Effect of cooling system in hot stamping process

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Abstract: Hot stamping process is used to produce automotive components that give a high strength-to-weight ratio, therefore it reduces fuel consumption and improves crashworthiness. Hot stamping is a non-isothermal process where forming and quenching takes place simultaneously. One of the major factors affecting the mechanical properties of components is the cooling rate which is controlled by the cooling systems. Direct cooling and indirect cooling (cooling channel) are the two cooling methods used in this process. In direct cooling, water is used as the cooling medium that gives higher cooling rate, however it induces large residual stress in the final component. In indirect cooling, cooling channels are used in die and punch for cooling purpose. In indirect cooling system residual stresses are not developed, but thinning occurs in wall region of the blank due to inhomogeneous contact between blank and die. Therefore, in this work, a new method has been proposed with the combination of direct and indirect cooling. In this combined cooling method, different coolant like spray water, air mist and compressed air was used for direct cooling. Simulation of the proposed approach was done by using PAMSTAMP software. The effect of the combined cooling system with various cooling medium was investigated and it was found that the air mist cooling with indirect cooling system resulted in 7% improvement in thickness distribution and 20% improvement in temperature distribution compared to the conventional method.

Keywords: - Combined cooling, Temperature gradient, Thickness distribution, Hot stamping

1. Introduction

Lightweight automotive vehicles release less CO₂ due to low fuel consumption but problem associated with lightweight component is less strength. Therefore to achieve high strength and crashworthiness, hot stamping process was developed [1]. Hot stamping is a non-isothermal process in which forming and quenching takes place simultaneously. 22MnB5 steel is used in the hot stamping process because a small quantity of boron addition can increase the hardenability of the material. This process is commonly used to produce components like B-Pillar, A-Pillar, Front bumper, Side rails, etc. Final mechanical properties and microstructure of the component in hot stamping process depends on various factors like deformation temperature, rate of deformation, cooling etc. Our main concern in this work is cooling system. Hot stamping process consist of two types of cooling system namely direct cooling and indirect cooling. In direct cooling, the cooling medium directly contacts with blank surface which increases the heat transfer and production rate. However in this method, due to high cooling rate, residual stress is induced in the blank. Hence, indirect cooling method is used conventionally, where inbuilt cooling channels in die and punch are used for cooling. Due to lower cooling rate in indirect cooling, inhomogeneous temperature distribution develops in the blank. Due to temperature gradient in the blank, excessive thinning occurred in the wall region. André et al [2] studied the gap behaviour between die and blank and found that the cooling rate reduced when gap thickness increased. Nakagawa et al [3] performed experiment in water submerged die to avoid local thinning but static water in the die cavity created a thermal shock as well as scale formation in the component. Ganapathy et al [4] rapidly pre-cooled the austenized blank in the transfer stage to acquire the minimum initial temperature for higher formability. However temperature control should be accurate in pre-cooling to avoid ferrite and pearlite formation. Maeno et al [5] used both indirect quenching and static water in a die cavity to achieve better formability and observed that the thickness distribution completely depends on the height of water in the die cavity. Eiichi et al [6], in their work air was impinged in the wall region of the blank to increase the flow stress. But air cooling did not give a significant improvement in thickness.
distribution. To reduce the temperature drop, Maeno et al [7] used a high speed mechanical servo press, but investment cost for servo press is too high. Suzuki et al [8] used specially designed transfer devices to clamp the blank in the wall region to reduce its temperature. However different arm holder needed for different shaped blank in this approach.

To overcome the above problem, combination of direct and indirect cooling (i.e. Combined cooling) was established. The principal objective of this proposed approach was to reduce the temperature gradient between the flange and wall region (Figure 1). Indirect cooling was implemented by cooling channel whereas spray nozzles were fixed in the desired position of the die wall for direct cooling. During stamping, direct cooling was done for few seconds to reduce the temperature in wall region of the blank. Different coolant like compressed air, air-mist and water spray were used in direct cooling. The simulation of the proposed method was carried out using PAMSTAMP software. The outcome of combined cooling with different cooling medium were investigated by thickness, hardness, and temperature distribution along the blank.

