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Liquid nitrogen jet impingement cooling of ultra-high strength steel in hot stamping process

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Abstract. In the hot stamping process, elevated sheet temperatures and uneven die cooling contribute to insufficient thickness uniformity in the formed parts, leading to reduced forming efficiency and inducing severe thermo-mechanical fatigue in the die. To address these issues, a novel in-die liquid nitrogen (LN2) jet impingement cooling method is introduced to achieve a low and uniform initial holding temperature. The high-temperature steel sheet is initially cooled to slightly above the martensitic transition temperature through the application of an LN2 jet during the forming stage, followed by pressure-holding quenching. This method demonstrates remarkable outcomes, including a notable 74.19% reduction in holding time and a substantial 24.72% decrease in the maximum thinning rate. Furthermore, the maximum temperature difference between the upper and lower dies sees significant reductions of 34.57% and 25.84%, respectively.

Introduction

In the hot stamping process, the efficiency and quality of part formation depend significantly on the cooling performance of the die, specifically in terms of cooling rate and uniformity. Consequently, the top priority for optimizing part quality is the design and optimization of the die's cooling system. Various methods, including optimizing the dimensional parameters of cooling channels [1,2,3], designing a conformal cooling channel structure [4,5,6], selecting the materials of coolant [7,8], calculating flow parameters [9], new structure of cooling systems [10] and upgrading die materials [11,12], have been explored to enhance cooling system performance. However, these approaches primarily focus on optimizing the indirect cooling of traditional hot stamping, yielding relatively modest improvements.

Furthermore, the spatial structure of the formed part often restricts material flow during the forming process, leading to local thinning and resulting in reduced contact pressure with the die or even the formation of gaps. This causes a significant decline in heat transfer performance, poor temperature uniformity, and the need for longer holding times to achieve the desired temperature reduction in the formed part [13,14]. Although improvements can be made through profile trimming, this increases manufacturing costs, and the aforementioned problems are likely to persist with increased wear. The continuous cycling of the hot stamping process also induces large cyclic changes in die temperature, potentially causing severe thermo-mechanical fatigue, increased wear, and even fractures [15]. This phenomenon significantly shortens the service life of the die.

This paper introduces a novel method of in-die liquid nitrogen (LN2) jet impingement cooling for high-temperature ultra-high-strength steel. The method aims to increase the cooling rate of high-temperature steel plates, facilitating the creation of a fully martensitic structure, and to reduce the entry temperature of the plates into the mold, thereby shortening the holding time. Additionally, in-die LN2 jet impingement cooling is employed for thermal management of the die, resulting in a reduction in the maximum temperature difference during cyclic changes in die temperature. This approach effectively mitigates thermo-mechanical fatigue, ultimately prolonging the service life of the die.

Structure of LN2 Jet Impingement Cooling Die

Control of Cooling Rate. The novel approach integrates an LN2 impingement cooling method with a hot stamping die by machining a 1 mm diameter deep hole on the die surface, establishing a connection to a channel inside the die. Fig. 1a schematically depicts the structure of LN2 jet impingement cooling combined with conventional hot stamping dies. The die, comprising an upper and lower component, incorporates uniformly distributed cooling channels on an isometric surface situated at a specific distance from the die surface. Jet holes, evenly distributed on the cooling channels, have their spacing adjusted to ensure uniform cooling.

