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Topology optimization for the design of additively manufactured hot stamping tools

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Abstract. The hot stamping process makes it possible to obtain complex-shaped parts with high mechanical properties. The hot stamping production rate is driven by the cooling system inside the tool. Improving the efficiency of the cooling system is a key factor as it reduces part production time and thus lower the cost. But an optimized cooling system requires complex internal geometries. That is why the development of additive manufacturing (AM) opens up new and good prospects for designing and making hot stamping tools with high cooling efficiency. This research proposes a two-step topology optimization procedure for hot stamping tools' design. In the first step, the fluid/thermal topology optimization is used to find the best design for the cooling system. As the printing time and cost for the additively manufactured tool depend on the amount of material used, the second step focuses on removing unnecessary materials in hot stamping tools.

Introduction

Hot stamping is a widely used process in the manufacturing of automotive parts. A thin sheet of Press Hardened Steel (PHS) is heated in a furnace at a high temperature (around *900 °C*) and then formed and quenched in the stamping tool. Quenching is a key step for part productivity. Effective cooling system is necessary to minimize the quenching time [1]. Usually, the cooling channels are drilled straight in the tools. On one hand, it is the easiest way to build the cooling system. On the other hand, this design is not the most efficient one. The aim of this work is to propose a general methodology to achieve the most efficient cooling design while the complexity of the resulting design and the difficulties to manufacture it are overcome by using additive manufacturing.

Modeling hot stamping is a multiphysics problem as it involves the use of mechanics, thermal engineering, and metallurgy. To optimize the cooling channels, solid mechanics, heat transfer and fluid mechanics must be considered. Thus, to reduce the difficulties, the optimization problem can be split into two sub-optimization problems: thermal-mechanical coupled optimization and fluid-thermal coupled optimization.

Thermal-mechanical coupled topology optimization

Thanks to the advantages of additive manufacturing, the cooling channels can reach closer areas of the tools' surface to increase cooling efficiency and reduce the production time. However, printing the whole tool may highly increase the tool's building cost, as the conventional hot stamping tools are usually cut from solid material. One direct way to reduce the printing cost is to use the hybrid printing method. Only the working part of the tool is printed on a conventional machined substrate. As the printing cost is directly related to the printed volume, the tool's printing cost can thus be reduced. On the contrary, the hybrid printing method can be difficult to apply,

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depending on the tool's geometry, the cooling design, and the used printing technology. For example, the Selective Laser Melting (SLM) technology needs a flat interface between the printed part and the substrate. All upper side of this interface will be printed, irrespective of necessity. Thus, material saving should be taken into account during the tool's design.

Topology optimization is a good tool to answer the printing costs problem. Pure mechanical topology optimization is now very common and widely used in the design of various parts. It can find the best material (solid or void) distribution and use only the necessary solid material to lighten the parts. By reducing the printed hot stamping tool, the printing cost is then reduced as well. Many commercial CAE software already include this function. Topology optimization has already been applied on the cold stamping tools using LS-TaSC with the LS-DYNA solver [2]. The optimized tools have been printed and used successfully, showing good production performance, particularly in terms of fatigue and wear resistance.

In a hot stamping tool, the volume of material and its distribution influence not only the mechanical performance but also the heat transfer from the blank to the cooling channels. Thus, the cooling performance of the tool should be considered in the optimization algorithm. Top3d [3] is used in this study for the thermal-mechanical coupled topology optimization. The idea is to study the influence of the amount of material used on both mechanical and thermal performance of the tool.

A standard topology optimization for linear elastic stress problem consists in minimizing the mechanical compliance of the system which is written as:

$$min\colon J_m^M = F^T U = U^T K_m U$$

$$s.t.:\ \frac{V_s}{V^*} \le f \tag{1}$$

where J_m^M is the mechanical compliance of the system, U and F are respectively the nodal displacement and the nodal force vectors, K_m is the stiffness matrix, V_s and V^* are respectively the used material volume and design domain volume. f is the volume fraction.

