Air jet impingement cooling for hot stamping dies

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Abstract
The strength of panel sheets can be increased by 2–3 times after hot stamping, and for high quality of hot stamped sheets, uniform cooling rate on the die face to quench the panel is needed. However, it is difficult for cooling water channels, commonly used for hot stamping dies, to dissipate heat evenly. In addition, dies are easily corroded by contact with water at high temperature. Thus, this study considers air cooling for the quenching process. The airflow can be applied to the sheet directly during the forming stage to cool and quench, eliminating difficulties with cooling channel design and providing more uniform cooling. Simulations and experiments were used to test the feasibility of air cooling for hot stamping with CSC-15B22 steel. A simple hot stamping tool with flat die face and either water or air cooling channels was used for testing, and results show that the both direct and indirect airflow can be used for hot stamping. With indirect air cooling, the cooling rate is sufficient for complete martensite transition, though the cooling rate is 40% lower than with indirect water cooling. To improve cooling efficiency of the air cooling system and obtain more uniform cooling, an air jet impingement cooling system (direct airflow cooling) was also tested. Results show that a similar cooling rate can be obtained in both indirect water cooling and the air jet impingement cooling. Thus, it is possible for air jet impingement cooling to provide hot stamping superior to water cooling. These results can be a reference for the design of new cooling systems for hot stamping dies.

Keywords Hot stamping · Cooling system · Air jet impingement · CSC-15B22

1 Introduction
The hot stamping process is widely used in the automotive industry, primarily due to its ability to increase the strength of steel sheets and thereby improve the crashworthiness of vehicles [1]. Increased formability of sheets due to the heating process is another benefit of hot stamping. Mori and Okuda [2] showed that heating the sheets reduces the forming load, prevents spring-back, and greatly improves formability. Hot stamping is a technique that combines the metal sheet forming process with the quenching process. Hot stamping produces parts with a fully martensitic microstructure and very high tensile strength and hardnes. Panel sheet strength can be increased by 2–3 times after hot stamping [3].

The quality of hot stamped panel sheets depends on the distribution of martensitic microstructure. To form high quality of martensitic structure steel, in addition to uniform heating, uniform cooling rate on the die face is critical. Lenze et al. [4] showed that cooling rates above 27 °C/s lead to the formation of a martensitic structure and lower cooling rates force the formation of a more ductile microstructure with lower strength, such as bainite or ferrite–pearlite. Due to the importance of cooling rate, many studies have focused on cooling system design for hot stamping dies. Lv et al. [5] proposed improvements to the cooling system for hot stamping dies calculating and optimizing the diameter of the cooling channels and the distance between consecutive channel centers by ABAQUS software. It was found that smaller diameter cooling channels provide better cooling. Lin et al. [6] studied a new multi-field simulation method for designing hot stamping tools with cooling systems, finding that both the distance between individual ducts and the distance between ducts and the tools loaded contour affected the quenching effect.

These and similar studies mainly focus on how die surface temperature affects the microstructural transformation
of materials, generally assuming that the cooling water channel dissipates heat evenly. However, in practice, the distance between the water channels and the distance between the water channel and the die face will directly affect heat dissipation. Furthermore, almost all related studies have used water cooling. However, dies are easily corroded by contact with water at high temperature, and curved water channels are limited by the manufacturing process. This may result in uneven cooling when there are substantial changes of die face. In particular, the geometry of automotive panel sheets using hot stamping is generally complex and more likely to cause material defects due to uneven cooling rates. Zhang et al. [7] analyzed the temperature distribution of the B pillar reinforcement blank, finding that the temperature in the holding area of the blank decreases quickly, whereas the sidewall and bottom cool slowly. This inhomogeneous temperature distribution of the blank will cause uneven material flow during the forming process.