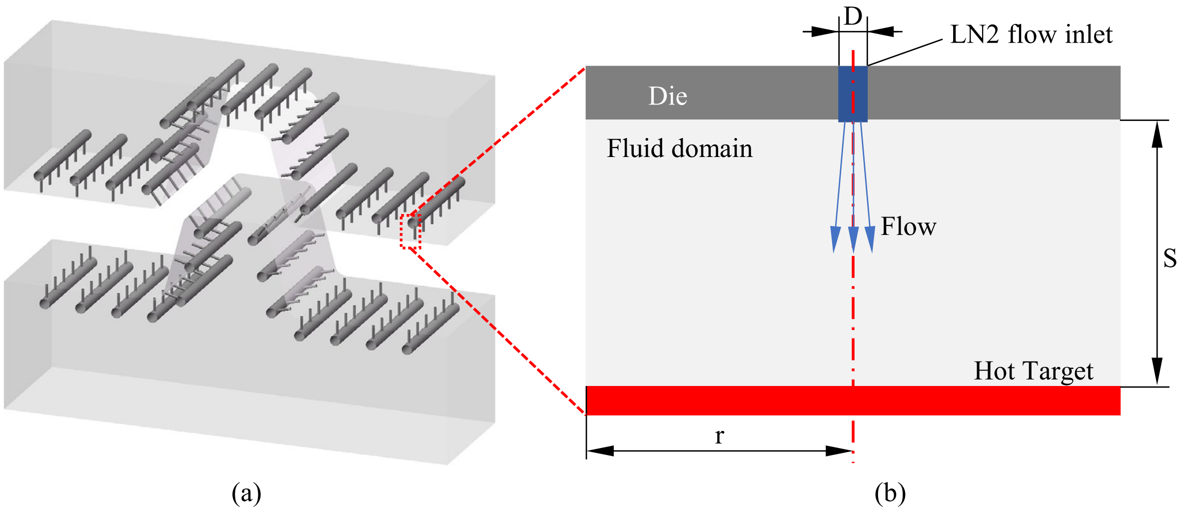


Fig. 1 Overview of (a) LN2 jet impingement cooling die model and (b) The simplified 2D model

The manipulation of injection parameters for the jet, including jet velocity, is achieved by adjusting the pressure or flow rate at the inlet. In the hot stamping process, the upper die steadily advances toward the sheet at a consistent speed until a snug fit is achieved. While the die is in proximity to the sheet, the surface undergoes impingement cooling through an LN2 jet. Precise regulation of the sheet's cooling rate is achieved by altering both the speed and duration of the jet. Analysis of Heat Transfer Efficiency. In Fig. 1b, the employed Computational Fluid Dynamics (CFD) model is depicted. This model comprehensively characterizes the entire jet phenomenon, considering parameters such as jet velocity, jet height, turbulence, LN2 evaporation, and sheet heat transfer. To simulate the cooling process, a simplified 2D model of the LN2 jet impingement cooling was utilized. In this simulation, LN2, acting as the primary phase, impinges on the high-temperature sheet's surface through a jet hole with a diameter (D).

The finite element analysis software Ansys Fluent was employed to simulate the LN2 jet impingement process through a pressure-based transient analysis. The simulation utilized the widely adopted k-epsilon model with standard wall functions to accurately capture the interaction between the flow and the wall. This model, well-established in industrial flows, ensured a comprehensive representation of the LN2 jet impingement process. The use of Ansys Fluent facilitated a detailed analysis of heat transfer dynamics and fluid-wall interactions during the simulation, contributing to a thorough understanding of the process.