Heat conduction optimization problem is very similar to the mechanical optimization problem. Instead of minimizing the system's mechanical compliance, the thermal compliance is minimized, by replacing the nodal displacement vector and the global stiffness matrix by the nodal temperature vector and the conductivity matrix respectively:

$$min\colon J_t^M = T^T K_t T$$

$$s.t.:\ \frac{V_s}{V^*} \le f \tag{2}$$

where J_t^M is the so-called system's thermal compliance, T is the nodal temperature vector, K_t is the conductivity matrix.

To combine the mechanical and the thermal optimization, the objective function needs to consider the tool's mechanical and thermal performance at the same time. As the values of J_m^M and J_t^M are not of the same order of magnitude, a weighting coefficient is usually used to combine the two objective functions. Choosing the appropriate value of such a weighting coefficient can be a tricky task. To overcome this difficulty, the coupled optimization problem can be formulated as:

$$min\colon J^M = J_m^M * J_t^M$$

$$s.t.:\ \frac{V_s}{V^*} \le f \tag{3}$$

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where J^M is the coupled objective function which is the product of J_m^M and J_t^M. This can be interpreted as: the algorithm seeks the distribution of the material to ensure good mechanical and thermal performance at the same time.

Thermal-mechanical optimization of a simplified tool

Common hot-stamped automotive parts generally have an omega-shaped cross-section, such as the A or B pillars, as the omega shape offers a compromise between part's mechanical strength and formability The previously described optimization procedure is then used to investigate a simplified Omega tool. The simplified Omega tool geometry, the mechanical boundary conditions and the thermal boundary conditions are described in Fig. 1. On the tool working surface, the thermomechanical loading experienced by the tool during the forming process is represented, in a simplified manner, by a pressure and a heat flux density.

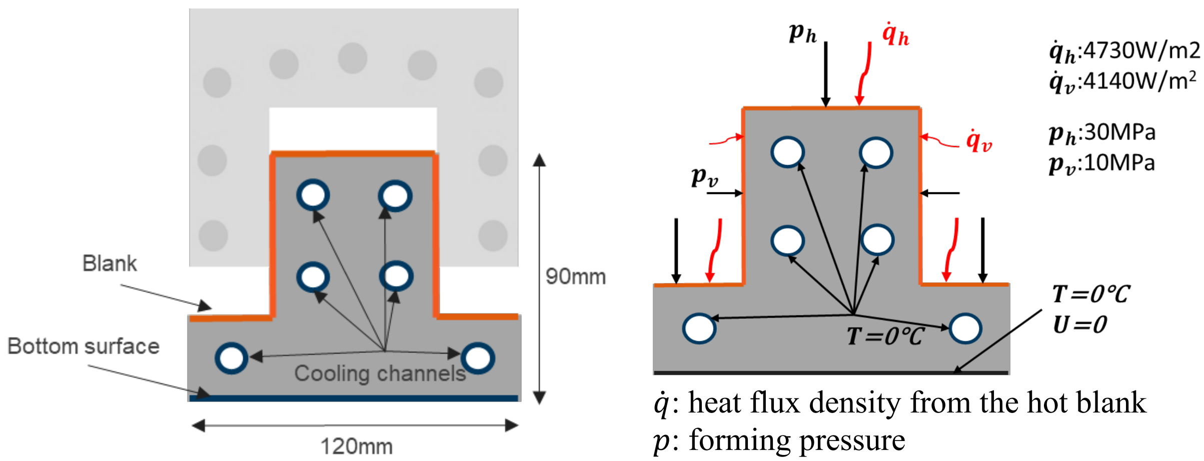

Fig. 1. Left) Simplified Omega punch used for optimization; Right) Boundary conditions for optimization.

The displacement is set to zero on the fixed face of the tool and the temperature is set to zero on the same face. The tool has *6* cooling channels *10 mm* in diameter and for simplicity, the temperature is set to zero at the surface of the channels. The optimization algorithm focuses on modifying only the solid material within the design domain (grey zone in Fig. 1 (Right)), while the position and geometry of the cooling channels remain unchanged because fluid mechanics is not taken into account.

