Fast-cooling of aluminium alloy sheet metal for hot-stamping applications

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Abstract. The paper reports an investigation into two rapid sheet metal cooling designs that are suitable for applications in hot-stamping production - air cooling and contact cooling, aiming at improving formability of the high-strength aluminium sheets for the forming of components with complex geometries with enhanced overall process efficiency. The investigation involved both numerical modelling and experimental trials using an in-house developed prototype cooling tools. A series of contact cooling experiments were conducted, considering process variables such as initial blank temperatures, cooling die temperatures, die materials, surface conditions, etc. The results demonstrated that the cooling rate of the aluminium blank could be accurately controlled by both methods with appropriate pre-setting of the equipment and control of the process parameters. The integration of the cooling system into a polit hot-stamping production was also tried, considering industry-scale applications related factors. The results can serve as a design guidance for an industry to introduce such cooling methods and manufacturing facilities.

1 Introduction

Research into lightweight material processing technology is one of the fastest-growing fields globally, significantly contributing to almost all industry sectors, environment and economy. The high-strength aluminium alloys remain one of the dominated metallic lightweight materials in the market, and a trend expected to continue [1]. Due to their exceptionally high strength-to-weight ratio, aluminium alloys are increasingly used in the aerospace and automotive industries. However, their poor formability at room temperature poses significant challenges to the forming of such materials with complex geometries while maintaining low manufacturing costs [2].

Several forming technologies, including warm forming, hot forming, and isothermal superplastic forming, continued being developed in recent years [3-6]. In particular, as a low-cost manufacturing technology, the hot stamping has drawn great attentions, particularly for the production of structural car-components with high-strength aluminium alloys. The process reduces sheet thickness and component weight by 30~50% while enhancing material

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strength and impact safety. Medium to high strength aluminium 5xxx and 6xxx series alloys have been used in some commercial vehicles. There has been a trend towards introducing the 7xxx series ultra-high strength aluminium alloy, that is traditionally used in aerospace, to the automotive applications to further reduce vehicle weight and optimise its performance [7-9]. The 7xxx series boasts the highest specific strength within the aluminium family. However, due to its distinct material characteristics, the forming conditions are critical to the success of the forming process. Moreover, the in-die forming and quenching used in hot stamping of aluminium subjects the dies to severe interface conditions, such as high thermal shock and significant stress concentration.

Recent research indicates that low-temperature hot stamping is an attractive option, comparing to a traditional hot-stamping process, which can be achieved through incorporating an intermediate fast-cooling process immediately before the hot stamping of aluminium alloy sheets is executed. This approach could effectively improve the formability of the aluminium sheet, enhance tool life, and increase productivity [10,11]. One critical processing parameter of the fast-cooling is the desired critical cooling rate that is controllable to prevent the formation of coarse precipitates at grain boundaries, which would diminish the post-form artificial aging response of the aluminium alloy. Controlling the cooling rate within a narrow process window within a couple of seconds is highly challenging in an industry system.

In the University of Strathclyde, two kinds of sheet-metal fast-cooling methods have been investigated, which involve development of design concepts, numerical simulation for the process optimisation, and prototype system construction and testing to validate the system concepts, considering industry application related factors in particular. These have laid down a solid foundation for the next step of developing industry systems for hot-stamping applications.

2 Fast-cooling as part of the innovative hot stamping process

In the conventional hot stamping process, the aluminium blank is heated to its solution heat treatment temperature and held at this temperature for a certain period time to reduce material strength and increase ductility. The material is then transferred to a cold forming die to perform the forming and quenching process, before the finished part is removed from the die. The primary purpose of adding fast cooling to the conventional hot stamping process is to quench the blank material from the solution heat treatment temperature to lower forming temperatures at a predetermined cooling rate.