In addition to water cooling, air cooling is another option [8]. For the hot stamping process, unlike the water-cooled design, air cooling heat transfer can pass through the die face, and leakage is allowed. Airflow can be blown on the sheet directly during the forming stage to cool and quench. Therefore, if the flow is used for cooling, the cooling channel design can be more flexible and more uniform cooling can be achieved [9]. Narayanasamy et al. [10] used both direct and indirect cooling to evaluate the effect on the hot stamped panel, showing that direct air cooling is applicable to hot stamping. Tian et al. [11] used air cooling tool design for treating hot aluminum blanks, finding that nozzle field air cooling is an excellent air cooling method for hot stamping. Though some studies have considered air cooling in the hot stamping process, there is a lack of systematic research. In the current study, simulations and experiments with CSC-15B22 steel were used to test feasibility of air cooling for the hot stamping process.

## 2 Research methods

### 2.1 Material properties

The sheet material used was CSC-15B22, as manufactured by the China Steel Corporation, which is a boron steel developed specifically for hot stamping processes. The chemical composition of CSC-15B22 is shown in Table 1 [12]. The material has ferrite and pearlite structures at room temperature and its tensile strength is 600 MPa. An austenite structure is formed when the material is heated to 850 to 900 °C and its ductility increases. The cooling rate for the quenching process is 30 °C/s so that the microstructure changes from austenite to martensite. The continuous cooling transformation (CCT) curves for hot stamped CSC-15B22 are shown in Fig. 1 [13].

### 2.2 Numerical study

Finite element analysis allows the study of the heat transfer phenomenon of a metal sheet and stamping die. The finite element software Fluent is used in this research. The simulation model includes hot stamping die, metal sheet, and cooling channel. To facilitate the experiment and comparison, the die is designed as a simple flat rectangle with a length, width, and height of 300 mm x 200 mm x 50 mm. The effect of heat transfer on the quenching process was also considered. A diagram of the simulation model is shown in Fig. 2, using both the tetrahedral and hexagonal mesh. The boundary condition between cooling channel and die was set as Assembly Meshing Contacts to conduct the heat transfer. The K-epsilon (k-ε) turbulence model was used to simulate flow characteristics. The material parameters of test sheet and die are shown in Table 2. The sheet material used was CSC-15B22. The initial sheet temperature of simulation was set as 750 °C. The specific heat is 800 J/kg K and the thermal conductivity coefficient is around 45 W/m K. The die material used was SKD61 steel. The initial die temperature of simulation was set as 27 °C. The specific heat capacity is 460 J/kg K and the thermal conductivity coefficient is approximately 24.6 W/m K. For the cooling fluid, the simulation properties of air and water are shown in Table 3. For air, the input temperature is 27 °C, the inlet velocity is 47 m/s, and the turbulence intensity is 4.4%. For water, the input temperature is 27 °C, the inlet velocity is 8 m/s, and the turbulence intensity is 3.9%.

| Element | C  | Si  | Mn  | P    | S    | B    |
|---------|----|-----|-----|------|------|------|
| Composition (wt%) | 0.19~0.25 | 0.15~0.25 | 1.05~1.35 | <0.02 | <0.01 | <0.003 |

![Fig. 1 Continuous cooling transformation (CCT) curves for hot stamped CSC-15B22 [13]](image-url)
The mesh convergence analysis shown in Fig. 3 was used to decide the number of elements. Results shows that the temperature variation of a specific measured point was stable after the number of elements reached 570,000. Therefore, the number of elements of 570,000 was selected to balance the simulation accuracy and the computational time.

The cooling channel diameter is 10 mm. The distance between the cooling water channel and the die surface is designed to be 1.5 times the diameter, and the distance between the channels is designed to be 4 times the diameter. To determine the direct air jet impingement effect on the test sheet, a series of tiny holes, 1 mm in diameter and 10-mm spacing between holes, were drilled from the die surface to the cooling channel. The standard hot stamping simulation process for this study used a 30-s cycle, which included 10 s for die opening and sheet location and 20 s for die closing and quenching.

