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Procedia Manufacturing 00 (2018) 000–000

Procedia MANUFACTURING

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17th International Conference on Metal Forming, Metal Forming 2018, 16-19 September 2018, Toyohashi, Japan

Numerical study on nozzle-field cooling of heated aluminium blanks for hot-stamping

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Abstract

Nozzle-field cooling is a popular cooling technology which uses a flexible array of low-pressure gas jets to quickly cool down components in a device working in conventional atmosphere. This cooling process is energy saving, free of toxic gases, and it can reduce workpiece distortion during cooling. In this study, nozzle-field cooling is adopted for a potential, fast cooling process for large metal blanks. Numerical simulations were conducted to investigate the performance of a designed cooling tool with different design parameters. In this paper, simulation results are presented, along with several considerations for the nozzle-field cooling system design.

Peer-review under responsibility of the scientific committee of the 17th International Conference on Metal Forming.

Keywords: Air cooling; Hot stamping; Coupled CFD – Thermal simulation; Aluminium alloys; Parametric simulation

1. Introduction

During the last decades, demands for the use of aluminium alloys in automotive and aerospace industries increase dramatically. This is largely because aluminium alloys usually exhibit low density and high yield strength, which makes this family of the material a promising alternative for other structural materials. However, aluminium alloys with high yield strength usually have lower formability, particularly at cold forming condition [1–3]. In order to address the poor formability of aluminium alloys and the problems of spring back and wrinkling of components after forming due to lower Young's modulus, several forming techniques, like warm forming [4–6], hot forming [4], [5],

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2351-9789
Peer-review under responsibility of the scientific committee of the 17th International Conference on Metal Forming.

and isothermal superplastic forming [7], [8], have been studied and developed for forming of aluminium alloys. Also, several investigations were conducted, focusing on the effect of cooling rate during the forming [1], [9]. Fast cooling is essential for obtaining optimal microstructure and appropriate mechanical properties for the forming of Aluminium alloys. It has been reported that an aluminium blank which is fast-cooled from solution heat treatment temperature to a designated forming temperature could maintain desired formability before the hot stamping [10].

As a pre-treatment for hot stamping, fast cooling of aluminium alloy is required to be controllable and repeatable. Nozzle-field air cooling is one of the most appropriate cooling processes for preparing the heated aluminium blank. Not like liquid cooling or mixed media cooling which could contaminate the surface of workpiece, affect the performance of lubricant for hot stamping, and even corrode the stamping die, air cooling leaves no residues on aluminium blank in the cooling process [11]. Another important merit of air cooling over other cooling processes is that the coolant will not exhibit phase change during cooling process [11]. In this case, heat is transferred more homogeneously and thermal distortion is reduced. Nozzle-field cooling process is one of the most popular gas cooling technologies which uses a flexible array of low-pressure gas-jets to quickly cool down components in a device working in conventional atmosphere [11]. Various investigations have been conducted to study the effects of different design parameters (nozzle diameter, pitch, nozzle-to-component distance etc.) on the cooling characteristics of the system (cooling rate, temperature uniformity) [12–14]. Brief guidelines and recommendations for the system design are concluded by Ferrari et al. [14] and Liščić et al. [11]. However, most of these studies focusing on air field cooling of small workpiece, which does not require high air volume.

This paper presents the numerical study of a nozzle-field air cooling process and air cooling tool design for preparing heated aluminium blank. In next section, models for the numerical studies will be firstly described. Then, the results of simulations will be presented. These include temperature distribution obtained from the simulations for different design and operational parameters on a single cooling unit and the result from a proposed cooling system for aluminium blanks of the size 270 mm × 170 mm × 3 mm. Finally, considerations will be given for the design of the air cooling system and the cooling process for aluminium blanks, metal sheets, in general, based on the numerical studies carried out.