Adding the critical cooling process before forming offers several advantages [10]. First, when the material is heated to near the solution heat treatment temperature, its ductility is significantly improved, but it can become too soft, potentially causing localised thinning or tearing during forming. This is particularly true for 7xxx aluminium alloy, which contains zinc as the primary alloying element. Zinc has a low melting point and can enter a liquid phase under the solution heat treatment temperature of the Al-alloy. Lower forming temperatures can slightly increase material strength while maintaining the required ductility for forming complex shapes.

Secondly, lower forming temperatures necessitate a slower forming speed to achieve the strain-hardening effect. This results in less impact load on the forming die and a lower speed requirement for the press. Thirdly, the reduced forming temperature minimises thermal shock to the forming die, thereby extending die life. Additionally, lower temperatures on the aluminium blank mean less heat transfer to the forming die, reducing the need for die cooling. Moreover, lower forming temperatures lead to shorter die quenching times, thereby improving the overall productivity of the manufacturing process.

Various research organisations and industrial companies have investigated cooling/quenching of metal sheets using methods such as quenching in liquid, mixed media spray cooling, and compressed gas cooling. However, these methods are unsuitable for this application because the blank surface or forming die may become contaminated by the liquid and the longer transfer time cannot match the narrow time window required in the hot stamping process. Insufficient data are available to support process/facility design and optimisation for industrial application in hot forming aluminium alloy sheets. The challenge associated with cooling aluminium alloy blanks is to achieve the high temperature gradient required for a suitable microstructure and mechanical properties. A specialised method is therefore required to handle high heat fluxes and achieve the desired thermal profiles.

In this research, two cooling methods were investigated: air cooling and contact cooling. The cooling principles of these methods differ; air cooling relies primarily on convection of airflow, while contact cooling relies mainly on conduction between contact surfaces. Each method has its advantages and disadvantages, and the selection of the appropriate method depends on factors such as the required cooling rate, the size of the blank, and the system cost.

2.1 Air cooling

Air cooling uses airflow as a cooling medium to remove thermal energy from the heated blank. The benefits of air cooling/quenching techniques include energy savings, reduced workpiece distortion, and the prevention of liquid contamination to the blank, leading to increased interest in developing such technologies. Various investigations have studied the effects of key parameters, such as nozzle diameter, pitch, and nozzle-to-component distance, on the cooling characteristics of the system, including cooling rate and temperature uniformity. Ferrari et al. [12] and Liščić et al. [13] have provided brief guidelines and recommendations for system design. However, most of these studies are based on cooling small workpieces, where the air volume requirement is modest.

One popular air-cooling technology is the nozzle-field cooling/quenching process, which uses a flexible array of low-pressure gas jets to quickly cool down the workpiece in a conventional atmospheric cooling system [14].

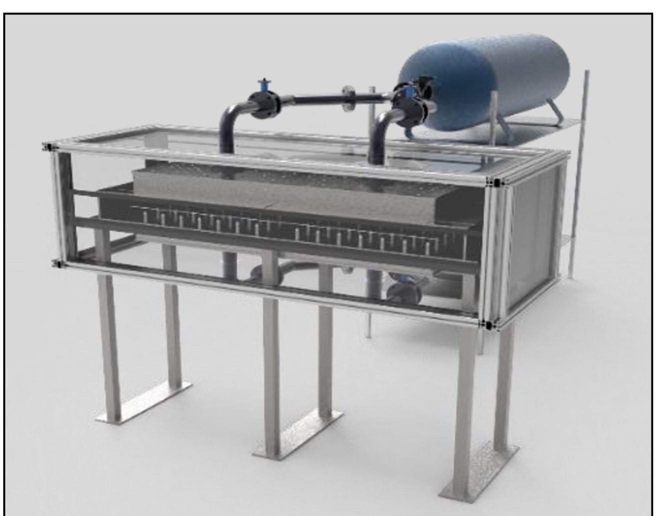

Fig. 1. Conceptual design of an air cooling system

Fig. 1 illustrates a conceptual design of an air cooling system. Since the cooling is primarily achieved by airflow, the cooling rate is proportional to air consumption. Consequently, the size and cost of the cooling system will increase significantly with the size of the blank.