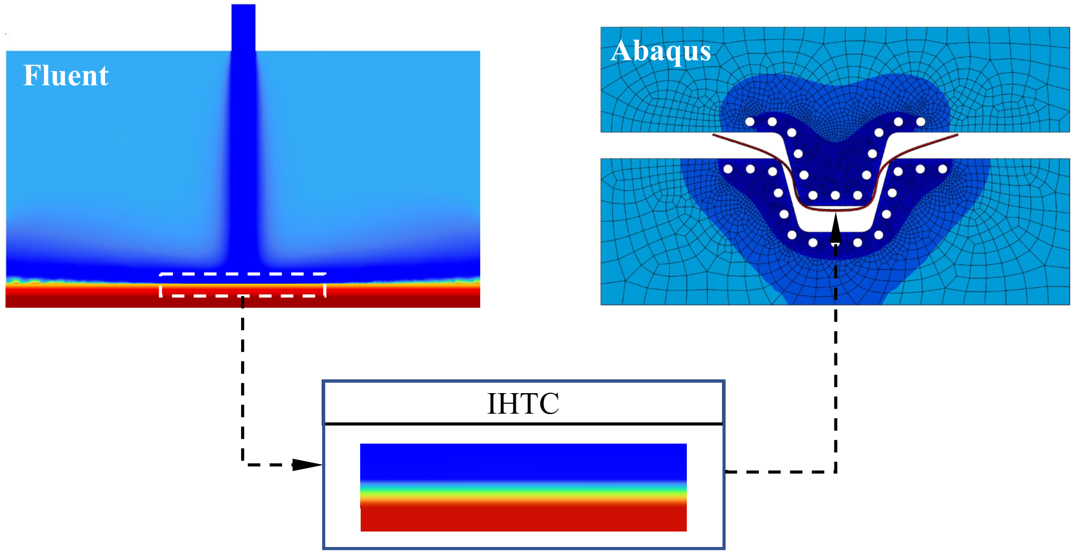
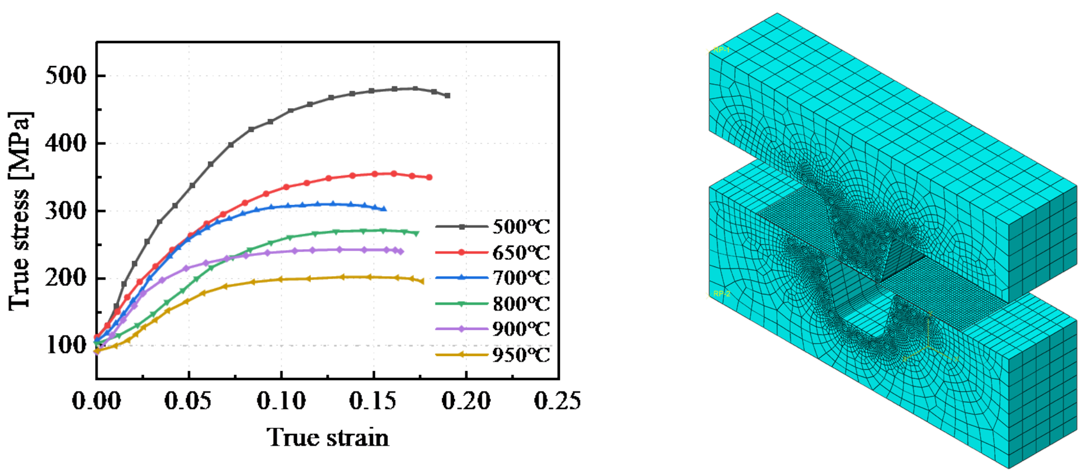


Fig. 2 IHTC transfer between Fluent and Abaqus

Regulation of the Forming Process. Following the analysis of heat transfer efficiency, interfacial heat transfer coefficients (IHTC) for LN2 jet cooling under various parameters were obtained. The forming process was then simulated using Abaqus, incorporating the corresponding IHTC for different regions and time periods, as shown in Fig. 2.

In the simulation of the forming process, the material of the sheet is 22MnB5, and its true stress-strain curve is shown in Fig. 3a. The die was composed of eight-node thermally coupled hexahedral elements of type C3D8T, whereas the sheet was composed of four-node thermally coupled doubly curved thin shell elements of type S4RT utilized in the three-dimensional finite element model. Meshes were finer in the rounded corners of the die and the walls of the cooling channels to improve calculation efficiency, whereas meshes were coarser in the other locations. The upper die, lower die and sheet were meshed using the Abaqus/Explicit mesh module, which contained 11735, 11070 and 3267 nodes as shown in Fig. 3b.