Nomenclature

D	diameter of the holes for ejecting cool air
H	distance from nozzle plate to the blank
P	distance between adjacent nozzles/exhaust channels
v	velocity of air exiting nozzles

2. Numerical Model

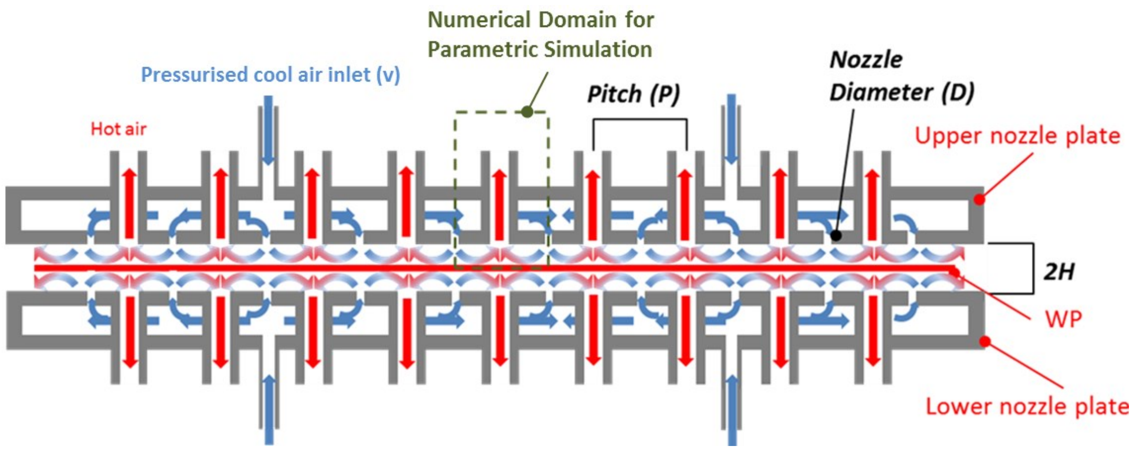


Fig. 1. Schematic drawing of a nozzle-field air cooling tool.

Numerical simulations were conducted by using commercial CFD software ANSYS Fluent to study nozzle-field air cooling of heated aluminium blanks for hot-stamping applications. Aluminium blanks of the size 270 mm × 170 mm × 3 mm were chilled from solution heat treatment temperature to a designated hot stamping temperature in a short time. Parametric simulation was conducted in order to study the cooling rate and temperature uniformity on the blank affected by the design of the nozzle array and operational conditions. Fig. 1. shows the schematic drawing of the cooling tool used in this study.

Table 1. Ranges of design and operational parameters for the parametric simulation.

Design Parameter	Range	Definition
Air Velocity (m/s)	60 - 110	v is the velocity of air exiting nozzles on the nozzle plates
Pitch (m)	0.032 - 0.05	P is the distance between adjacent nozzles / vents
Nozzle Diameter(m)	0.004 - 0.025	D is the diameter of holes for ejecting cool air
Distance from Nozzle to Workpiece (m)	0.024 – 0.032	H is the distance from nozzle plate to the blank

The cooling tool mainly consists of two parts, namely upper nozzle plate and lower nozzle plate. On each of these nozzle plates, the compressed cool air is supplied through the pressurized cool air inlet. The high velocity air separates and distributes in the chamber inside the nozzle plate. Cool air with high velocity and low pressure then flows out from the plates through the nozzle array. Finally, the cool air contacts with the surface of the heat blank, takes the heat away from the blank, and escapes from the system through either the exhaust channel sits between every two adjacent nozzles or the edge of the system. Pitch (P), representing the distance between every two nozzles (or exhaust channel), nozzle diameter (D), and the distance between the upper and lower plates (2H) are the key dimensions for the nozzle plate design. Initial design values for these dimensions were generated based on empirical guidelines suggested by Liščić et al. [11]. They were 50 mm for the pitch, 6 mm for the nozzle diameter, 9 mm for the diameter of the escape channel, and 87 mm for the distance between the two nozzle plates. Besides the design of nozzle plate, velocity of air flow also plays an important role in deciding the cooling performance of the system. Initial value used in the coupled thermal – CFD simulation was selected to be 100 m/s. A parametric simulation was conducted to study the cooling rate and temperature distribution on the blank affected by different design parameters and input air velocities. Table 1 lists the ranges of different parameters studied in this parametric simulation.

