# Heuristic optimization of cooling channel design in the hot stamping die for hot stamping process

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**Abstract.** In hot stamping process, similar die is used as in cold stamping process but with additional cooling channels. The cooling channel systems are integrated into the die design to control the cooling rate for quenching process of hot blanks. During quenching process, the die is effectively cooled to achieve the optimum cooling rate and homogeneous temperature distribution on hot blanks. In this paper, heuristic method with finite element analysis (FEA) of static analysis and thermal analysis are applied to determine the cooling channel size, pitch size between channels and channel distance to the blanks surface. This static analysis identifies either the tool able to stand the pressure applied or not, while the thermal analysis is to ensure the die obtains the high cooling efficiency with homogenous temperature distribution. In this heuristic method, each parameter of the cooling channels inside the die are optimized and benchmarked with traditional Taguchi method. The results showed that the heuristic method coincides with Taguchi method even better and achieved the acceptance error between FEA in temperature distributions.

## Introduction

The development of hot stamping to produce ultra-high strength parts especially in automotive has been developed since years. This process undergo several important process such as forming, quenching and austenization in order to achieve final product with tensile strength about 1500 MPa of yield strength. In hot stamping, there are exists in two different types of methods which are direct and indirect method [1]. For this paper, the method of indirect is chosen due to simple die design and suitable for complex die design. It starts when the blank is cut off then heated the blank inside the furnace up to 900°C. Then, the blank must be transferred quickly to the hot stamping tool to avoid the part is cooled before forming. After that, the blank is formed and cooled simultaneously by the water cooled die for 5-10s. Due to the contact between the hot blank and the cool tool, the blank is cooled in the closed tool [2].

Since the process requires the tool to cool down the blank rapidly, a cooling system must be integrated into the tool. The optimum design of cooling channel such as diameter, pitch and distance to loading surface of cooling was introduced by [3-7], in order to achieve maximum cooling rate and homogeneous temperature distribution of the hot stamped part. There have some optimization method that is used by the researcher. Hoffmann et al. [3] and Steinbeiss et al., [8] utilized Evolutionary Algorithm as optimization method. Meanwhile, Jiang et al. [5], Kumar et al. [6] and Lui et al. [7] used heuristic method in numerical simulation and theoretical analysis was employed by Zhong et al. [4]. All the method leads to the optimization of the geometric design of the cooling system. The result shown the cooling system with cooling ducts near to the tool contour is currently well known as an efficient solution [3-7]. For the diameter of cooling channel, small diameter is suggested as the amount of cooling channel can be increase and result the improvement of cooling performance [8]. For current case, based on practice by Miyazu (M) Sdn. Bhd, the cooling channel design for hot stamping are diameter of cooling channel is 8mm to 12mm, pitch is 10mm and distance to loading surface is 10mm to 15mm.

Till now the entire researcher had defined the method to optimize the cooling channel parameter, however the method in choosing the cooling channel parameter is undefined. So, this paper shows the use of DOE to simplify the chosen of cooling channel parameters. The heuristic optimization of cooling channel for hot stamping tool will be presented by studying the cooling channel parameters such as the size of the cooling channel *a*, pitch between cooling channels *b* and the distance between cooling channels to loading surface *c*, as shown in Fig. 1. Then, the result obtained will be analyzed by using two different types of DOE which are heuristic method and Taguchi method.

