Numerical Validation of an Optimized Cooling System for Hot Stamping Die

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Abstract. Numerical analysis of hot stamping process is very complex mainly due to thermo-mechanical processes involved. Many variables such as heat transfer coefficient, density, young modulus and other thermal parameters are temperature and pressure dependent. The paper presents results of CFD analysis on the near optimized cooling system of hot stamping die for automotive structural part. By using actual parameters obtained from the industry production line, this research is aimed at comparing the performance of actual cooling system with the results obtained by CFD simulation using commercial software. The die and blank were modelled as 3D volume mesh in a closed position thus ignoring blank history data prior to stamping operation. Temperature distribution representing hardness of the simulated final part is an agreement with the QA data of the actual part thus showing viability of this method to be used in cooling system design

1. Introduction

Hot stamping or press hardening is currently the most viable process to produce automotive structural parts with tailored properties. It has many advantages over its contemporary the conventional cold stamping. First, it's increased tensile strength up to 4 times than the material as delivered. Hot stamped part has also minimum spring-back. More importantly 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]

A typical hot stamping process starts with the blank heated at 950ºC for about 4-10 minutes inside a furnace. It is then placed on top of a die by a robot hand. Simultaneous forming and quenching take place immediately after this. The holding time is typically 10 seconds. When the die is open the part temperature is within few hundred degrees Celsius. Finally the excess material of the hardened part is trimmed by a CNC laser cutter.

Hot stamping is very complex as it involves combined thermo-mechanical and micro-structure evolution [2]. 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. 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. Due to manufacturing constraints, conformal cooling channel design may not be economical. Hence the straight hole type is more popular in practice. Hu et al[4]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. Chen et al [5] 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. It is found that that the parallel design is more efficient.

Finite element method has been successfully implemented in simulation of hot stamping of Boron and other quenchable steels. 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. This can only be achieved if the cooling channels are optimized. In an attempt to accurately simulate the heat transfer during the cooling process, the use of the correct heat transfer coefficient (HTC) has been proposed in the literature. It has been shown that HTC is dependent on contact pressure between the blank and die surface. However Zhang et al [6] defined this value as a function of time. The main objective of this paper is to illustrate a simple methodology based on CFD analysis for validating an optimized cooling system design by considering several critical thermal parameters obtained from a hot stamping line.

2. Methodology

A fairly complex cooling system of a hot stamping die shown in figure 1 is taken as a case study. Surface hardness distribution of the actual part shown in figure 2 was measured by a portable hardness tester.

2.1. *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. Heat is released by the blank and transferred to die and cooling water by convection and conduction. If the heat loss due radiation and latent heat generated by the blank are ignored then the steady state energy balance can be written as

$$Q_b = Q_d + Q_w \tag{1}$$

Where 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. To expand equation 1 further

$$h_bA(T_b-T_d) = k_dV(T_b-T_d) + h_wA(T_d-T_w) \tag{2}$$

where h_b and h_w are HTC for the blank-die and water , T are temperatures of blank , die and cooling water , A is the surface area and V is the die volume.

2.2. *Numerical simulation via CFD*

In order to reduce the computing times the die block, blank and cooling channels were volume meshed separately using element size of 0.05 and 0.006m respectively as shown in figure 1. Since there is no pressure involved, the HTC value used is 1300 W/m^{2}K and other parameters such as material model and boundary conditions are given in Table 1. AcuSolve solver was used to run the analysis. The results of changes 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.

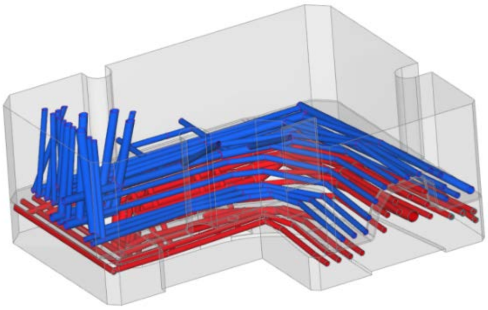

Figure 1. Cooling system

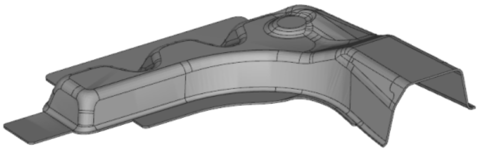

Figure 2. Final Stamped Part

Table 1. Mechanical, Thermal Properties and 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
Cool	water	1000	0.598	4163	3000	280

3. Results and Discussion

Temperature response after 0.1 and 8 seconds for major components is shown in figure 3 and figure 4. 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.

