International Journal of Engineering & Technology, 7 (3.13) (2018) 68-71

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

CFD Evaluation of Hot Stamping Die Cooling System

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Abstract

This paper presents the results of CFD analysis on a complex near optimized cooling channels of hot stamping die for automotive structural part. Near optimum design is acceptable since cooling channels design is limited by its machining constraints. The objective of this evaluation is thus to determine the efficiency the cooling system by monitoring its cooling rate during 8 seconds of the quenching process. The die and blank were modelled as 3D volume mesh in a closed position thus ignoring the blank history data prior to the stamping operation. Temperature distribution representing hardness of the simulated final part is compared with the actual stamped component. The same procedure was validated against another structural component of different cooling channel design. The results show temperature pattern after 8 seconds can be used to predict harness distribution of the final part, thus indicating the viability of this method to be used in cooling system design.

Keywords: *CFD; Cooling system; Hot Stamping.*

1. Introduction

To date, the most viable technique to produce automotive structural parts with tailored properties is hot stamping or press hardening. It offers many advantages over its contemporary, the conventional cold stamping. Firstly, it's increased tensile strength of up to 4 times than the original material as delivered with minimum spring-back. Secondly the final properties of the part can be varied along its length. This is extremely useful property for parts require higher crashworthiness such as B-Pillar [1].

Hot stamping process is very complex since it involves combined thermo-mechanical and micro-structure evolution [2]. It follows that numerical simulation of such a process is difficult. A prior knowledge in terms of temperature dependent stress strain parameters, heat transfer between the blank and the die, coupled thermo-mechanical calculation and the material evolution of micro-structure allow engineers to predict the final properties of the part. In this respect, die design plays an important role in hot stamping to ensure the part is formed and quenched according to the desired geometry and properties. Besides having to withstand press cyclic loading, die material should able to extract the heat from the blank. This means the die must be able to absorb and evacuate energy of up to 100KW [3] by means of cooling channels. Therefore, location and size of the cooling channel are critical to guarantee a complete martensitic transformation [4]. Fig. 1 shows a typical complex cooling channel design [5].

Ideally conformal cooling design is preferred, however due to manufacturing constraints, it may not be economical to use. Hence the straight-hole type is more popular in practice. Chen et al [6] classify cooling channel design into two: namely parallel type and serial type. In the parallel design, output channel of die insert is connected to the input of the following insert. Whereas in the case of serial design each die insert has its own input and output cooling channel.

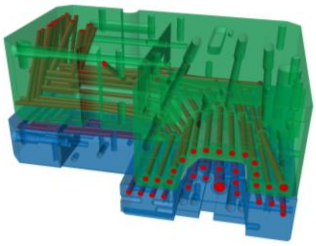

Fig. 1: Hot Stamping Cooling System.

It is found that that the parallel design is more efficient. Hu et al [7] investigated the performance of five different cooling designs namely straight-hole, longitudinal CCC (conformal cooling channel), transversal CCC, parallel CCC and serpentine CCC. Each design performance index is measured by the figure of merit (FoM) concept. The longitudinal CCC design scores the highest FoM, therefore giving the highest cooling efficiency. This finding is supported by He B et al [8], via numerical experiment by comparing straight-hole design and longitudinal design. Reduction in average blank temperature and temperature deviations were achieved. Optimization of cooling system should consider diameter of cooling channel, distance between them and die strength as proposed by Mengmeng et al [9]. However, this can become very complex as the part surface get complex.

Finite element method has been successfully implemented in simulation of hot stamping of Boron and other quenchable steels [10]. In addition, many commercial codes are now available to assist tool design engineers. However most of these codes assume the die temperature during quenching is uniform which can only be achieved if the cooling channels are optimized [11, 12]. Simulation of hot stamping cooling system can be performed in three ways. Firstly, by considering thermal modelling only where the blank is in closed position within the fixed tools. Secondly, thermal and mechanical models are coupled with a rigid tool under pressure. Thirdly, thermal-mechanical coupled with elastic tool under pressure. The second approach was adopted by [13] primarily because of microstructure evolution. Other important parameter to be considered in simulation is the heat transfer coefficient (HTC) between the blank and the tool surface. Several values have been proposed in the literature. It has been shown that HTC is dependent on contact pressure between the blank and die surface [2]. However, Zhang et al [14] defined this value as a function of temperature. Determination of heat transfer coefficient is still an on-going research elsewhere. This is heat transfer coefficient between the blank and die surface. Its value is considered important in order to precisely describe the blank temperature history. It varies linearly with the contact pressure from 100W/m^2.K to 1200 W/m^2.K [2]. Solomonson et.al [15] defined HTC response to contact pressure by NURB- spline curve. Measured and simulated response results of 22MnB5 and USIBOR 1500 showed some similarity as opposed to errors when using a constant HTC. More recently Kim et al [16] modeled the interface heat transfer by a power law of contact pressure. The study showed a linear relationship with the contact pressure until 10 MPa. The HTC of 7000 W/m^2.K remains constant after this. Alternatively, Shvets [2] suggested an equation which takes into consideration the roughness parameter and the rupture stress. Finally Zhang [14] confirmed that the HTC is non-linear when an experiment was conducted at contact pressure of 9 MPa using blank material of 1.5mm thick. Maximum HTC of 4300 W/m^2.K was achieved at 873^{o}K of blank temperature while the lowest HTC of 1400 W/m^2.K observed at 673^{o}K. HTC appears to increase a little bit at the temperature drops further. However at 0 MPa of contact pressure HTC between 750 and 1300 W/m^2.K has been reported [7].