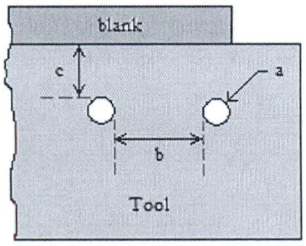


**Fig. 1**: Schematic of cooling channel parameters for hot stamping tool [17]

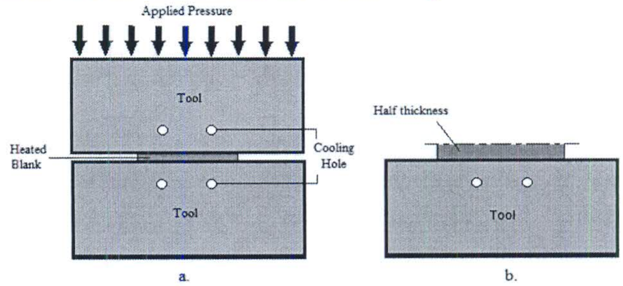


**Fig. 2**: a) Simplified hot stamping process condition, b) Finite element model simplification[17]

## Methodology

**Finite Element Analysis (FEA).** In order to study the hot stamping tool, the actual process of hot stamping in a laboratory scale experiment is replicated where the process is simplified into a simple compression of tensile test blank in contact with the tool [9]. In the finite element analysis (COSMOS software), the 3D model of the tool and the blank is simplified by modelling only the lower half and half thickness of the blank to reduce the number of element as well reducing the iteration time as shown in Fig. 2.

In this study, the cooling channel parameters are optimized using finite element analysis. The finite element analysis consists of two main analyses; static and the thermal analysis. The purpose of static analysis is to study the deformation of the tool as a result of the distance c of the cooling hole to the tool contour, under the forming pressure of 35MPa [9]. While in thermal analysis, the cooling characteristics of the tool is analyzed as the blank comes into contact with the tool surface. The tool initial temperature is set at 20°C, while the thermal contact resistance between the tool and blank surface is given by $1.25 \times 10^{-4}$ $m^2K/W$ [3]. The heat convection coefficient at cooling holes surface is constant at 4877.4 $W/m^2K$ based on the calculated minimum flow rate to achieved turbulent flow inside the cooling hole [10]. Based on the research that had been done previously, the FEA result is compared with experimental result to figure out the differences between both experiments. As an outcome, the FEA result is proven and valid with the experimental result. Thus, Fig. 3 shows the results of temperature distribution of hot stamping tool cooling rate for FEA and experimental result [18]. From this FEA results, it is extending to optimization in this paper using Heuristic and Taguchi Methods.

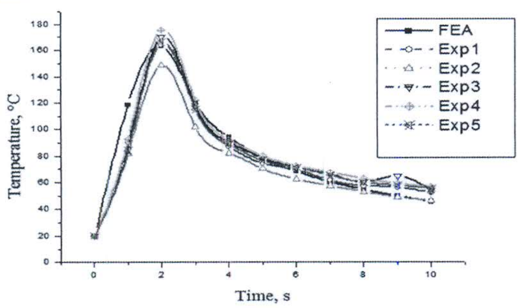


**Fig. 5**: Comparison temperature distribution between FEA and Experiment [18]

**Heuristic Method.** Basically heuristic method is often resort to solve real optimization [11]. A heuristic method also called an approximation algorithm, an inexact procedure, or, simply, a heuristic. It is a well-defined set of steps for quickly identifying a high-quality solution for a given problem, where a solution is a set of values for the problem unknowns and quality is defined by a stated evaluation metric or criterion [12]. Beside that heuristic also is used to specify the class problem from the decisions of some a priori knowledge [13].

In this paper the heuristic in designing the optimum cooling channel design is the size of the cooling channel is kept constant at 8.0mm. While for the distance between cooling channels **(b)** the ranging distance is from 6.0 to 12.0 mm and distance to tool contour **(c)** ranging from 4.0 to 10.0mm. As mentioned earlier, FEA is used to define the optimized the cooling channel parameters. In the static analysis, the value of the maximum von Mises stress (VMS) will be measured as the value obtain must not exceed the yield strength of the tool material. Otherwise, the tool cooling channel design is fail. Then, in the thermal analysis, the lowest tool temperature after 10 seconds with different parameter of cooling channel was chosen. This is because the lowest temperature will give high cooling efficiency on the tool. From the analysis, the data on heat transfer of the tool is obtained. Thus, the data rate of cooling for the tool can be determined. In order to obtain the rate of cooling, heat transfer formula need to be used which is:

$$Q = \Delta U = mc_{avg}(T_2 - T_1) \tag{1}$$

$$m = \rho \acute{v} \tag{2}$$

where, $m$ is the mass, $c_{avg}$ is the average specific heat evaluated at the average temperature, $T$ is the temperature, $\rho$ is the density and $\acute{v}$ is specific volume. Normally, the rate of heat transfer change during the process with time. Thus, the rate of cooling for tool and blank can be determined by dividing the amount of heat transfer with time interval [14].