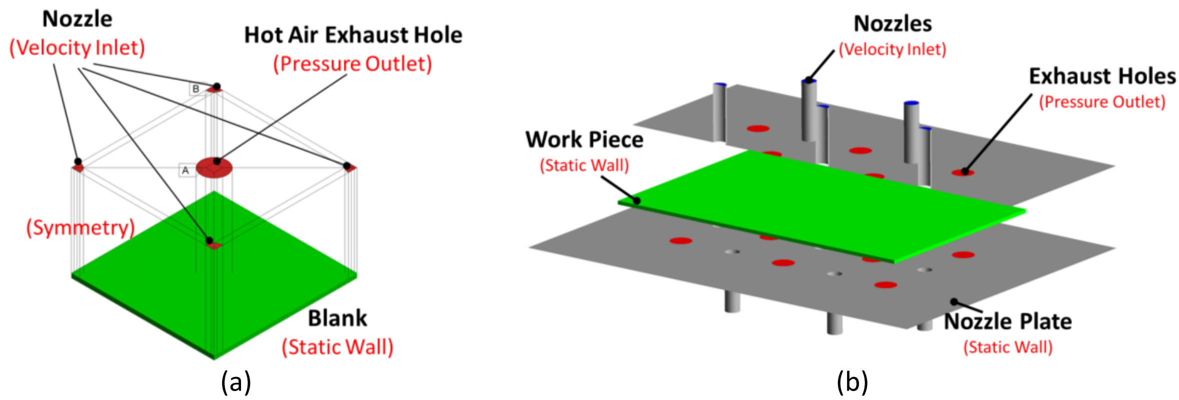


Fig. 2. (a) Geometry used for parametric simulation and (b) geometry used for the numerical study of nozzle field cooling of aluminium blank.

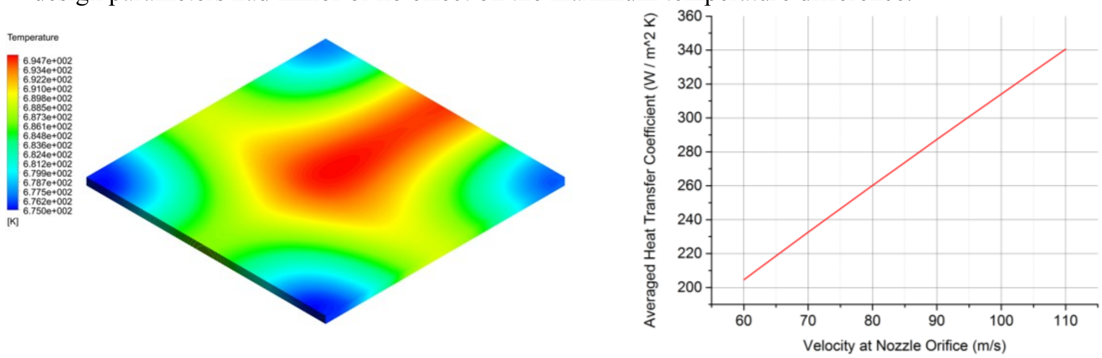
Transient simulations were adopted for all numerical calculations conducted in this study. Realizable k – epsilon model with Scalable Wall Functions was used to capture the movement of turbulent flow. Air flow was treated as incompressible because the maximum air velocity was far less than the speed of sound. Temperature of air changed from 26 °C when it entered the system to an exit temperature which was about 100 °C. Increase of temperature caused the increases of thermal conductivity and viscosity. However, according to temperature – dependent material properties, the thermal conductivity and viscosity were increase by small amount (which were from 2.624 × 10 ^ -2

W/mK to 3.186 × 10 ^ -2 W/mK for thermal conductivity and from 1.846 × 10 ^ -5 kg/ms to 2.181 × 10 ^ -5 kg/ms for viscosity), so these two properties of air were considered constant in all the simulations. Gravitational acceleration was assigned as perpendicular to the largest flat surface of work piece. In order to shorten the period of calculation cycle and also considering the highly patterned distribution of nozzles and exhaust holes, the numerical model was simplified. Fig. 2. (a) presents the geometry used for the parametric simulation. A hot air exhaust hole sits in the centre of the numerical domain and four one-quarter nozzles locate at four corners. The model represents a single cooling unit in the whole gas cooling system, which is indicated as numerical domain for parametric simulation in Fig. 1., so the side walls and the bottom of the model were set as symmetric boundaries. The blank had an initial temperature of 500 °C and the maximum, minimum, and averaged temperatures on the blank after 3 seconds of cooling were recorded. After studying the effect of design parameters on aluminium blank cooling, a simulation for the whole cooling system was conducted to investigate temperature distribution developed on the blank, which took the free air flow at the edge of the system into consideration. In this simulation, the blank also had an initial temperature of 500 °C. Fig. 2. (b) shows the geometry used for the simulation of the whole system. The size of the blank was set to be 270 mm × 170 mm × 3 mm. There were 7 nozzles and 8 exhaust holes on each of the nozzle plate. Edges of the blank were contacting with free air.