![Figure 1. (a) Conventional cooling (b) Combination of direct and indirect cooling](image)

2. Methodology

2.1 FE Simulation

The combined cooling method was simulated by FE simulation to study the temperature distribution and thinning behavior. The commercial FE code PAMSTAMP was used for thermo-mechanical simulation, which comprises different stages (Process cycle) like Transport, Holding, Stamping, Quenching and Cooling on air. Tools for the hat shaped part was designed in SolidWorks and imported to PAMSTAMP. Punch, die and blankholder were assigned as a rigid body. 10 mm² mesh size was used for the surface blank. To capture the effect of strain rate and tempeature, various experiments were performed in Gleeble to find the flow behaviour of boron alloyed steel (22MnB5). This flow behaviour of material is used for simulation. Blank holding force, coefficient of friction and other parameter values are given in table 1. Heat transfer coefficient is the most important parameter in the simulation for analysis of thermal behaviour. Except heat transfer coefficient to each combined cooling method, all other simulation parameters were kept identical in all simulation. For all simulations, direct cooling was assumed for one second.

| Table 1. Properties used for FE simulation |
|-------------------------------------------|
| Properties                         | Values               |
| Dimension of blank/ specimen       | 300*140*2.4 mm       |
| Blank-holding force                 | 150kN                |
| Tool temperature                    | 70 °C                |
| Coefficient of friction             | 0.4                  |
| Yield criteria                      | Hill 48              |
| Punch velocity                      | 10mm/s               |
| Time for austenization              | 3min                 |
| Transfer time                       | 5s                   |
| Stamping temperature                | 800 °C               |
| Quenching time                      | 15s                  |
| Cooling on air                      | 120s                 |
2.2 Heat Transfer Coefficient

The cooling behaviour of the stamped component is determined by the heat transfer coefficient. Heat transfer coefficient decides the temperature distribution that impacts the microstructure and mechanical property of the end product. Selection of proper heat transfer coefficient is essential for the simulation of heat transfer problems to get nearly precise results. Therefore, heat transfer coefficient calculation method for different methods is discussed below.

Indirect cooling heat transfer coefficient was calculated based on the energy balance method. The convection heat transfer coefficient was calculated by using Dittus-Boelter equation for the internal flow of water\[^9\]. Sudhanshu et al.\[^10\] suggested that cooling channel diameter and the water flow rate were 12 mm and 30 l/min respectively for better properties of end product therefore in this work dimension of cooling system were taken according to this analysis.

\[
\text{Nu}_D = \frac{h_c \cdot D}{k_f} = 0.023 \cdot \text{Re}_D^{0.8} \cdot \text{Pr}_f^{0.3}
\]  

---(1)

An array of round shaped nozzles were placed in the wall region to impinge the air. The heat transfer coefficient expression is based on the flow rate, diameter, and distance between the nozzles which were selected as 100m/s, 1.5mm, 3mm respectively\[^11\]. K and G are the dimensionless coefficients.

\[
\frac{\text{Nu}}{\text{Pr}_f^{0.42}} = 0.5K \cdot G \cdot \text{Re}^{2/3}
\]  

---(2)

Breitenbach et al.\[^12\] developed a theoretical model for water drop impact on film boiling regime and expression for heat transfer coefficient. Water flux, drop diameter, velocity and saturation temperature were selected as 3 l/m\(^2\), 350µm, 15m/s and 150°C respectively.

\[
\alpha_{ht} = 8.85C \cdot \left(\frac{mGe_w(T_0 - T_{sat})}{\rho_f \Delta T(K + 2G)d_0^{0.8}\cdot u_{w}^{0.5}\cdot \eta_{wet}}\right)
\]  

---(3)

Constantin et al.\[^13\] did the heat transfer experiment in a platinum strip from 1200°C with air mist cooling and obtained an expression. It mainly depends on water flux and velocity. The water flux, drop mean diameter and drop velocity were selected as 3 l/m\(^2\), 30µm and 10m/s respectively.

\[
h = 379.93w^{0.318}u_{w}^{0.330}T_{w}^{-0.895}d_{30}^{-0.024}
\]  

---(4)

Heat transfer coefficient of indirect cooling, air cooling, water spray cooling and air mist cooling were calculated by equation 1, 2, 3 and 4 respectively. Based on heat transfer coefficient(HTC) value, cooling rate was calculated for direct cooling. Reduction in initial temperature of the blank in wall region was calculated by using cooling rate and time.