To demonstrate the capability of the optimization procedure, five optimal configurations were determined by varying the solid volume fraction parameter f in Eq.3, modifying the amount of solid material in the tool. The five optimal configurations are shown in Fig.2. The vertical and horizontal structures observed in the tool result from the optimization algorithm. This ensures the mechanical strength of the tool. In addition, the material between the working surface of the tool and the cooling channels is kept to ensure heat transfer between the latter. These optimal designs are compared with the original tool in terms of thermomechanical behavior using finite element models with Abaqus software.

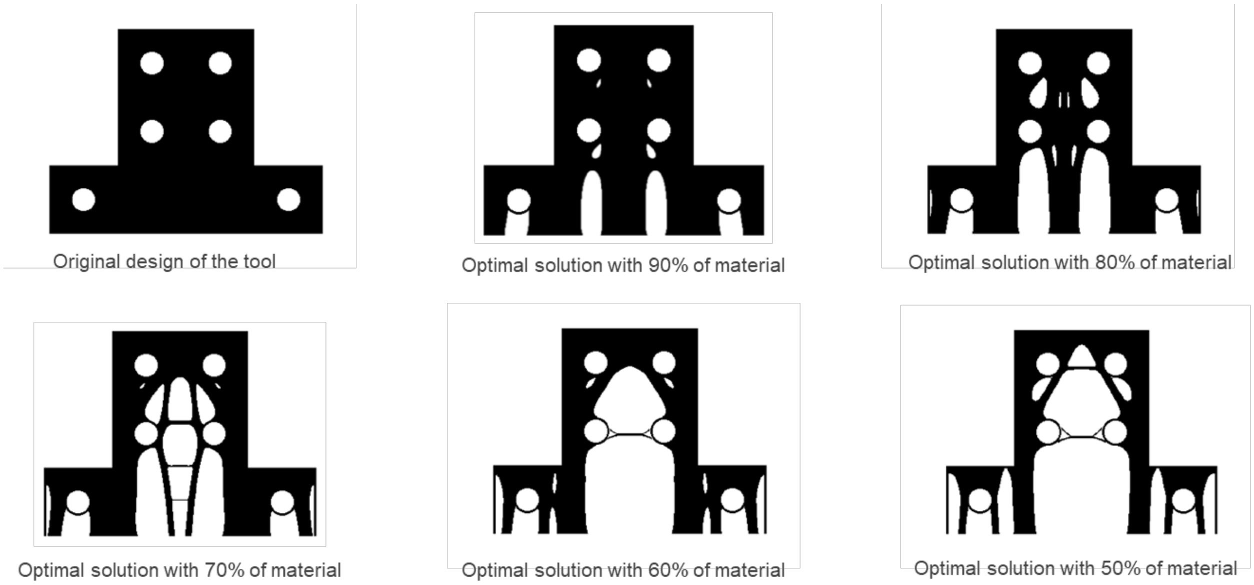

Fig. 1 Different optimal designs obtained by thermal-mechanical coupled topology optimization.

To validate the tool cooling performances, the optimized tool shapes are subjected to a cyclic thermal loading and the heat transfer is analyzed for each configuration. For each thermal cycle, a blank with an initial temperature of *750 °C* (to take into account the transfer of blank from the furnace to the press) is brought into contact with the tool for *8* seconds. This corresponds to the quenching operation during the hot stamping process. Afterwards, the contact condition is deactivated for *22 s* (zero heat transfer to represent the tool opening operation). The material properties, summarized in Table 1, are supposed as temperature independent. A total of *30* cycles were simulated to ensure stabilization of the temperature field.

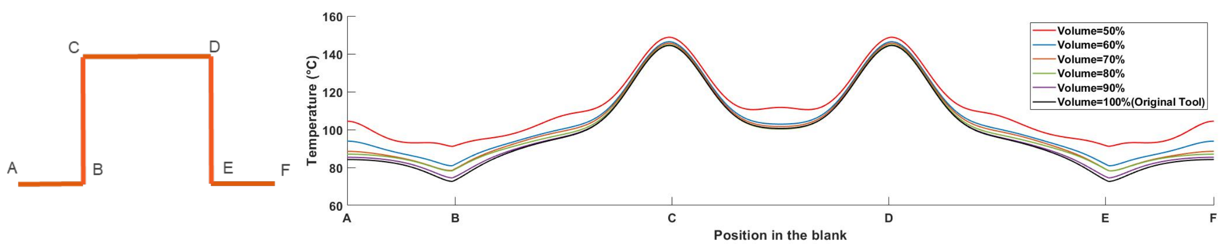

Fig. 2 Blank temperature after the 30^{th} quenching.