3. Results and Discussion

Fig. 3. (a) shows the temperature distribution on a 50 mm × 50 mm area of the aluminium blank after 3 seconds of air cooling. The blank was cooled by air cooling system with nozzles of 6 mm diameter. Averaged temperature on the blank was cooled down to about 414 °C from 500 °C. Highest and lowest temperatures on the blank after cooling were 402 °C and 422 °C respectively. Same numerical set-up was also applied to other simulations of different design parameters. Fig. 3. (b) presents the linear relationship between applied air velocity and the averaged heat transfer coefficient. Heat transfer coefficient between air and workpiece changed from 205 W/m^2K to 341 W/m^2K when air velocity increased from 60 m/s to 110 m/s. Results of maximum, minimum and averaged temperatures on the blank were collected and plotted in Fig. 4. Some observations have been made according to the parametric simulations:

- Diameter of nozzles (Fig. 4. (a)) and the velocity of the air stream (Fig. 4. (d)) had positive effects on the total temperature drop on the workpiece in 3 seconds. While the effect of pitch (Fig. 4. (b)) on the temperature drop was negative. Changing the nozzle to the workpiece distance (Fig. 4. (c)) did not show significant effect on the cooling process.
- Considering the required air flow rate of the system, when the nozzle diameter (Fig. 4. (a)) or the air velocity (Fig. 4. (d)) was increased or the distance between adjacent nozzles (pitch) (Fig. 4. (b)) was decreased and other parameters were kept constant, the resulting air flow rate increased as a result. Volume of air used for the cooling process had a closed relationship with the cooling rate on the blank.
- Temperature uniformity on the workpiece was greatly affected by the nozzle diameter (Fig. 4. (a)). Other design parameters had minor or no effect on the maximum temperature difference.



(a) (b)

Fig. 3. (a) Temperature distribution on the blank. (b) Relationship between air velocity and heat transfer coefficient.

Results from the initial parametric simulation show the significant effects of designed nozzle diameter, pitch, and air velocity on the cooling performance of the device. However, changing the value of these design parameters will also dramatically influence the total amount of consumed air, which naturally has a positive effect on convective cooling. Air flow rate required by the cooling system can be approximated by Eq (1) which is correlated to nozzle diameter, gas velocity, and pitch. In order to investigate the effect of design parameters and exclude the influence from flow rate, a second parametric simulation was carried out to change the values of two design dimensions together and tried to keep the flow rate constant. The results are presented in Fig. 5. and conclusion can be drawn as follow:

- Increasing the nozzle diameter and pitch at the same time to keep the air velocity constant led to a slight decrease of averaged temperature drop on the workpiece. And the temperature uniformity across the workpiece was adversely affected.
- Reduction on air-cooling efficiency was observed when the nozzle diameter was increase and the air velocity was decreased.