2.3 Experimental method

Based on the design of the simulation model, an experimental apparatus for air jet impingement cooling was developed, as shown in Fig. 4. The cooling air was produced by an air compressor. The airflow rate was measured by a float airflow meter with the measured range between 20 and 30 LPM. The cooling water was recycled using an air-cooled chiller. The cooling water maintained a temperature of 27 °C and the water flow velocity was set at 8 m/s. The sheet was first heated in a muffle furnace to 900 °C, and the die temperature was recorded using a BTM-4208 thermometer and AVIO G100EXD thermal camera. The SHIMADZU HMV2 microhardness tester and CCD camera were used for measuring the Vickers microhardness of specimens. The measuring load and duration time were set at 1.96 N and 15 s, respectively, in this research. An OLYMPUS-STM6 microscope with digital imaging system was used for microstructure observation.

3 Results and discussion

3.1 Air jet impingement test

A simple direct air jet impingement test was studied first to evaluate the feasibility of using air cooling for hot stamping. An air blower gun was used to determine the direct air jet impingement cooling effect on the heated sheet.
A CSC-15B22 steel sheet 100 × 20 × 1.5 mm was heated to 900 °C in a furnace, and then, air was blown on the sheet surface with flow velocity of 103 m/s (240 LPM) for 10 s. The experimental is shown in Fig. 5 and temperature variation in Fig. 6. The initial temperature was only slightly less than 700 °C, because the test sheet had started to cool after the sheet had moved from the furnace to the work platform. In the first second of air impingement cooling, the temperature dropped more than 200 °C. After 10 s of air impingement cooling, the temperature had decreased to 57 °C. The cooling rate was much more than 27 °C/s, which is greater than that which...
is required for change to the martensite phase. The average hardness was HV 480 or tensile strength of 1555 MPa [14]. These results show that the air jet impingement cooling can be used in the hot stamping process. To realize the in-die cooling design, the next stage was design of the air nozzles.

3.2 Indirect cooling with cooling channel

This section describes the indirect air cooling channel and direct air nozzle developed for further study according to the cooling channel design parameters from Yu-Chi [15], using both simulation and experimental methods. In the first stage, the test sheet is cooled indirectly with a die that is cooling only with a cooling channel inside the die, without an air nozzle. Figure 7 shows the temperature variation of test sheet at the central area of test sheet. The timing began after the test sheet was put on the die. The initial state for the simulation assumes the die is already closed, so the data starts at the third second. In the first 10 s, the temperature decreases from 750 to 395 °C with the experimental case, for a cooling rate can of 35.5 °C/s. For the simulation data, the temperature drops more than 500 °C in 10 s. Both cases show that the cooling rate is more than 27 °C/s, which is that required for the martensite transition. However, there is a clear difference in cooling rate between the experiment and simulation. The temperature decreased smoothly in the experiment, whereas it dropped very quickly in the first few seconds in the simulation. This is because in the simulation the sheet is in perfect contact with both upper and bottom die faces, resulting in perfect cooling. In contrast, these conditions cannot be achieved in the experiment.
Temperature variation of die during the hot stamping process is an influential factor, and Fig. 8 shows temperature variation of die during the hot stamping. The initial die temperature is 27 °C for both simulation and experiment. The temperature increases to the highest at the 4th second and then decreases gradually. However, the simulated temperature is higher than the experimental temperature throughout the process. The highest temperature in the simulation is 22 °C higher than the experimental temperature. Even in the cooling stage, there is around 30 to 40 °C difference between the experimental and simulated temperatures. Moreover, the simulated temperature variation is also more smooth, which is because the idea conditions used for the simulation neglect do not consider heat loss during process. However, results show that the temperature variation trends for simulation and experiment are similar.

To determine the die temperature after multiple hot stamping cycles using an air cooling system, temperature variation in the die over 5 stamping cycles was measured using experimental method. Figure 9 shows that the maximum die temperature reaches a stable state gradually after the 4th cycle, and the temperature can drop below 60 °C after each cycle. This result shows that the indirect air cooling system can maintain the die temperature within a specific range. However, the cooling efficiency is slightly lower than with indirect water cooling.