Effectiveness of cooling system can be measured by uniformity of temperature distribution during quenching, thus determining the cooling rate. While coupling CFD and stamping operation will determine accuracy of cooling efficiency hence affecting the hardness distribution of the stamped part, it is argued however by knowing how the blank temperature history during quenching we can predict its hardness. Rapid cooling will result in an increased in hardness while slow cooling will result in the opposite. If the temperature variation of the blank can be kept to minimum, then we can classify this as an efficient cooling. The main objective of this paper is to illustrate a simple methodology based on CFD analysis for validating an optimized cooling system design based on a thermal model only. This is also a continuation work of the same authors [5].

2. Description of the Case Study

As a case study, two hot stamped part are used, namely test part and validation part. Both are made of Boron steels. The size of test part is 900 mm x 450 mm x 2 mm shown in Fig. 2 while the validation part is 677 mm x 236 mm x 1.2 mm shown in Fig. 3.

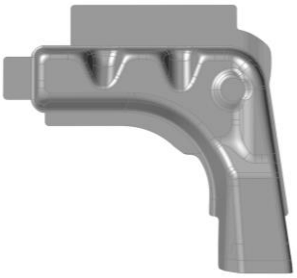

Fig. 2: Hot Stamped Test Part

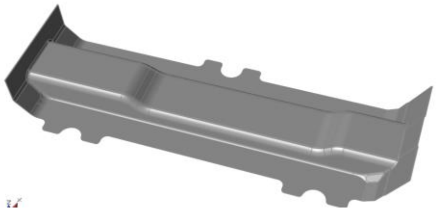

Fig. 3: Hot Stamped Validation Part

Fig. 4 shows the part temperature curve as it passes through different stages as recorded by a Fluke thermal camera. It begins with pre-heating, post heating, pre-stamping and post stamping and quenching.

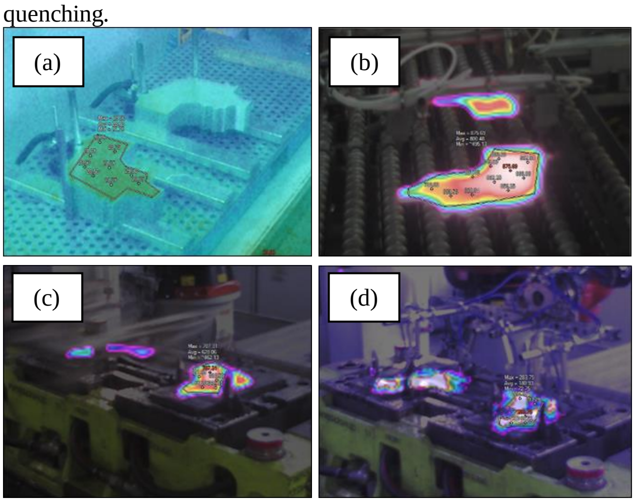

Fig. 4: Temperature History of the Test Part

The blank was initially at 28.6^{o}C (a) and its temperature increased to 800^{o}C upon exiting the furnace (b) but temperature at the edge is 500^{o}C. The temperature drops to 628^{o}C (c) when it reaches on top of die assembly. Finally, its temperature drops further immediately after quenching. The final average temperature is about 180^{o}C (d). It is noted that the part temperature was not uniform throughout the process.

The straight hole-type of cooling channel was adopted in the design of the stamping die. The upper and lower die consist of several inserts and the cooling channels pass through them. Due to its complexity and limited by the machining (drilling) constraints, many intersections are of 90 degrees or less. Fig. 5 shows the design of the cooling system.