$$\dot{Q} = \frac{Q}{\Delta t} \tag{3}$$

**Taguchi Method.** Taguchi design of experiment method was used in this project to evaluate the relative contribution of cooling channel design toward the hot stamping tool. The main effect was employed to investigate the results and the optimum parameters of cooling channel can be established [15].

Table 1 shows the Taguchi test matrix for the tests to be performed on the tool structure which is able to stand high forming load and another table is for tool cooling performance. To design experiment matrix for three factors with three levels, the $L_9$ orthogonal array (OA) was the most applicable. The $L_9$ array requires the minimum number of test (14) to investigate the hot stamping tool, as tabulated in Table 2. The total should be known in two ways using Minitab software [16]. In this study, the factor that contribute toward the hot stamping tool are diameter of cooling channel $a$, pitch between cooling channel, $b$ and distance cooling channel, $c$ to loading surface [3]. Those factors will result the maximum VMS and cooling rate of hot stamping tool.

**Table 1**: Factor and Level Description

| Factor | Factor Description | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| A | Diameter of Cooling Channel (mm), $a$ | 6 | 8 | 12 |
| B | Pitch Between Cooling Channel (mm), $b$ | 8 | 10 | 12 |
| C | Distance Between Cooling Channel to Loading Surface (mm), $c$ | 6 | 8 | 10 |

## Result and Discussion

**Heuristic Method.** As a result for static analysis, Table 3 shows the value of the maximum VMS on the tool for all cooling channel parameter did not exceed the yield strength of the tool material. In addition, the maximum von Misses stress on the tool seems to decrease with increasing values of distance $b$ and $c$. The value of maximum VMS less in 35MPa is selected for thermal analysis.

**Table 2**: $L_9$ Test matrix

| DOE | Factor | | |
|---|---|---|---|
| | A | B | C |
| 1 | 6 | 8 | 6 |
| 2 | 6 | 10 | 8 |
| 3 | 6 | 12 | 10 |
| 4 | 8 | 8 | 8 |
| 5 | 8 | 10 | 10 |
| 6 | 8 | 12 | 6 |
| 7 | 12 | 8 | 10 |
| 8 | 12 | 10 | 6 |
| 9 | 12 | 12 | 8 |

**Table 3**: Result of maximum von Mises stress (MPa) on hot stamping tool.

| b, (mm) / c, (mm) | 6 | 8 | 10 | 12 |
|---|---|---|---|---|
| 4 | 50.896 | 44.251 | 38.995 | 36.404 |
| 6 | 45.827 | 40.328 | 38.071 | 34.320 |
| 8 | 38.834 | 36.811 | 32.042 | 31.889 |
| 10 | 35.794 | 33.867 | 31.221 | 30.672 |

In thermal analysis, it shows that, with increasing the distance *c* 6 to 10mm, the cooling rate of the hot stamping tool is slightly increase compare to the increasing distance of *b* as shown in Table 4. This can be conclude that, the distance **c** give the major effect in designing the cooling channel for hot stamping tool [3]. In addition, based on thermal analysis the combination cooling channel parameter of a=8, b=10, c=8 gave the higher rate of cooling for this hot stamping tool.

