it impossible to calculate meaningful gradients for an algorithm which uses gradient information or deduced gradients. Particle Swarm Optimisation (PSO) introduced by Kennedy and Eberhard [14] is an optimisation algorithm which does not need any gradient information. It is derived from the behaviour of bird swarms searching for food by flying through the space. The communication between the particles (i.e. process and design variants) is described mathematically and used for searching good solutions in a given design space without the necessity of gradient information. Because of possible high numbers of degrees of freedoms (geometry and process parameters), the design space can be high-dimensional. Therefore it is necessary to adopt the number of initial particles to the size of the design space. However, increasing the population size slows down the convergence rate. The solution for this contradiction is an adaptive algorithm which reduces the population size based on the concept of an artificial potential of each evaluated particle. It uses a special routine of moving barriers, calculated with Bernoulli’s equation of colour temperature [15]. The combination of PSO and adaptive reduction of population results in a suitable algorithm for optimising hot stamping tool segments, as presented in this work.

4. Application of the Virtual Tool Design Software Framework
The optimisation procedure of the duct layout design of a cooled stamping tool segment is presented. Figure 5 shows the simulation model surfaces of the design template (left) and a design variant of the stamping tool segment (right), considered in this work. The design template represents a simplified model of the stamping tool segment and hence shows slightly different boundary conditions, given in table 1.

![Figure 5](image)

**Figure 5.** Simulation model surfaces of the design template (a) and a design variant of the stamping tool segment (b), considered in this work: (10)...active surface; (20)...outer surface; (30)...segmentation surface/base surface; (40)...surface to environment; (50)...duct surface; (70)...base surface isothermal.

The parameters for the boundary conditions ($P1, P2$) in table 1 are calculated as described in chapter 3.1. Looking at the parameters for surface 10 (active surface) it is obvious that for the simulation of the time-averaged working temperature, the transient heat input from the blank is replaced by a mixed BC. The determination of the respective parameter values based on an energy balance at the stamping tool is described in [9]. The segmentation surfaces and also the base surface of the design template (surface 30) are assumed to be isolated. Heat losses to the environment are considered at the stamping tool segment (surface 20 and 40) only. The convection heat transfer coefficient at the cooling ducts (surface 50) is calculated with the analytical expression for forced, turbulent convection in pipes of Gnielinski [16]. The base surface (surface 70) of the stamping tool
segment is assumed to be at environmental temperature; this assumption is true for cooled segments and needs to be proven from case to case.

Table 1. Boundary condition types and values for the surfaces of the design template and the stamping tool segment considered in this work: boundary conditions: R…mixed BC (Robin, )

| surface | BC type | P1   | P2   |
|---------|---------|------|------|
| 10      | R       | 350  | 850  |
| 20      | R       | 16   | 390  |
| 30      | N       | 0    | -    |
| 40      | R       | 16   | 390  |
| 50      | R       | 14307| 25   |
| 70      | D       | -    | 25   |

4.1. Design template

For the optimisation with the design template, the objective function \( OF=\text{minimise}[\text{abs}(T_{av}-T_{nom})] \) is used, whereas the objective temperature for the active surface is set to \( T_{nom}=115^\circ C \) for this particular stamping tool segment. The constraints were set to \( 10K<dT<50K \), meaning that a specific spatial temperature range \( dT \) is tolerable. Otherwise the solution would be trivial: a homogeneous temperature distribution will be achieved through a very dense duct layout. Two variable geometric parameters \( Q1 \) and \( Q2 \) are considered with the optimisation: (i) the normal distance between the active surface and the duct axes \( (Q1, \text{continuous}) \) and (ii) the distance in between the ducts axes or rather the duct spacing \( (Q2, \text{vector}) \). The values for the optimisation are set to \( 0.008< Q1 < 0.07 \) and \( Q2 = [0.0105 0.013 0.0168 0.024 0.042 0.056 0.084] \), representing feasible duct layouts. SI units are used for the parameters \((Q1, Q2) = \text{m} \).

For the presented use case, the optimisation of the geometric parameters \( Q1 \) and \( Q2 \) is of interest, but in principal any parameter of the geometry and the process (e.g. duct diameter, cycle time, closed time of tool, initial blank temperature, temperature and velocity of cooling medium, heat loss to environment, conductivity of tool material, environmental temperature) can be considered and optimised.

4.2. Design variants

Besides the described optimisation procedure using a design template, the approach using design variants of a stamping tool segment is applied too. Therefore, nine cooling variants, defined through the vector \( V = [1 2 3 4 5 6 7 8 9] \), were designed. Some of these design variants are illustrated in figure 4, figure 9 and figure 10. Each of them represents a single, feasible duct layout. The single variants of this use case mainly differ with their average normal distance between the active surface and the duct axes \( Q1 \) and the average distance in between the duct axes \( Q2 \), similar to the parameters of the design template before.

For the optimisation of the presented use case, the parameter \( P1 \) of surface (50) in table 2 is set continuous in the range of \( 10000<P1<20000 \), defining feasible values of the convective heat transfer coefficient at the duct surface. Equal to the optimisation with the design template, any process parameter could be set variable and optimised.
An optimisation run is performed with the two parameters $V$ (discrete) and $P1$ (continuous). The objective function $OF=\text{minimise}[dT]$ is used in order to optimise towards a homogeneous temperature distribution on the active surface of the stamping tool segment. The constraints are set to $75^\circ C < T_{av} < 155^\circ C$, meaning that an average temperature of the active surface $T_{av}$ in the given range is tolerable.