In hot stamping process, the quenching time is determined by the temperature of the hot spot on the work piece when the tool is opened. Thus, the temperature of the blank after the 30^{th} strokes is shown in the Fig. 3. It can be observed that the hot spots are located at point C and D due to the geometry of the tool.

The difference between the optimized tool's hot spot temperature and that of the initial tool is depicted in Fig. 4 for each of the five investigated configurations. These results show that the hot spot temperature increases when the quantity of solid material is reduced. But it should be noted that when *60 %* of the material is used in the tool, the temperature only increases by *2 °C*. For a hot spot temperature of around *160 °C*, it is obvious that this slight difference of *2 °C* will not impact productivity.

	Tool material properties (H13)	Blank material properties (Usibor®1500)
Thermal conductivity (W/m²•K)	25	20
Density (kg/m³)	7800	
Specific heat capacity (J/kg•K)	460	
Contact property (thermal transfer coefficient) (W/m²•K)	On horizontal surfaces: 4730	
	On vertical surfaces: 4140	
Film condition on bottom surface and cooling channels' surfaces	3340W/m²•K to 25°C	
Thermal expansion coefficient (/K)	$1.26 \ 10^{-5}$	

Table 1. Simulation parameters.

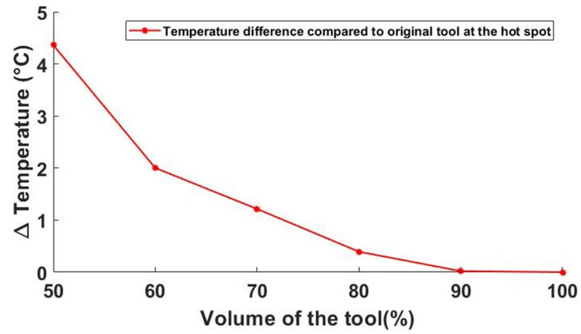

Fig. 3 Hot spot's temperature difference.

In addition to cooling efficiency, mechanical resistance is the other requirement for a hot stamping tool. To verify that the removal of solid materials from the tool does not excessively compromise its load capacity, a stress analysis was carried out on the optimized designs of the tool. For these stress analyses, the boundary conditions are those used for topology optimization. Regarding loading, two load cases were considered. The first load case consists of a static pressure applied on the tool's working surface. The obtained von Mises stress field and the displacement field are depicted in Fig. 5 for both the original tool and the optimized tool with *50 %* material. Despite the maximum stress increasing from *119.1 MPa* to *177 MPa*, it remains significantly below the yielding stress of H13 steel for example (a typical steel used for hot stamping tools). The maximum displacement increases from *0.01264 mm* to *0.03407 mm* which is again very small.