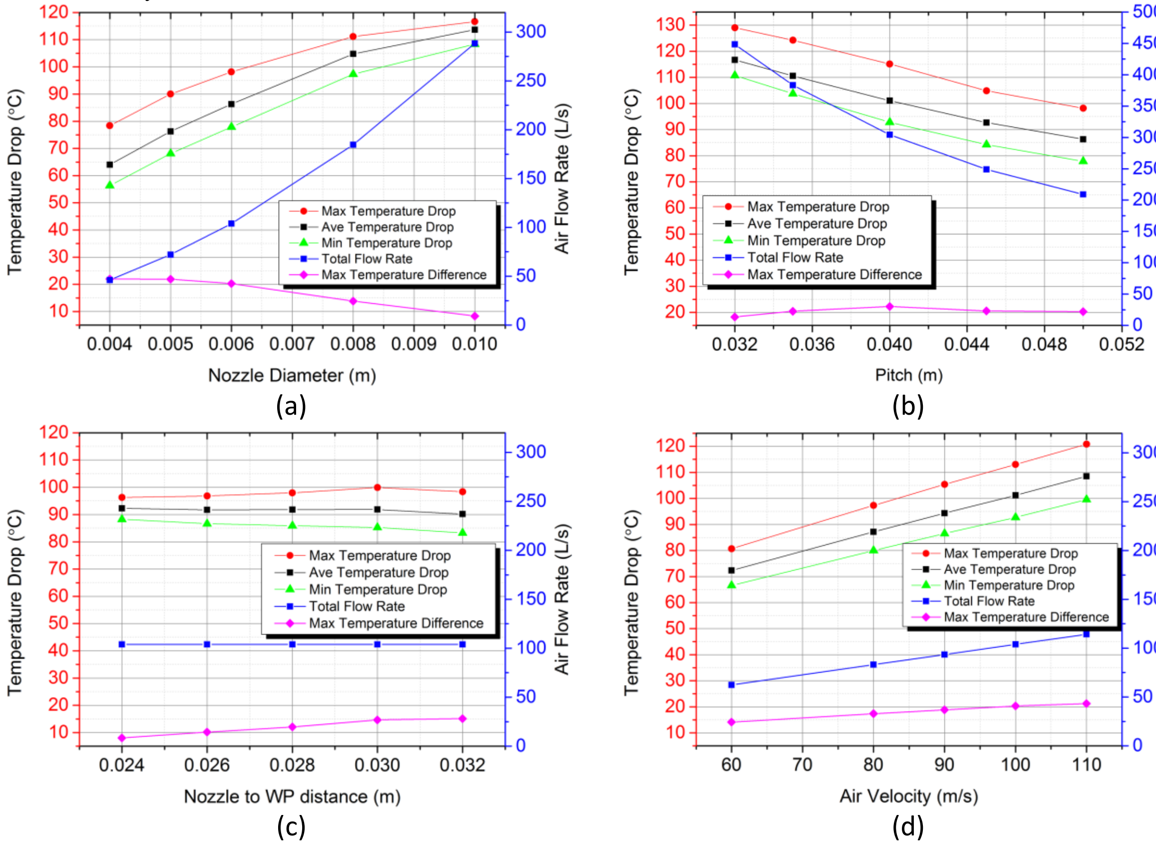
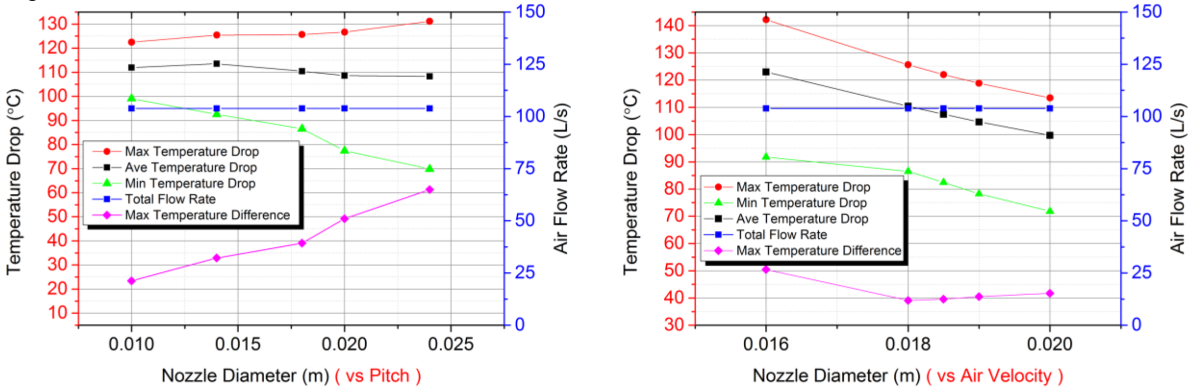


Fig. 4. Results of parametric simulations for different design parameters.

$$\text{Flow Rate} \approx \pi \times \left(\frac{D}{2}\right)^2 \times v \times \left[\frac{0.27m \times 0.17m}{(P)^2}\right] \tag{1}$$

After the parametric study was analysed, the initial diameter of the nozzle was selected as 0.012 m with a nozzle-to-nozzle distance of 0.05 m for the numerical study of air cooling for aluminium blank of 270 mm ×170 mm ×3 mm. Fig. 6. shows the temperature distribution on the workpiece after a three-second cooling. The blank had an initial temperature of 773.15 °K (500 °C) before the cooling process started. Compressed air of 108325 Pa absolute pressure (7000 Pa gauge pressure) was forced to flow through the nozzles. After 3 seconds of cooling, the temperature on the workpiece ranged from about 658.5 °K (385.35 °C) to 703.1 °K (429.95 °C). Different operational air pressures were studied and the results of air consumptions and averaged temperature drops on the workpiece are listed in Table 2.