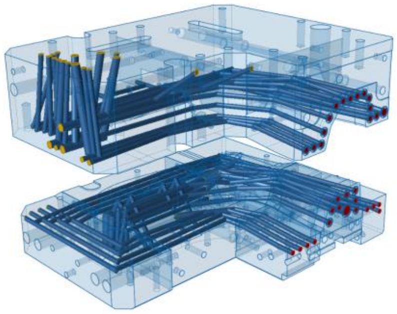

Fig. 5: Lower and Upper Cooling Channel for the Test Part

3. Methodology

3.1. Heat Transfer Model

Ignoring the stages prior to stamping, the die assembly in a closed position is considered in this study. This would allow, a pure CFD analysis to be carried out. The oversimplified model is shown in Fig. 6. Heat is released by the blank and transferred to die and cooling water by convection and conduction. The heat loss due radian and latent heat generated by the blank are ignored in this study. Q_b is the heat released by the blank, Q_d is the heat absorbed by the die block and Q_w is the heat dissipated to the cooling system. Conjugate heat transfer takes place between die and cooling channels.

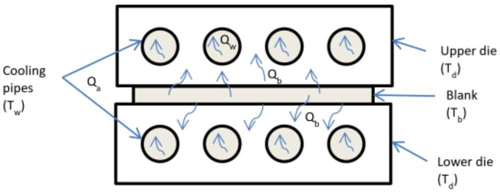

Fig. 6: Heat Transfer Model

3.2. CFD Simulation

In order to reduce the computing times, the die block, blank and cooling channels were volume meshed separately using element size of 0.05 m and 0.006 m respectively. Since there is no pressure involved, the HTC value used is 1300 W/m^2.K [6, 10] and other parameters such as material model and boundary conditions are given in Table1.

Table 1: Boundary condition

	Material	ρ kg/m^3	k W/mK	c J/kg^{2}K	h W/m^2.K	T, ^{o}K
Blank	Boron	7800	35	800	1300	900
Die	HTCS	7870	66	465	-	303
Coolant	Water	1000	0.598	4163	-	280

Spalart-Allmaras (SA) turbulence model was selected throughout this transient analysis due to its quicker computing time in conjunction with a commercial solver AcuSolve. The results of changes in the blank temperature distribution throughout the holding period of 8 seconds can be used to determine the performance of the cooling system. Temperatures of other components were also monitored at selected points. The same procedure was repeated for the validation part. Total computing time for each part is 5 days.

4. Result and Discussion

The blank temperature history from t = 0 to t = 8 seconds is shown in Fig.7.

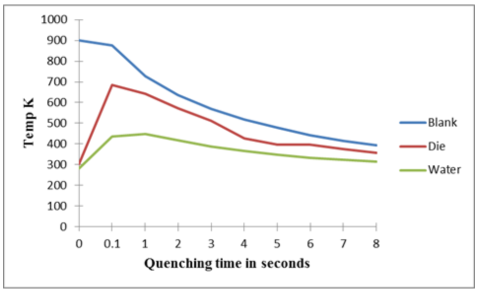

Fig. 7: Die, Blank and Water Temperature during Quenching of 8 seconds

It depicts rapid cooling of the stamped part from initial temperature of 900^{o}K. After 0.1 seconds the heat released by the blank causes the die and water temperatures to rise by 100^{o}K and 10^{o}K respectively. At the end of the holding cycle of 8 seconds average temperature of the blank is about 400^{o}K. This behaviour is shown in Fig.8.