(a) (b)

Fig.3. (a) True stress-strain curve, (b) Meshing in forming models

In contrast to conventional hot stamping, the closing process of jet impingement-cooled hot stamping involves the continuous presence of an LN2 jet, cooling the sheet until the die is fully fitted. Subsequently, as the jet hole becomes blocked, the cooling method transitions primarily to indirect cooling. The hot stamping process using LN2 jet cooling and conventional cooling is shown in Fig. 4. This regulatory approach enhances the understanding of the dynamic cooling mechanisms during the forming process. In instances where gaps exist between the plate and the fully closed die, the LN2 can flow through these openings, enhancing local heat transfer.

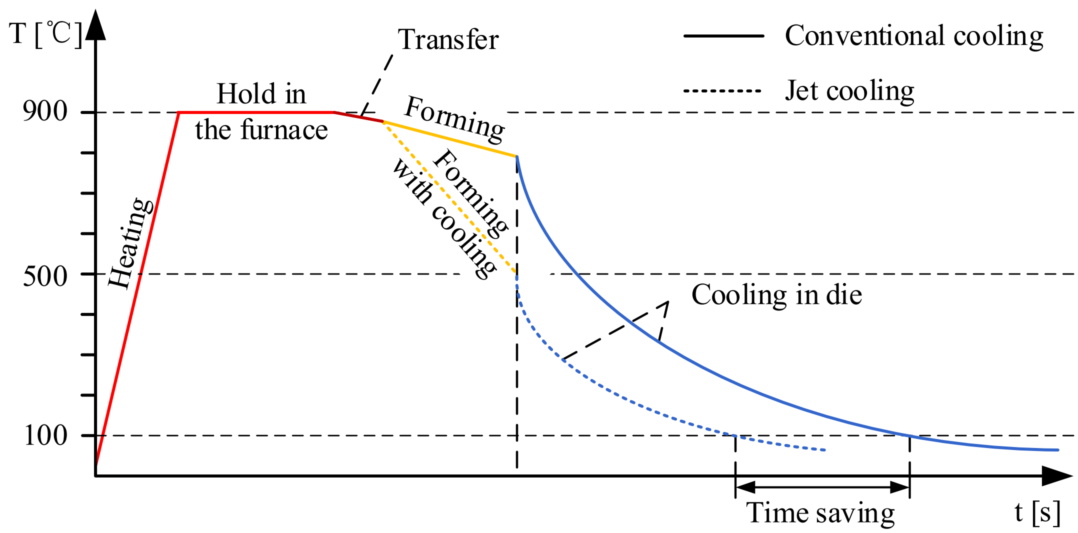


Fig. 4 Temperature paths for high-strength steel sheets under different cooling methods

Results and Discussion

The simplification of the CFD model assumes the presence of only LN2 at the injection inlet, excluding any nitrogen. Additionally, it presupposes that only LN2 is present at the injection holes, and the experimental environment consists of nitrogen. Relevant parameters employed in the model are detailed in Table 1. The initial state of liquid nitrogen at the inlet was determined based on its inherent properties, and the jet height was defined in relation to the gap between the mold and the sheet in the actual stamping process. Additionally, it was assumed that the sheet enters the die at a temperature of 800°C after transfer and undergoes cooling to a temperature slightly above the martensitic transition temperature during the forming process. In other words, the sheet's temperature is within the range of 500-800°C.

Table 1 CFD model parameters

Parameters	Value
Inlet phase	LN2 (no gas) at 76 [K] (-196 [°C])
LN2 jet velocity at inlet, V_{inlet}	5-20 [m/s] (uniform)
Saturation temperature at 1 bar	77 [K]
Jet hole diameter, D	1 [mm]
Hole-target spacing, S	5-20 [mm]
Distance from the intersection of jet centerline along the target wall, r	10 [mm]
Temperature of the target wall	500-800 [°C]