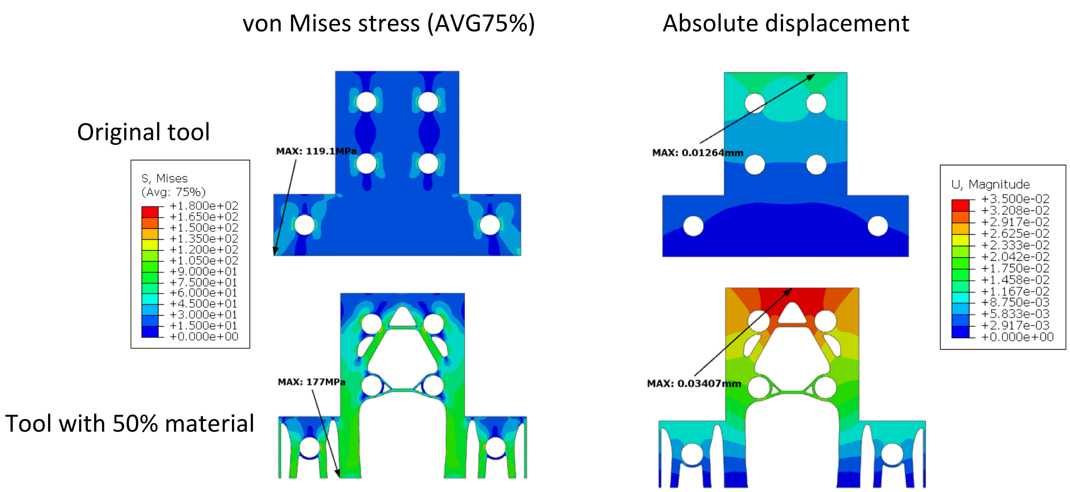

Fig. 4 von Mises stress field and the displacement field under static loads.

The second load case combines the previously described one (pressure on the tool's working surface) with the cyclic thermal loading (thermal expansion). During the last quenching cycle, the maximum stress is reached after a contact time between the flank and the tool of *0.8* seconds. The obtained von Mises stress fields are shown in Fig. 6, and the stress evolution along the surface is plotted in Fig. 7. The maximum stress is located at points C and D due to the local high temperature. It should be noted that thermal stress is strongly linked to the temperature field. Since the tool are subjected to the same thermal loads and the cooling performance has been well optimized, the stress distributions on the contact surface are very similar. Compared to the original tool, the optimized tool with *50 %* material has approximately the same maximum stress. Thus, the optimized tool has the same load bearing capacity as the initial tool with a material saving of *50 %*.

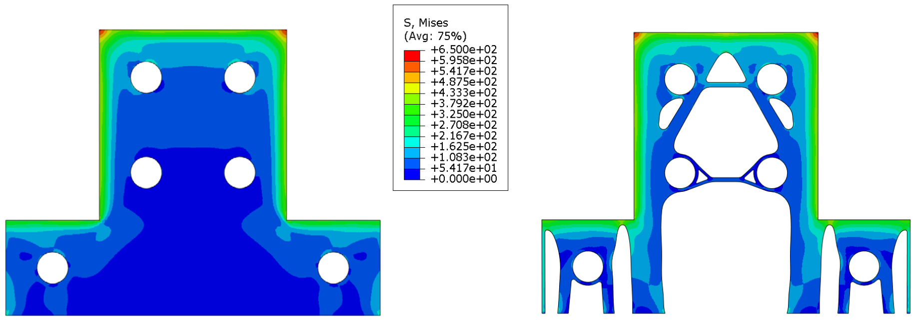

Fig. 5 von Mises stress field, under thermal expansion Left) Original tool; Right) Tool with 50 % material.

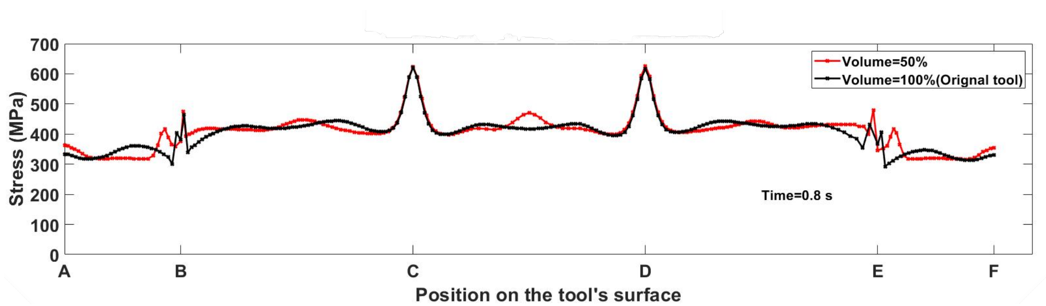

Fig. 6. Surface von Mises stress at t=0.8 s.