**Table 4**: Result of thermal analysis

| Cooling Parameter (mm) | Hot Stamping End after 10s (°C) | Cooling Rate (kJ/s) |
|---|---|---|
| 8 12 6 | 42.757 | 22.097 |
| 8 10 8 | 44.477 | 22.242 |
| 8 12 8 | 44.922 | 21.569 |
| 8 8 10 | 45.614 | 21.922 |
| 8 10 10 | 45.906 | 21.546 |
| 8 12 10 | 46.085 | 21.536 |

**Taguchi Method.** The value for the maximum VMS and cooling rate were obtained after conducting the FEA for all nine DOE. Each result represents one FEA in the OA as shown in Table 5 which summarizes the maximum VMS value and rate of cooling for hot stamping tool under constant of *a, b,* and *c*. All the results were analysed by conducting the main effect and later a confirmation test was carried out to compare the simulation results and the predicted results of the minimum value of maximum VMS and higher value of cooling rate.

Hence, in Table 6 summarizes the average main effect for maximum VMS and cooling rate which obtain from each factor i.e. A, B, and C array each level (Level 1, level 2 and level 3). The quality of characteristics analysis in the current study was the smaller is better for maximum VMS value and larger is better for cooling rate due to the optimization in designing the cooling system for hot stamping tool [3]. It can be observed that the parameters and their levels of combination for maximum VMS are $A_1$, $B_3$ and $C_3$ and for the cooling rate, the combination is $A_1$, $B_2$ and $C_1$.

**Table 5**: Summarizes result from the Taguchi method

| DOE | Factor | | | Result | |
|---|---|---|---|---|---|
| | A | B | C | Maximum von Mises stress (MPa) | Cooling Rate (kJ/s) |
| 1 | 6 | 8 | 6 | 37.711 | 22.50 |
| 2 | 6 | 10 | 8 | 33.152 | 22.045 |
| 3 | 6 | 12 | 10 | 30.431 | 21.690 |
| 4 | 8 | 8 | 8 | 36.664 | 21.974 |
| 5 | 8 | 10 | 10 | 31.221 | 21.546 |
| 6 | 8 | 12 | 6 | 34.320 | 22.097 |
| 7 | 12 | 8 | 10 | 33.120 | 21.355 |
| 8 | 12 | 10 | 6 | 39.950 | 22.712 |
| 9 | 12 | 12 | 8 | 33.708 | 20.332 |

**Table 6**: Average main effect for both respond

| Symbol | Parameters | Average Main Effect | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Maximum von Mises stress (MPa) | | | | Cooling Rate (kJ/s) | | | |
| | | Level 1 | Level 2 | Level 3 | Rank | Level 1 | Level 2 | Level 3 | Rank |
| A | a (mm) | 33.76 | 34.07 | 35.59 | 3 | 22.08 | 21.87 | 21.47 | 3 |
| B | b (mm) | 35.83 | 34.77 | 32.82 | 2 | 21.94 | 22.10 | 21.37 | 2 |
| C | c (mm) | 37.33 | 34.51 | 31.59 | 1 | 22.44 | 21.45 | 21.53 | 1 |

**Comparison between Heuristic and Taguchi Method.** Results are obtained from both DOE method show the differences in optimization cooling parameter for hot stamping tool. These results need to recheck and redefined as to observe the suitable criteria of cooling channel in hot stamping tool. Thus, the results that are obtained from Heuristic is 08,10,08 while based on Taguchi method the results shows 06,08,06 and 06,12,10 respectively. In hot stamping tool, lower maximum VMS and higher cooling rate value are the criteria that need to focus on. Thus, Fig. 4 shows the temperature distribution for cooling channel design selected that is gain from FEA. From the result, it shows that the patent of each cooling design is same, but the result of the tool performances is different. Tool with parameter 08,10,08 give a better cooling performance because, the tool had less maximum temperature achieved after the heated blank is transfer to the tool. While in Fig. 5 shows the concluded results of the cooling parameter that had been selected.