LN2 was injected onto the surface of the high-temperature sheet at a velocity of 20 m/s from the exit of the jet hole, dispersing along the surface to both sides at a velocity of approximately 20.56 m/s after dispersion, as depicted in Fig. 5a. In the proximity of the contact between the center axis of the jet and the sheet, the jet velocity experiences a sharp decrease, creating a stagnation zone and resulting in high static pressure in this region, as illustrated in Fig. 5c. Fig. 5b provides insight into the interaction between LN2 and a high-temperature sheet. At the center of the jet, there exists a very thin gas film between the LN2 and the sheet. With increasing distance from the axis of the jet center, the gas film thickness increases, impeding heat exchange and leading to a gradual decline in the heat transfer coefficient.

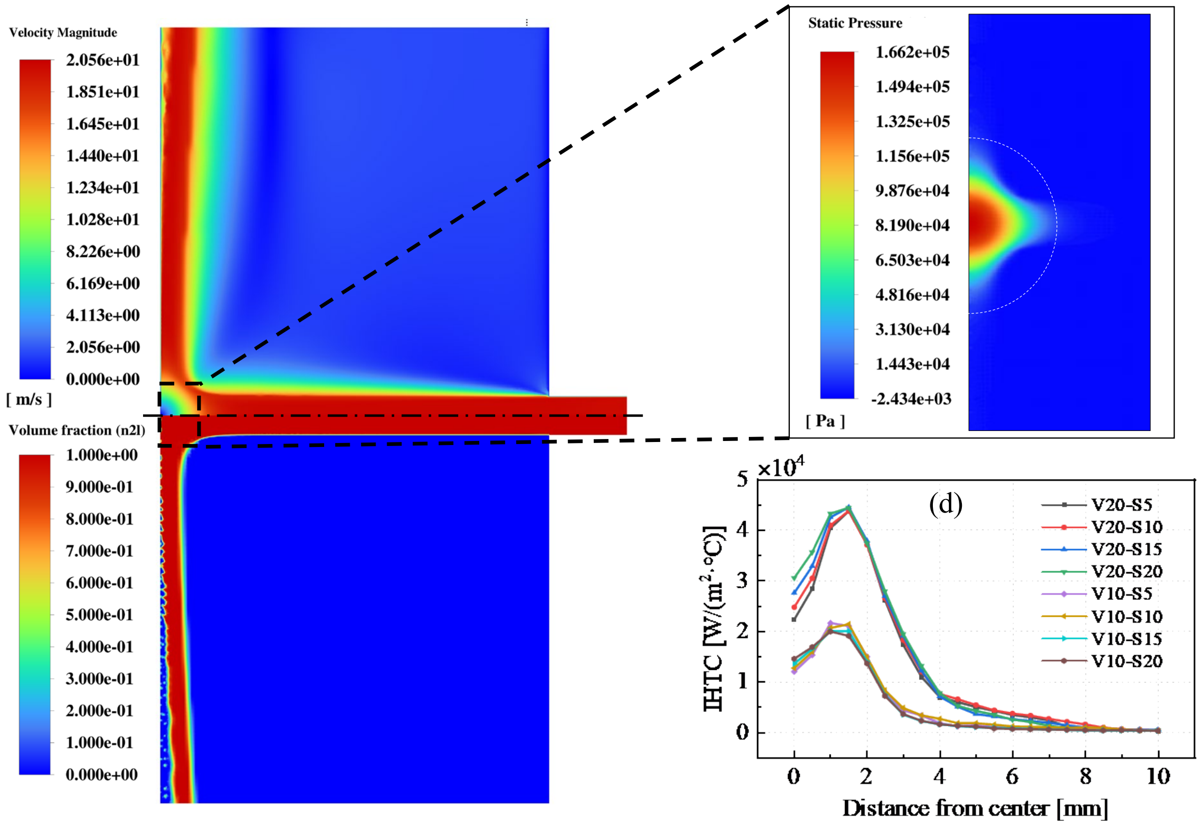
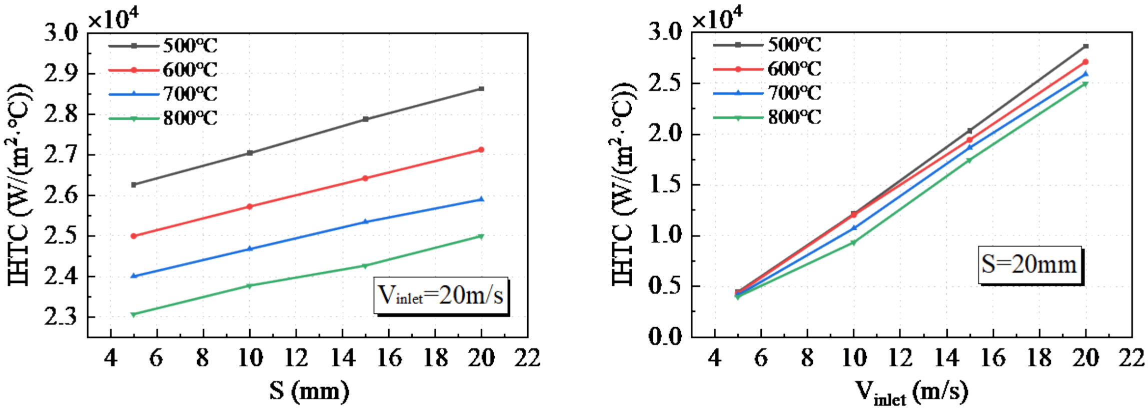