Figure 10 compares temperature change of die and test sheet using indirect water cooling and using air cooling. The left coordinate axis shows the sheet, with die temperature on the right coordinate axis. The die and sheet temperature using water cooling are significantly lower than those using air cooling. The measurement point is at T1, where it is the center of die face, as shown in Fig. 4. Taking the die temperature as an example, the air-cooled die reaches the highest temperature of 143 °C in the 4th second. At this time, the water-cooled die temperature is only 83 °C, and the water-cooled die reaches the highest temperature of 98 °C in the 8th second, but after the 10th second, both water cooled or air-cooled dies have little difference in temperature. This can be attributed to the thermal conductivity of water being more than 20 times higher than air, so when the hot sheet first touches the die, the water removes the heat rapidly. After few seconds, the temperature of die and sheet have cooled gradually and the temperature difference between two methods is smaller because temperature difference is the driving force for heat transfer, so the amount of heat transferred is directly proportional to the temperature change.

3.3 Direct cooling with air jet impingement cooling system

These results show that the cooling rate of indirect air cooling method is high enough to form martensite after hot stamping, though the cooling efficiency is lower than water cooling. Die temperature may increase after long operation time, which may result in insufficient cooling rate for indirect air cooling. Thus, to improve the cooling efficiency of air cooling system and obtain more uniform cooling, an air jet impingement cooling system is designed for the hot stamping die.

The die for direct air jet impingement cooling is designed as follows: a series of 1 mm orifices at 10-mm spacing between orifices are drilled from the die surface to the cooling channel. To reduce development cost of the test die, the test die has orifices above only one of the cooling channels of the original die, as shown in Figs. 2 and 4. When the hot stamping process is in progress, direct and indirect air cooling are carried out simultaneously. Air outlet velocity from
orifices was set as 4.2 m/s and 6.3 m/s to examine cooling rate of the test sheet.

To understand the influence width of the air impingement flow, simulation analysis was first performed. In the actual conditions, the sheet and die are not in close contact, so the test sheet is set as 0.1 mm away from the die face for the simulation model. Figure 11 shows die temperature distribution after 15-s cooling. Since air orifices are drilled above only one of the cooling channels, only the lower half of the die is significantly cooled. Figure 12 shows the test sheet temperature distribution after 15-s cooling, and only the test sheet near the orifices is obviously cooled rapidly. For air velocity of 4.2 m/s, the average influence width is 19.8 mm or 19.8 times larger than the orifice diameter. With air velocity of 6.3 m/s, the average influence width is 23 mm which is 23 time larger than the diameter of orifice, indicating that the influence width increases with increased air velocity. The average influence width for air velocity of 6.3 m/s is around 15% higher than that the air velocity of 4.2 m/s.

Figure 13 shows the temperature changes of die and test sheet using direct air cooling. The measurement point is at T3, between two air orifices, as shown in Fig. 4. Results show that the cooling rate increases with increased air velocity. For the sheet temperature, the average cooling rate decreases by 20.9% from air velocity of 6.3 to 4.2 m/s. For the die temperature, the average cooling rate decreases by 17.6% for those two air velocities. Detailed temperature change of the test sheet shows that the temperature drops...
significantly in the first second, and the cooling rate can reach 200 °C/s with the air velocity of 4.2 m/s. The temperature then drops slowly and the cooling rate is reduced to 12.3 °C/s until the 4th second. The temperature then drops again, and the cooling rate increases to 62 °C/s. After the temperature drops to around 200 °C, the cooling rate is slightly reduced. Based on the CCT curve diagram shown in Fig. 1, the sheet can be completely undergo martensite transformation. Figure 14 shows the microstructure of the sheet after direct cooling with air jet impingement at air velocity of 4.2 m/s. The microstructure shows packets of parallel lath crystals and needle-like patterns suggesting martensite within the smaller grains of material.