Fluid-thermal coupled topology optimization

As presented in the previous sections, optimizing the material used in the tool may reduce the printing cost without changing the tool's cooling performance and its load bearing capacity. However, to improve the cooling efficiency of the tool, the geometry and position of the cooling channels need to be optimized and this involves taking into account the fluid flow in the cooling channels. To achieve this, a fluid-thermal coupled topology optimization algorithm is developed in the software FreeFEM [4]. Most topological optimization algorithms in fluid mechanics focus on laminar flow with the Navier-Stokes (NS) equations. [5]. When the flow velocity becomes high, the turbulence appears in the flow. The turbulence problem in fluid mechanics is highly nonlinear and unstable, which makes fluid topology optimization a very difficult task. Research reported in the literature shows that fluid topology optimization algorithms have been developed and successfully used for flows with Reynolds numbers up to *200*. In the hot stamping tools used for productions, the fluid flow in the cooling channels generally has a Reynolds number of between *4000* and *11000* [6]. Such high flow velocities are sought to increase the cooling efficiency of the tool, as turbulence promotes heat transfer from the tool to the cooling fluid. To overcome this difficulty, the NS equation is simplified as Stokes equation. Without the convective term in the NS equation, the turbulence is neglected, and the flow is considered as fully laminar. This simplification may lead to errors in the calculation of the temperature field in the fluid domain. However, the temperature is more sensitive to the position of the channels. Thus, this method should be able to create continuous channels at hot areas to dissipate heat.

In optimizing heat transfer systems, both hydraulic performance and thermal performance are concurrently considered. The pressure drop of the system is usually minimized to prevent unreliable solutions. It can be written as [7]:

$$J_f^F = -\int_{\Gamma_{Inlet} \cup \Gamma_{Outlet}} p\vec{u} \cdot \vec{n}\, d\Gamma \tag{4}$$

where $\boldsymbol{p}$ is the flow pressure and $\vec{\boldsymbol{u}}$ is the velocity vector.

As explained earlier, the cooling performance of a hot stamping tool is quantified by the workpiece hot spot temperature. By eliminating the effects of poor contact between the tool and the workpiece, the hot spot on the tool and the hot spot on the workpiece are identical. Consequently, the maximum temperature on the working surface of the tool will be used. When the optimization goal is to minimize the hot spot temperature on the tool working surface, the objective function can be written as [8]:

$$J_t^F = \left(\int_{\Gamma_{Contact}} T^{\beta}\, d\Gamma\right)^{\frac{1}{\beta}} \tag{5}$$

where T is the temperature field, β is a positive large number and $\Gamma_{Contact}$ is the tool working surface.

However, the calculation of extremely large values of T^{β} may lead to computational issues. To overcome this difficulty, the following thermal objective function is used.

$$J_t^F = \int_{\Gamma_{Contact}} \left(\frac{T}{40}\right)^{20} d\Gamma \tag{6}$$

The values are chosen based on numerical tests. As the temperature on the surface is always higher than *40 °C*, the term of $\frac{T}{40}$ is larger than 1. By powered by *20*, the cooling performance at the hot spot takes more importance during the optimization. Combining Eq. 4 and Eq.6, the coupled fluid-thermal topology optimization problem can be reformulated as:

$$min: J^F = J_f^F + \tau_{obj} * J_t^F$$

$$s.t.:\ \frac{V_f}{V^*} \leq f \tag{7}$$

where τ_{obj} is a weighting factor for optimization function and V_f is the fluid volume in the domain.

Applying the topology optimization to a large-scale 3D problem such as the hot stamping tool involves many computation difficulties, in particular the efficiency in terms of computational time. To achieve this, the domain decomposition method is used for parallel computation [9]. Highly efficient solvers are also implemented for solving fluid equations, thanks to the interface between FreeFEM and PETSc [13]. Mesh adaptivity is also used to ensure the solution quality while keeping reasonable computational time. These mentioned methods are implemented into optimization algorithm to ensure that the computation time remains acceptable. To address the challenge posed by heat transport problem with high Péclet numbers, the Streamline Upwind Petrov-Galerkin (SUPG) type stabilization method is employed along with adaptive mesh near the fluid solid interface [10]. The techniques described above are combined with the adjoint method to achieve a highly efficient optimization procedure.