Fig.5 CFD simulation results for (a) Velocity cloud, (b) Volume fraction of LN2, (c) Pressure at the stagnation point and (d) Distribution of IHTC on the sheet surface

Fig. 5d showcases IHTC on the sheet's surface at varying distances from the jet center axis. Interestingly, the maximum heat transfer coefficient occurs at 1.5 mm from the jet center, rather than at the intersection of the jet center axis and the sheet. This is attributed to a severe decrease in LN2 flow rate at the center, weakening the heat transfer effect, while the fluid velocity increases at 1.5 mm from the center of the jet, enhancing heat transfer efficiency.

The interfacial heat transfer coefficient, calculated within a 5mm radius from the center of the jet, serves as a key parameter influenced by different combinations of height, jet velocity, and sheet surface temperature. Fig. 6a illustrates the IHTC corresponding to a jet inlet velocity of 20 m/s, with variations in jet distance between 5-20 mm and sheet surface temperature ranging from 500-800°C. The heat transfer coefficient exhibits an increasing trend with the augmentation of the jet distance, possibly because the increased distance causes the vortex created by the jet to be fully developed. This compels the diverted LN2 to approach the surface of the sheet, thereby enhancing heat transfer efficiency.Fig. 6b showcases interfacial heat transfer coefficient curves at a jet inlet velocity between 5-20 m/s and a sheet surface temperature between 500-800°C, with a fixed jet distance of 20 mm. The interfacial heat transfer coefficient increases gradually with the rise in jet velocity. The heightened jet velocity enhances the heat transfer between LN2 and the high-temperature sheet surface. However, as the surface temperature of the sheet increases, the interfacial heat transfer coefficient gradually decreases. This decrease is attributed to the intensification of vaporization of LN2 due to the increase in superheat, and the generated nitrogen gas hindering heat transfer.