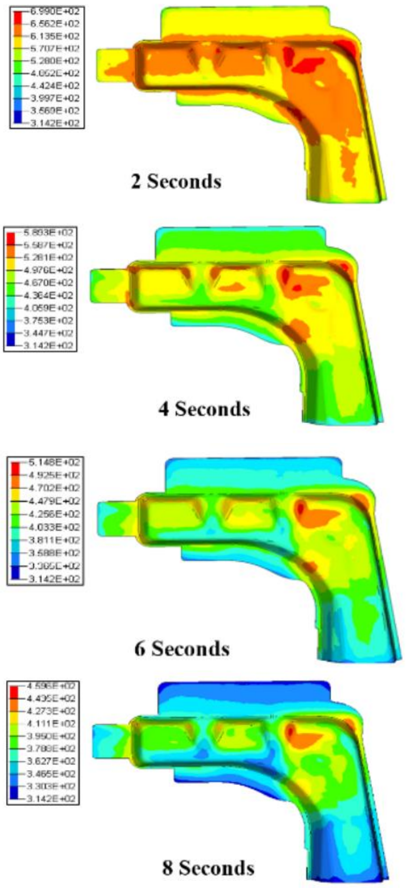

Fig. 8: Temperature History of Test Part in 8 seconds

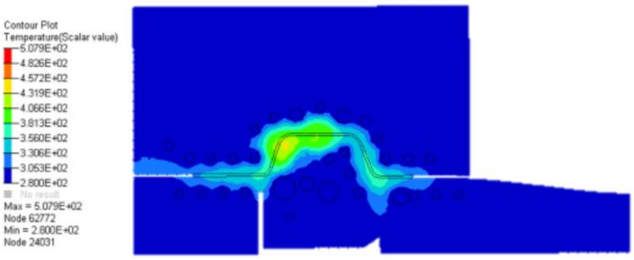

Fig. 9: Temperature Pattern at the Red Spot

Upon examination of the simulated part closely, it is evident the cooling is not uniformed. Some portions remain at high temperature of 450^{o}K and others at about 350^{o}K. The red spots show insufficient cooling at the areas. In fact, this non-uniformity is attributed to manufacturing constraint stated earlier. Fig.9 shows area of hot spot unreachable by the cooling channel. Temperature difference of the actual part is 108^{o}C compared to 100^{o}C obtained by this simulation. Maximum hardness of exceeding 40HRC is observed at the areas which cooled faster (points 1,2,3,6 and 9). However, the hardness reading for the red spots (points 4, 5, 7, 8, 10, 11, 12, 13 and 14) are lower than 40HRC.

Fig. 10 and Table2 gives detailed hardness distribution of the actual part. As expected the percentage of martensite formed at the areas surrounding points 1, 2, 3, 6 and 9 are higher hence giving higher hardness value. Despite having this variation, it is considered small and acceptable by the industry standard.

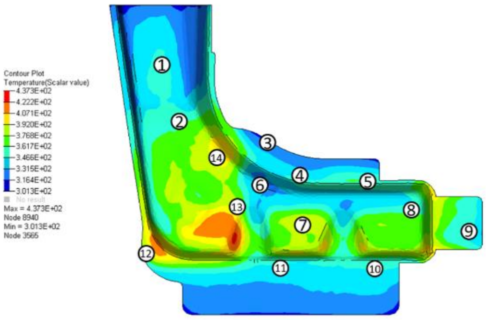

Fig. 10: Temperature and Hardness Distribution of the Test Part

Table 2: Hardness HRC

	Point	HRC	Point	HRC	Point	HRC
	1	47.5	6	49.5	11	38.3
	2	41.7	7	29.3	12	36.3
	3	49.7	8	37.6	13	36.3
	4	39.7	9	46.8	14	36.4
	5	36.6	10	37.3		

The hardness distribution of the validation part as shown in Fig. 11 can also be represented by the hardness distribution. Areas in the middle appear to cool faster than the edges. As a result, the middle portion is harder than the later. The maximum hardness recorded are at points 13 and 15 as shown in Table3. Incidentally, the cooling channels design for this part is simple straight and symmetrical, therefore uniform hardness distribution can be achieved. The edges are less important since they are to be trimmed out anyway.

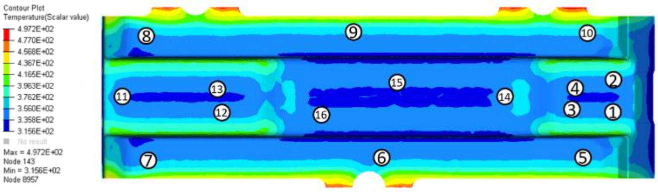

Fig. 11: Temperature and Hardness Distribution of the Validation Part

Table 3: Hardness HRC validation part

	Point	HRC	Point	HRC	Point	HRC	Point	HRC
	1	43.2	5	38.3	9	33.8	13	50.6
	2	38.5	6	36.0	10	36.7	14	38.1
	3	41.7	7	32.2	11	43.7	15	51.7
	4	46.3	8	34.2	12	40.4	16	42.3

5. Conclusion

It is obvious that thermal parameters play a very important role in determining the accuracy of the numerical experiment results. By considering thermal model only, it is verified that this technique is able to evaluate the efficiency of a cooling system. An optimum cooling system will result in uniformity of part temperature distribution during cooling. This in turn will determine uniform hardness distribution throughout the part. The simulated temperature pattern results of this CFD analysis are in a closed agreement with the actual hardness distribution data. This is applicable to both the test and validation parts. Despite limitation by the manufacturing constraint, the present cooling system design can still achieve an acceptable level heat transfer efficiency between the die and its cooling channels. This research attempted to demonstrate that the proposed methodology is able to evaluate the efficiency of complex cooling system. The next level of work could be to predict the hardness value based on the temperature distribution obtained by CFD analysis.

Acknowledgement

The authors would like to acknowledge the Ministry of Science and Innovation Malaysia (MOSTI) for funding this research. Thanks also to our industry partner MIYAZU Sdn. Bhd. for providing technical support.

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