Fluid-thermal topology optimization of a simplified tool

The developed fluid-thermal topology optimization procedure is tested on a simplified geometry, Fig. 8A, which is representative of a hot stamping tool. Water is used as the coolant for cooling channels. The value of volume fraction parameter $\boldsymbol{f}$ in the Eq.7 is chosen such that the fluid volume is identical to the one used in a conventional cooling channel shown in the Fig. 9A.

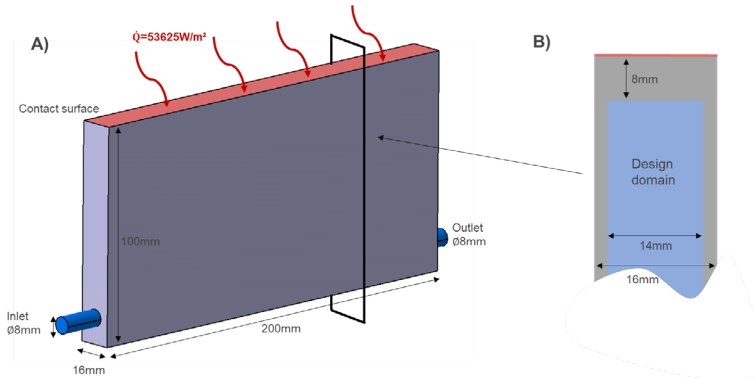

Fig. 7. A) Simplified geometry for optimization B) Design domain for optimization.

As the optimization algorithm is for steady laminar flow, the cyclic thermal load is simplified as a constant heat flux *53625 W/m²*, applied on the contact surface. This heat flux represents the averaged heat flux resulting from a *0.75 mm* thickness blank being cooled from *750 °C* to *200 °C* within a cycle time of *30* seconds. To prevent water from going directly to the surface, creating an unrealizable solution, a solid offset on surfaces is set as a constraint for optimization (Fig. 8B). The inlet temperature is fixed as *20 °C*. The flow velocity at inlet is supposed as a fully developed laminar flow using Hagen–Poiseuille equation:

$$\vec{u}_{Inlet} \cdot \vec{n} = u_{max} * \left(1 - \frac{r^2}{R^2}\right) \quad (8)$$

where u_{max} is the maximum velocity at the center of inlet, chosen as *1 m/s*. r is the distance to the inlet center and R is the radius of the inlet which is *4 mm*.

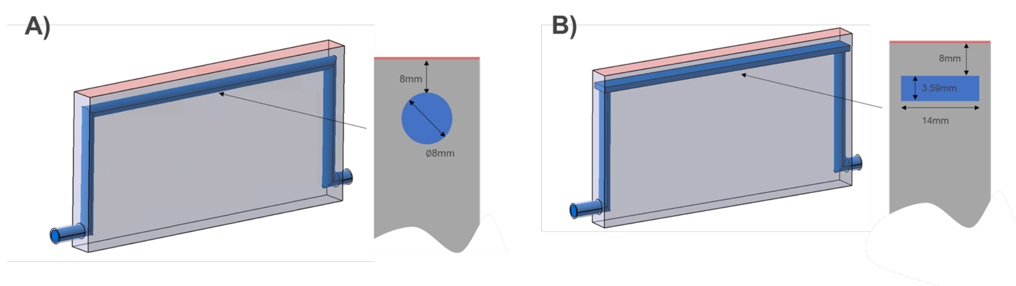

Fig. 8 A) Conventional cooling channel B) Rectangular cooling channel.

Choosing different values for the weight parameter τ_{obj} in Eq.7 may lead to different design solutions. When τ_{obj} is too high, the algorithm would neglect the hydraulic optimization leading to unrealizable solution with non-connected channels. On the other hand, when τ_{obj} is too low, the cooling performance of the tool would be degraded. In this work, an interesting solution is found by initializing τ_{obj} at *1000* and gradually decreasing it to *10* during the iterations. A twisted shape channel is obtained to better mix the water inside the channel. The solution is then exported and reconstructed in CAD software, shown in the Fig. 10.

Obviously, the optimization algorithm directs the water flow toward the contact surface to extract the heat. Moreover, as the τ_{obj} is high enough, a twisted channel geometry is found. As the cold water is heated up while flowing though the channel, the topology optimization algorithm has well captured the temperature gradient in the channel. The twisted geometry promotes the mixing of heated water with cold water to increase cooling efficiency. Some similar geometries are artificially created following the same idea [11].