Table 2. Design variants $V$ of the use case with their average distances $Q1$ and $Q2$; initially realised variant: $V=9$.

| $V$         | duct axes - duct axes, $Q2$ |
|-------------|-----------------------------|
|             | 0.014 0.028 0.043           |
| surface     |                             |
| duct axes   |                             |
| $Q1$        | 0.012                         |
|             | 2 6 3                         |
|             | 8 5 2                         |
|             | 7 4 1                         |

5. Results

In the following, the results of the two optimisation approaches based on (i) a design template and (ii) design variants are presented and discussed.

5.1. Results using the design template

The evolution of the PSO algorithm towards an optimal solution using a design template is shown in figure 6. The movement of the particles in the design space $Q1$ and $Q2$ towards an optimal solution is illustrated. The optimal parameters are $Q1=0.008$ and $Q2=0.024$, leading to an objective function value of $\text{abs}(T_{av}−115)=6K$ and a constraint value of $dT=21.3K$.

Figure 6. Evolution of Particle Swarm towards optimal solution: iteration 1 (a), iteration 4 (b) and iteration 10 (c). The colours represent the $OF$ values in Kelvin.

The optimal parameter $Q1=0.008$ is rather small for cooling ducts of industrial stamping tools. Raising $Q1$ to a feasible level, the geometric solution from the design template is very close to the design variant $V=6$ (see table 2; $Q1=0.012$, $Q2=0.028$) of the stamping tool segment. Compared to the initially realised variant $V=9$ (see table 2; $Q1=0.012$, $Q2=0.014$) this optimal solution leads to a significant reduction of the number of cooling ducts due to the double average distance in between the duct axes $Q2$. 
The respective simulation result of the optimal solution is shown in figure 7, representing a non-trivial solution of the constraint optimisation problem with an average active surface temperature of $T_{av}=121^\circ C$ and a spatial temperature range of $dT=21.3K$.

![Temperature simulation result of the optimal solution of the PSO algorithm using the design template; temperatures in °C](image)

**Figure 7.** Temperature simulation result of the optimal solution of the PSO algorithm using the design template; temperatures in °C

5.2. Results using design variants

The evolution of the PSO algorithm towards an optimal solution using design variants is shown in figure 8. The movement of the particles in the design space $V$ and $P1$ towards an optimal solution is illustrated. The optimal parameter set is $V=6$ and $P1=20000$, leading to an OF value of $dT=190K$ and a constraint value of $T_{av}=145^\circ C$. The respective simulation result of this optimal solution is shown in figure 9.

![Evolution of Particle Swarm towards optimal solution: iteration 1 (a), iteration 2 (b) and iteration 9 (c). The colours represent the OF values in Kelvin.](image)

**Figure 8.** Evolution of Particle Swarm towards optimal solution: iteration 1 (a), iteration 2 (b) and iteration 9 (c). The colours represent the OF values in Kelvin.

The common result of both approaches is, that the design variant $V=6$ offers an optimal solution for the stated use case in terms of surface temperature and temperature homogeneity. The initial duct layout contains 12 ducts (see figure 10) while the optimised solution only contains 6 ducts (see figure 9). Hence, the optimisation procedure leads to a design with a reduced number of cooling ducts by 50%.
6. Validation
The reduced simulation method applied within this work has been validated on cooled stamping tool segments in [9]. A further validation with the particular stamping tool segment used within this work has not been performed.

The validation of the optimisation results is performed virtually by comparing the initial, non-optimised cooling duct design, shown in figure 10, with the optimised cooling duct design, shown in figure 9. The difference in the average surface temperature of the active surface is $\Delta T_{av} = 11K$ ($T_{av, init} = 134^\circ C$, $T_{av, opt} = 145^\circ C$), the difference in the spatial temperature range is $\Delta dT = -11K$ ($dT_{init} = 201K$, $dT_{opt} = 190K$). Considering this rather small differences which, of course, are related to the specific use case of this work, the optimised design reduces the number of cooling ducts significantly by 50% compared to the initial design while maintaining the cooling performance of the stamping tool segment.

7. Conclusion
The presented method for virtual tool design using a software framework that interconnects a CAD-software, a numerical solver and an optimisation algorithm was successfully applied to a cooled segment of a hot stamping tool. Two approaches were presented: (i) a design template to optimise the principal geometric configuration of a cooling duct layout and (ii) design variants to optimise process parameters based on arbitrary cooling ducts designs. Both approaches can be utilised individually. Within this work, both approaches led to similar results on an industrial stamping tool segment.
The result of the optimisation with the design template was a geometric configuration, similar to the design variant that is finally determined as optimal ($V=6$). For this first optimisation approach, the objective function was related to a nominal average surface temperature of the active surface. The final optimal design variant $V=6$ was also obtained with the second optimisation approach based on nine individual design variants. For this optimisation, the objective function was related to homogeneity of the surface temperature. It was shown, that both approaches lead to the same optimal and feasible design, reducing the number of cooling ducts by 50%.

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