3. Results & Discussion

3.1 Temperature distribution:

The simulation was done for each set of combined cooling and conventional cooling method. Half of the hat shaped component which is highlighted in figure 2a was selected for analysis due to symmetric nature. The initial temperature at the wall region of blank was decreased based on the heat transfer coefficient value of direct cooling. Temperature distribution of the stamped component after quenching for 2.5s is shown in figure 2b. High temperature gradient was observed in indirect cooling and it was compared with combined cooling method. Figure 2b clearly shows that the temperature gradient in air cooling is not significant due to less heat transfer. The water spray method resulted in 6% improvement when compared to air cooling. But overall air mist cooling provided 20% improvement in temperature distribution from the conventional method. Because, air disintegrates the water into small sized droplets which improves the heat flux by increasing the surface area.
3.2 Thickness distribution

Thinning was observed near the punch corner area in the conventional method. It was shown in figure 3 that air cooling with indirect cooling resulted in negligible amount of improvement in thickness distribution. But in case of air mist cooling with indirect cooling as shown in figure 3 that 7% improvement in thickness distribution that reduces the thinning problem and also indirectly increases the forming depth.

Figure 3. Comparision of thickness distribution from flange to center of the blank for indirect cooling with air cooling, water spray and air mist cooling.
Temperature and thickness distribution values obtained in table 2 are calculated using

\[
\text{Combined cooling} - \text{conventional cooling} \times 100
\]

which shows the improvement % in temperature and thickness of combined cooling.

**Table 2. Improved property percentage of combined cooling compared with conventional method**

| Types of cooling system                      | Temperature distribution | Thickness distribution |
|----------------------------------------------|--------------------------|------------------------|
| Air cooling with indirect cooling            | 3.25                     | 0.55                   |
| Water spray cooling with indirect cooling    | 9.37                     | 1.44                   |
| Air mist cooling with indirect cooling       | 19.54                    | 7.25                   |

**3.3 Hardness distribution**

No significant variation in hardness distribution was observed for different types of cooling system as shown in figure 4. This clearly indicates the uniform martensite formation at the end of varying cooling cycle.

![Figure 4](image)

**Figure 4.** Hardness distribution from flange to center of the component for different cooling systems

**4. Conclusion**

In this work, different types of cooling system were simulated under different cooling medium to reduce non-uniform thickness and temperature distribution. In combined cooling, three different cooling medium were compared to find out the medium that gives the best thickness and temperature distribution. Some of them are new approach to reduce the temperature gradient throughout the blank as seen in simulation. If it used in experiment, it will give better results. Conclusions from the above work is as follows:

- The temperature gradient in the blank was less in case of combined cooling as compared to the conventional cooling method.
- Air-mist cooling provides a 7% improvement in thickness distribution and 20% improvement in temperature distribution compared to conventional methods which is also higher than the other cooling medium.
- No significant changes were observed in hardness distribution for different cooling system.
**Nomenculture**

| Symbol | Description |
|--------|-------------|
| Nu     | Nusselt number |
| Pr     | Prandtl number |
| D      | Diameter of the nozzle |
| H      | Distance between the nozzle and blank |
| A_r    | Area covered by air |
| d_0    | Drop diameter |
| K,G    | dimensionless coefficient |
| α_h,t  | Heat transfer coefficient |
| α_C,G  | dimensionless coefficient |
| m      | mass flux density |
| e_w    | thermal effusivity of wall |
| T_0    | Initial wall temperature |
| T_sat  | Saturation temperature |
| w      | local water impact density (or flux)) |
| η_wet  | effective wetted ratio |
| T_w    | Surface temperature |
| d_30   | Volume mean diameter |
| u_z,v  | volume-weighted mean of velocity magnitude of z-velocity component |
| ρ_f    | Density of liquid |
| k_f    | Thermal conductivity |

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