The optimized cooling channel has been compared with the conventional cooling channel (Fig. 9A) though a CFD model developed in COMSOL Multiphysics. As the optimized channel has a larger width compared to the conventional channel, a rectangular cooling channel (Fig. 9B) is included in the comparison. All these three cooling channels are designed with the same fluid volume. The steady *k*-*ε* turbulent model is chosen to simulate the real situation [12]. The domain is meshed using tetrahedral elements with *8* layers of prismatic element in the fluid domain. After a mesh convergence study, the global element size in the fluid is set to *1 mm*.

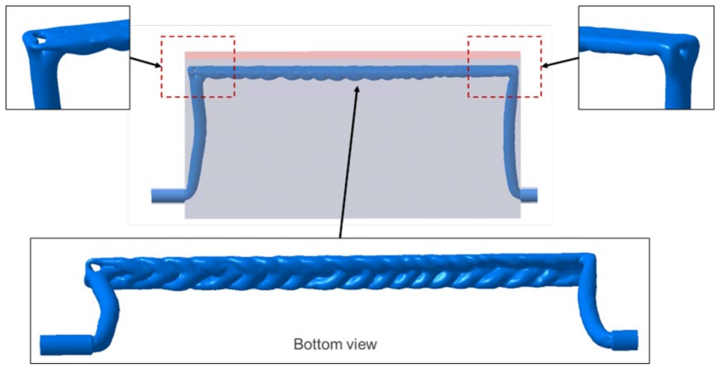

Fig. 9 Optimal solution obtained by fluid-thermal coupled topology optimization.

Fig. 11 shows a comparison between three designs in terms of temperature evolution along the contact surface centerline. It can be observed that the conventional channel (circular shape) has an overall higher temperature along the surface centerline. The temperature with rectangular channel increases almost linearly. The highest temperatures are all located near the end of the surface due to the geometry. Though, the temperature with optimized channel is better controlled. The maximum temperature obtained with the optimized channel is more than *5 °C* lower than those obtained with the other designs. Considering this is a simplified case, the gain in temperature may be much higher while facing to a more complex real tool.

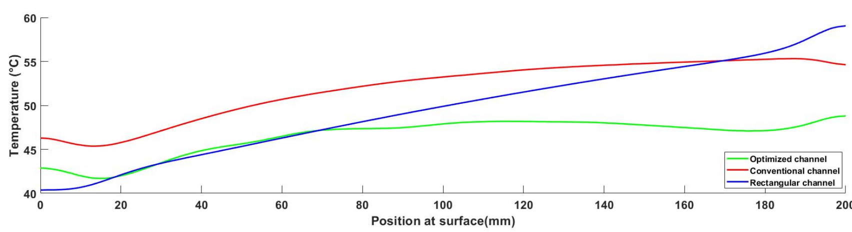

Fig. 10 Temperature comparison with three cooling channels.

Summary

In this study, topology optimization has shown its high suitability for designing hot stamping tools. In thermal-mechanical coupled optimization, around *40 %* of the solid material in a simplified Omega tool, without changing the tool's cooling performance. Even with a 50% material reduction in material, the reduction in tool load bearing capacity is not critical. This may lead to the price reduction and the building time saving for hot stamping tools. In fluid-thermal coupled optimization, the algorithm shows well its ability for cooling system designs. It does not only send water to the contact surface, which can be potential used for conformal cooling design, but also creates the twisted cooling channel. Even if the flow is supposed as fully laminar during optimization, the heated water mixed well with cold water to achieve a better cooling performance. In the case of a real industrial tool, the design process would start with fluid-thermal optimization for the cooling system design, followed by applying thermal-mechanical optimization for the solid volume reduction. Further studies will continue applying topology optimization algorithms on real hot stamping tools to answer the following questions:

- Printability is not considered in the optimization algorithms
- Mechanical resistance is not considered during the cooling system design
- Using Stokes flow in optimization may not represent the real flow distribution

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