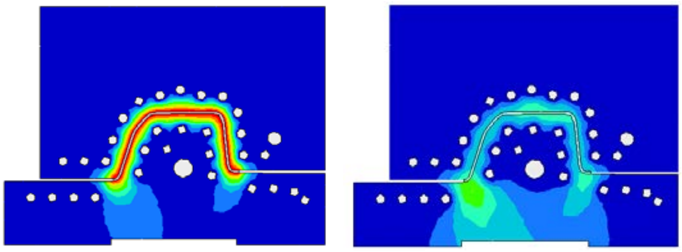

Figure 3. Blank Temperature after 0.1 and 8 seconds

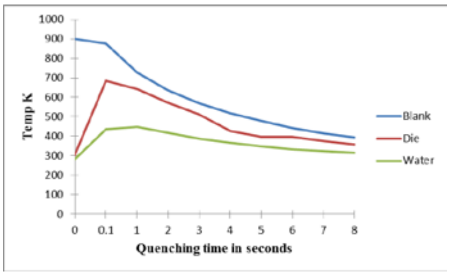

Figure 4. Temperature Response

Upon examination of the simulated part closely, it is evident the cooling is fairly 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 the manufacturing constraint stated earlier. Temperature variation of the actual part is 108^{o}C as compared to 100^{o}C obtained by this simulation. The best temperature distribution is at point 5 which records a maximum hardness of 45HRC. The hardness value for areas 2, 3 and 4 is slightly above 40 HRC. Detailed hardness distribution of the actual part is given in figure 4. It is inferred that the percentage of maternsite formed by the areas which cooled faster is higher than the later hence giving higher hardness value. Despite having this variation, its magnitude is considered small and acceptable by the industry standard.

No	Hardness (HRC)
1	43.5
2	40
3	40.3
4	40.8
5	45
6	44.5
7	45.6
8	42.6
9	41.9

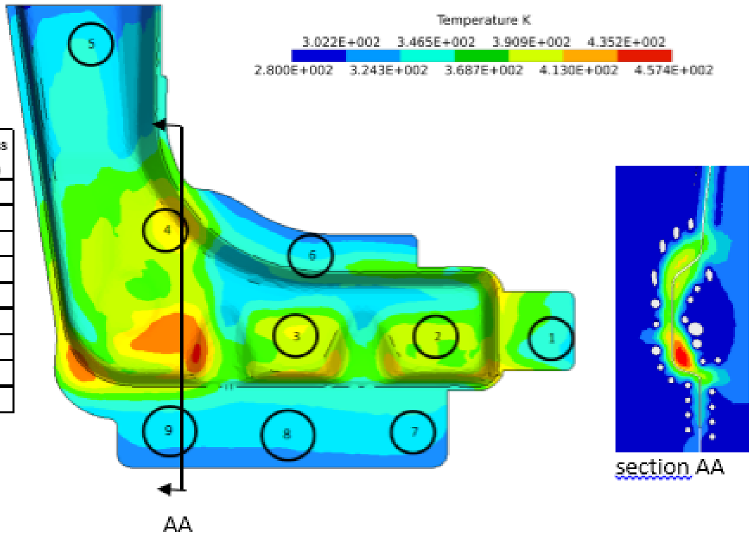

Figure 4 Temperature Pattern of Simulated Part. Cross sectional area shows insufficient cooling

4. Conclusion

It is obvious that thermal parameters play a very important role in determining the accuracy of the numerical experiment results. The simulated temperature pattern results of this CFD analysis are in a closed agreement with the actual data. In this research we have attempted to demonstrate that the proposed methodology is able to validate the actual optimized cooling system. This in turn can be used as a tool for cooling system optimization analysis.

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