The cooling effectiveness is mainly influenced by the rate of airflow. The airflow rate of the entire cooling system can be approximated by Equation 1, where "D" is the nozzle diameter, "v" is the gas velocity, "A" is the cooling area, and "P" is the pitch between nozzles.

$$Flow\ Rate \approx \pi\ x\ (\frac{D}{2})^2\ x\ v\ x\ \left[\frac{A}{P^2}\right] \qquad (1)$$

Different operating pressures have been simulated, and the results for air consumption and average temperature drop on the workpiece are plotted in Fig. 2. The graph clearly demonstrates that increasing air consumption, resulting from higher operating pressure, leads to a greater temperature drop on the workpiece. However, a significant issue is that the high airflow generates excessive noise during operation. Therefore, it is recommended to construct a noise reduction housing to mitigate this problem.

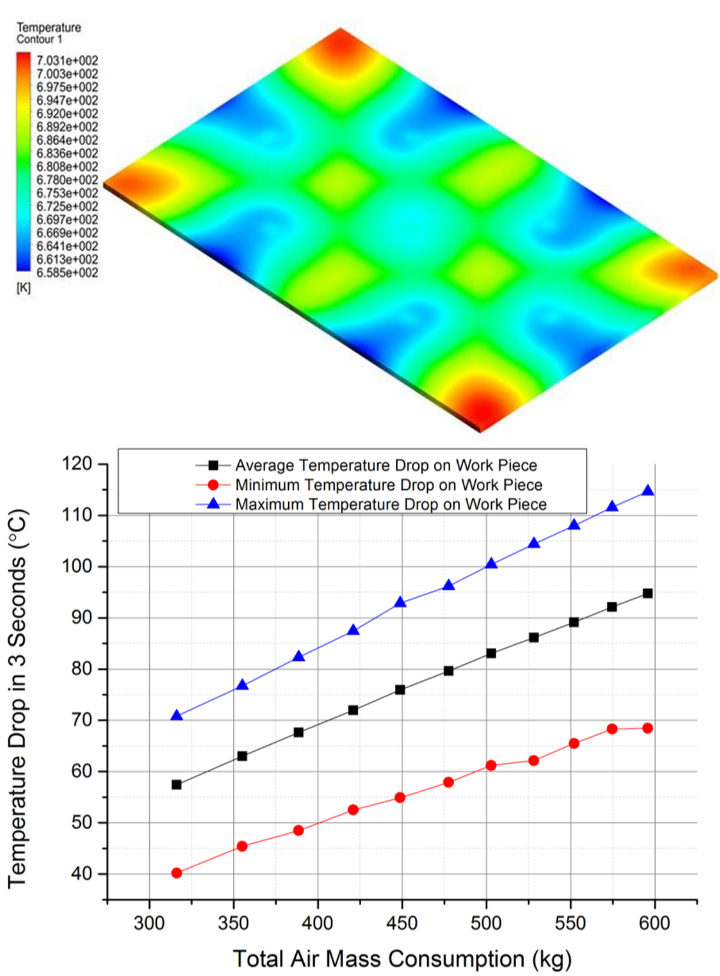

Fig. 2. Simulation of air cooling (left); Relation between the air consumption and the temperature drop (right)

2.2 Contact cooling

The contact cooling method operates through thermal conduction between the heated blank and a set of cooling plates. Fourier's equation of heat conduction, shown in Equation 2, describes this process, where 'Q' is the heat flow rate by conduction, 'k' is the thermal conductivity of the materials, 'A' is the cross-sectional area normal to the direction of heat flow, and 'dT/dx' is the temperature gradient:

$$Q = -kA(dT/dx) \quad (2)$$

This cooling method can achieve a high cooling rate because metals generally has high thermal conductivity. Additionally, different cooling rates can be easily achieved and accurately controlled by adjusting process parameters such as contact plate materials and pre-set cooling plates temperatures.