The overall temperature variation generally presents a step-by-step decrease, which may be because when the sheet is just moved into the die, the airflow is directly impinging on the sheet. The high-pressure and low-temperature airflow jet causes the temperature of the sheet to drop rapidly, and
then, the die is moved to the bottom center and the sheet partly blocks the air orifices, reducing the cooling rate. Then, heat transfer through the die again increases the cooling rate. For the change in die temperature, the die cooling is mainly though heat transfer from the air cooling channel, so the temperature change is similar to the indirect cooling method.

Figure 15 shows temperature variations of the test sheet using 4 different cooling methods, indicating that cooling with indirect air cooling has the slowest cooling rate. The average cooling rate is 27% lower than indirect water cooling. However, direct cooling with air jet impingement cooling in both air velocity has higher cooling rate than indirect water cooling. Table 4 shows hardness of the test sheet after hot stamping process using 4 different cooling methods. The hardness of original 15B22 steel is about 170 Hv. After hot stamping, the hardness value corresponds to the cooling rate. Since indirect air cooling has the lowest cooling rate, the average hardness is only 273 Hv. However, the hardness is 100 Hv higher than the original 15B22 steel, indicating that the hot stamping process is effective. To see the indirect water cooling, the average hardness is 392 Hv similar to that with air velocity of 4.2 m/s for direct air cooling. A very clear hot stamping effect was observed. Moreover, the material hardness continues to increase with higher direct air velocity. With air velocity of 6.3 m/s, the average hardness can reach 420 Hv. These results show that using air jet impingement cooling can achieve the same or better hot stamping effect as water cooling.

**Table 4** Hardness of test sheet after hot stamping process using 4 different cooling methods

| Cooling method      | Hardness (Hv) | Tensile strength (MPa) |
|---------------------|---------------|------------------------|
| Indirect water cooling | 392           | 1255                   |
| Indirect air cooling  | 273           | 865                    |
| Direct air 4.2 m/s  | 388           | 1250                   |
| Direct air 6.3 m/s  | 420           | 1350                   |

Figure 14 Microstructure of the sheet after direct cooling with air jet impingement cooling system in the case of air velocity of 4.2 m/s

**Fig. 14** Microstructure of the sheet after direct cooling with air jet impingement cooling system in the case of air velocity of 4.2 m/s

**Fig. 15** Temperature change of test sheet using 4 different cooling methods

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4 Conclusions

Simulations and experiments were used to test the feasibility of air cooling for hot stamping. A simple flat hot stamping die model for cooling analysis and an experimental apparatus for air jet impingement cooling were developed. The comparison of water cooling and air cooling was analyzed. Indirect water and air cooling, as well as direct air jet impingement cooling, were set as parameters for discussion. A simple direct air jet impingement method was tested initially and preliminary findings confirmed that air jet impingement cooling can be used for the hot stamping process. The cooling rate can reach 27 °C/s, which is sufficient for the martensite transition. Simulation results are similar to experimental results, though the ideal assumptions for the simulation yielded faster cooling than the experimental results. Efficiency of indirect air cooling is 27% lower than water cooling, and with indirect air cooling, hardness of the hot stamped sheet is 100 HV higher than that of the original 15B22 steel. However, due to the lower cooling efficiency, die temperature may increase after longer operation, which may result in insufficient cooling rate with indirect air cooling. Using direct cooling with air jet impingement, a clear hot stamping effect was observed, and the cooling rate is even better than indirect water cooling. The hardness increased from 170 HV to around 390 HV after hot stamping process in with direct air jet impingement, similar to that with indirect water cooling. The microstructure photo indicates that martensite transition of the sheet is complete. In sum, air jet impingement cooling can provide the same hot stamping effect as water cooling. It is possible that the best and most uniform cooling effect would be obtained by combining the two cooling methods.

Author contribution All authors contributed to the study conception and design. Also, the material preparation, data collection, and experimental were performed by all authors together. The first draft of the manuscript was written by Li-Wei Chen and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

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