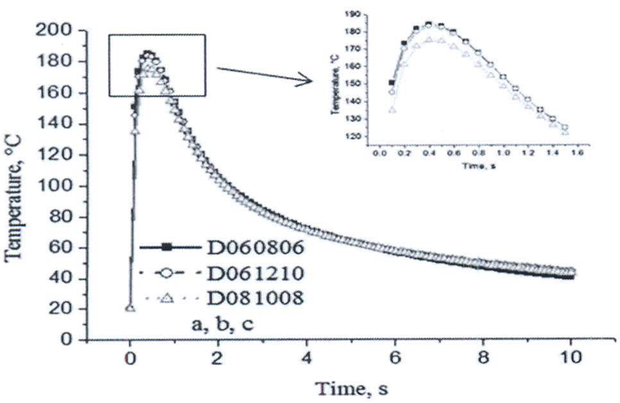


**Fig. 4**: Temperature distribution for cooling channel design selected

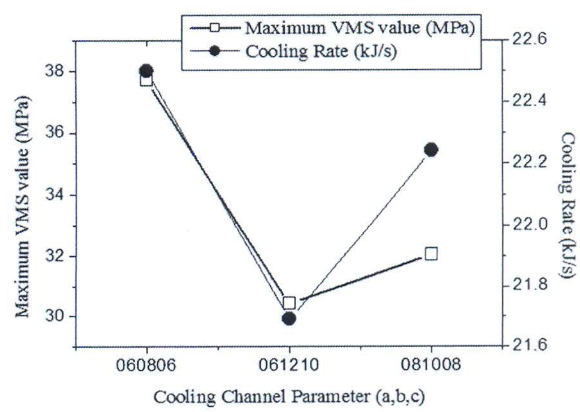


**Fig. 5**: Result of cooling channel design performance

Parameter of 06,08,06 results the highest maximum VMS and cooling rate and as for parameter 06,12,10, the results shows the lowest maximum VMS and cooling rate. This results is achieved due to major difference distance to the loading surface, **c** where the distance for 06,08,06 is the shortest also result in high maximum VMS that will affect the deformation of the tool. As for longer distance form loading surface, the results is vice versa. In this study, parameter 08,10,08 give the better results where it have lower maximum VMS (Fig. 6) and higher cooling rate value (Fig. 7).

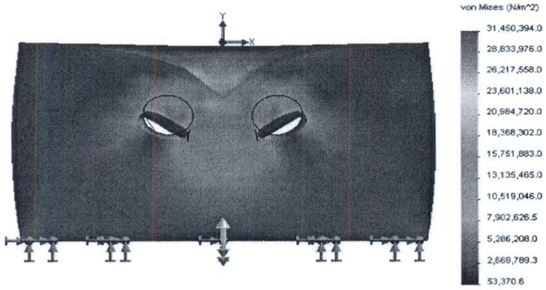


**Fig. 6**: FEA for static analysis

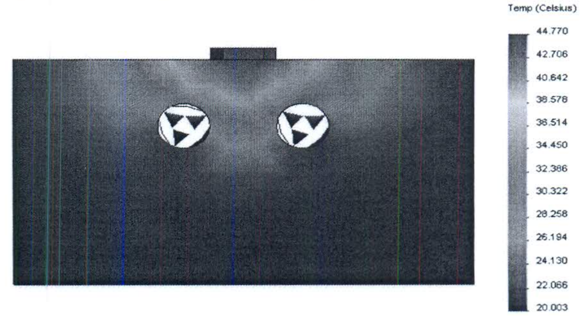


**Fig. 7**: FEA for thermal analysis

## Conclusion

In conclusion, new method for designing and optimizing cooling channel is presented to obtain a better performance of hot stamping tool. The DOE of heuristic method is coincides with Taguchi method and even gives the better result in choosing the cooling channel design parameter. Among the parameters, the distance to loading surface, **c** give a major effect to hot stamping tool performance. Prototype tool for this research is currently being built and experiment will be carried out for validate this proposed method in future work.

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