Fig. 3 illustrates a conceptual design of a contact cooling system. The contact fast-cooling tool is first preheated to the desired working temperature, which should remain steady to ensure a reliable cooling rate for the blank in a production line. Ideally, during operation, the heat transfer from the hot metal blank to the fast-cooling plates and the heat loss on the plates should be balanced, enabling a very fast production cycle time. The cooling system's temperature is constantly monitored and adjusted by an automatic control system. If the actual temperature exceeds the set working temperature, the cooling element is activated to remove the excess heat. Conversely, if the actual temperature is lower than the set working temperature, the heaters are turned on to supplement the heat loss. There are several advantages to using contact cooling for hot stamping applications, including simple system design, suitability for different size of blanks, and ease of integration into existing production lines.

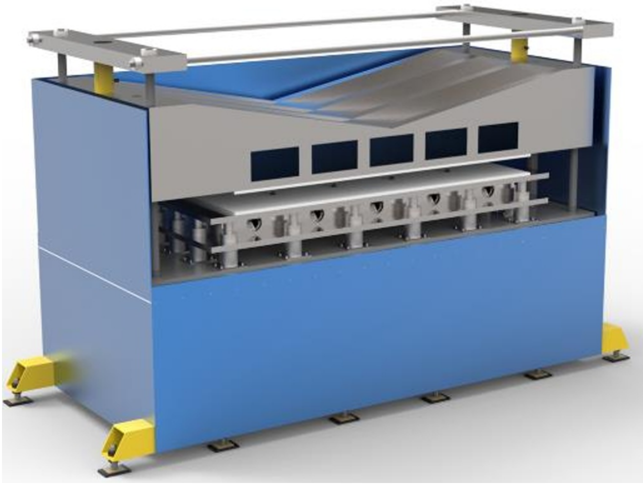

Fig. 3. Conceptual design of a contact cooling system

The simulation on contact cooling was conducted considering various parameters, such as pre-setting temperature, contact plate materials, and applied pressure. The simulation results are shown in Fig. 4, demonstrating that the targeted cooling rate can be achieved with appropriate process parameters.

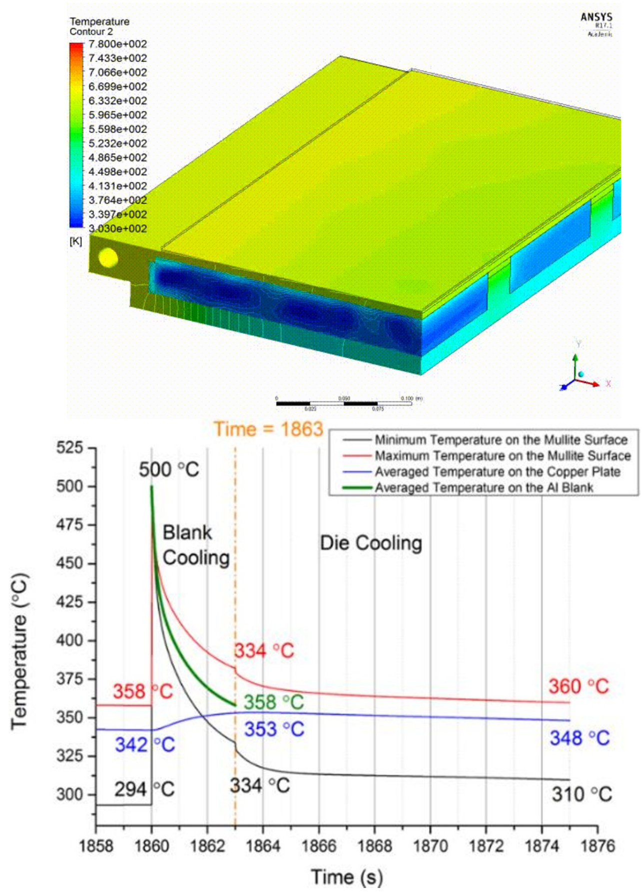

Fig. 4. Simulation of contact cooling (left); Temperature drop of heated al-alloy blank (right)

Contact cooling experiment was performed using a fast-cooling prototype developed in-house. Machine settings, pre-heating, and controls were optimised to achieve the targeted cooling rates of 50°C/sec, as shown in Fig. 5.