(a) (b)

Fig. 5. Results of parametric simulations for different design parameters excluding the effect of consumed air flow rate.

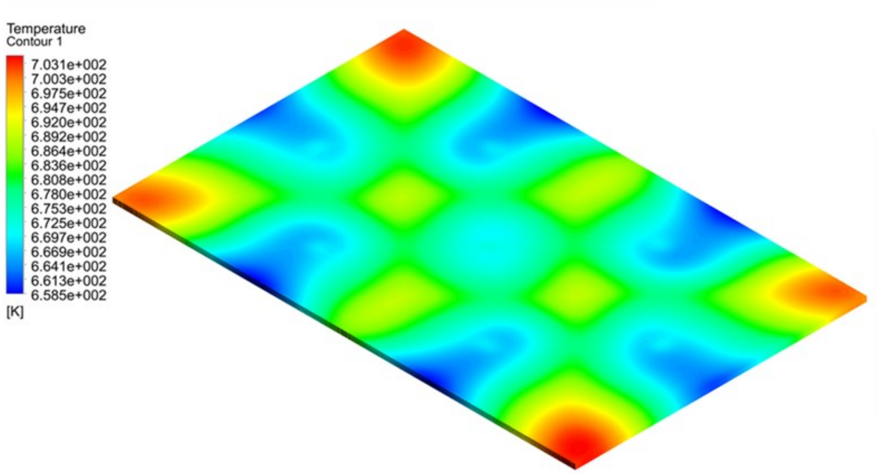


Fig. 6. Temperature distribution on aluminium blank.

Table 2. Simulation results of air consumptions at different operating pressure.

Operating Pressure (Pa)	Air Mass Consumption (kg)	Air Volume Consumption (L)	Averaged Temperature Drop (°C)
103325	0.316236	258.1518367	57.436
104325	0.388602	317.2261	67.62
105325	0.448725	366.3061224	75.965
106325	0.502812	410.4587755	83.093
107325	0.552027	450.6342857	89.155
108325	0.595758	486.3330612	94.787

4. Conclusions

In this study, numerical simulations were used to investigate the air cooling process for cooling down the heated aluminium blanks for hot stamping applications. The blanks was cooled from the solution heat treatment temperature to a designated forming temperature by nozzle field air cooling which uses flexible arrays of air nozzles. Effects of design parameters of the cooling tool and operational conditions on cooling performance were studied through parametric simulations. Based on this exercise, the following conclusions may be drawn:

- The mean cooling rate of a cooling system was affected dominantly by the flow rate of air that could be supplied. Increasing the nozzle diameter, increasing the air velocity, or decreasing the pitch, positively influence the cooling rate, due to applying higher air flow to the blank surfaces.
- If the upper limit on the air flow – rate is fixed by the system, smaller orifice and denser nozzle distribution should be used to achieve higher cooling rate. It also means smaller blanks could only be cooled.
- The maximum temperature difference on the blank after cooling changed with different combinations of nozzle diameter, pitch, and air velocity. For a fixed air flow – rate, cooling system with smaller nozzle size and denser nozzle distribution would produce smaller temperature gap on the blank. Decrease of temperature difference was also observed from system with larger nozzle diameter and low air velocity.
- The Maximum temperature on the blank after cooling was at the corners where the contact between surface of the blank and the high – velocity air stream was not enough.
- The air velocity is another important parameter affecting the cooling efficiency of the system. A system with larger nozzle and lower air velocity would result in lower cooling rate of the blank, when a similar flow rate is used.

A system design for high cooling rates has been proposed and was numerically studied. By providing sufficient air, the system is able to cool a metal blank from 500 °C to 400 °C in 3 seconds.

According to the simulation results, nozzle field air cooling is an ideal air cooling process for preparing heated metal blanks for hot stamping applications. To build a practical cooling system, nozzle design, nozzle distribution, air supply system, cooling system operation conditions, etc. should be carefully considered and studied in detail. Moreover, special attentions should be given to the selection of a reliable air source enabling provision of a high flow rate as well as associated cost, and to the safety issue relating to dealing with the high-temperature exhaust air.

Acknowledgement

Support from the European Commission for conducting research into the “Low cost materials processing technologies for mass production of lightweight vehicles” through the LoCoMaTech project (NMBP GA723517) is acknowledged. Collaboration with all project partners in developing the manufacturing facilities in this project are particularly acknowledged.

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