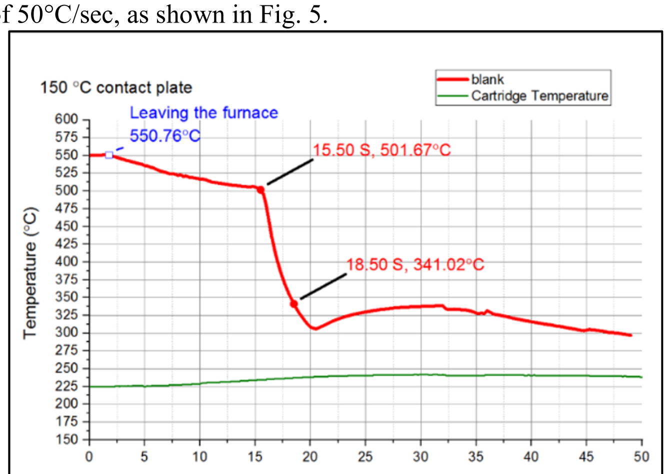

Fig. 5. Contact cooling experiment result

3 Discussion

3.1 Cooling methods

Both cooling methods eliminate the use of liquid, resulting in several merits such as being environmentally friendly and reduced waste-disposals. Additionally, there is no phase change of the liquid near the surface of the workpiece during the cooling process, which maintains a constant heat transfer coefficient constant and minimises distortion of workpiece. Furthermore, since no coolant is used on the surface of the workpiece, allows it to proceed directly to the next processing step, enhancing the workflow efficiency.

Nevertheless, each method has its own limitations. Air cooling requires a very high air-consumption rate to achieve a fast cooling rate, leading to substantial capital investment and operational costs, which may be impractical for a large-scale operation. Contact cooling, on the other hand, although it is ideal for cooling large blanks with a simple and efficient system design, it is not suitable for tailored blanks with variable thickness and requires good contact between the workpiece and the cooling tool. In other words, a high surface flatness of the sheet metal would be desired.

3.2 System design considerations for integration

To integrate a cooling system- indicated above into a hot stamping production line, following issues should be addressed.

- System Layout and Logistics: Redesigning the system layout is essential in order to accommodate the new cooling equipment while maintaining efficient workflow and minimising disruptions to the existing production
- Handling System: Effective system/device for handling and transferring the sheet-metal before and after fast-cooling has to be implemented to ensure a smooth process, including avoid unnecessary delay that results the significant temperature drop of the sheet metal before the hot-stamping process starts.
- Equipment Monitoring and Precise Control: Monitoring and precise control of the temperature profile of the cooling equipment are critical to the achievement of the desired cooling rate of the sheet metals.
- Production Management: Production schedules need to be coordinated by considering the cooling system's capabilities to enhance the current production with greater flexibility that allows tailored processing windows to be implemented.

4 Conclusion

Development of the fast-cooling technology and systems for pre-cooling the aluminium blank as part of an innovative hot stamping technology aims at improving material formability, increasing die-life, and enhancing process efficiency and productivity. This study compared two different cooling methods: air cooling and contact cooling, including their respective merits and disadvantages. Both simulation and experimental work demonstrated that the target cooling rate could be achieved with both methods through optimised controls of the machine setting and process parameters. In general, contact cooling is recommended for cooling large blanks and integration into a production line due to the simple system design, elimination of blank contamination, and ability to achieve a fast, controllable cooling rate, while air cooling would be ideal for relatively small blanks as well as non-flat sheet blanks.

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