(a) (b)

Fig. 6 Variation of IHTC with (a) different jet speeds and (b) different jet distances

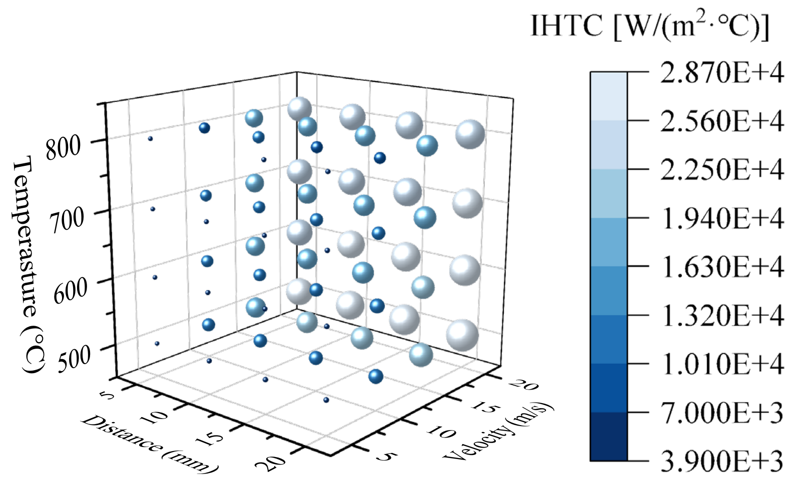
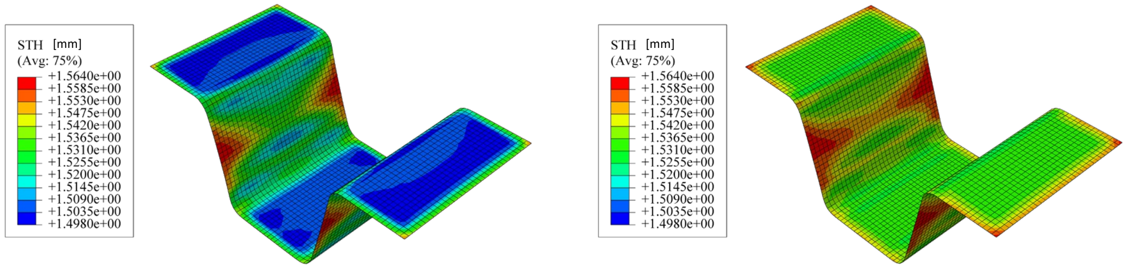


Fig. 7 Interfacial heat transfer coefficient under the combined effect of sheet temperature, jet distance, and jet velocity

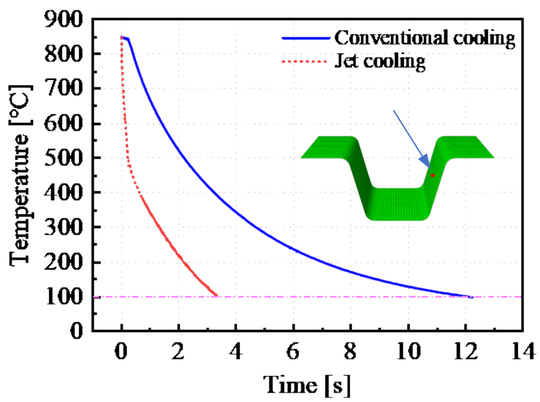
Fig. 7 displays the corresponding heat transfer coefficient profiles when employing a jet velocity ranging from 5-20 m/s, a jet distance spanning 0-20 mm, and a sheet surface temperature between 500-850°C throughout the forming process. These profiles serve as a guide for selecting the appropriate IHTC in Abaqus for forming simulations.

Fig. 8a depicts the cloud view of the thickness distribution for the final formed part in the 10th hot stamping cycle under two distinct hot stamping processes. The thickness uniformity of formed parts using the LN2 jet impingement cooling method is significantly better than that achieved with conventional cooling methods. Selecting a jet velocity with a heat transfer coefficient of 6000 W/(m^2·°C) led to a rapid temperature drop of the sheet during the forming stage, plummeting from 850℃ to 478℃ in just 0.25s, as illustrated in Fig. 8b.The sheet's cooling rate far surpasses the martensitic transformation cooling rate of 27°C/s, and no bainite or pearlite is formed during the forming process. Analyzing the temperature change of the sheet during the 10th hot stamping, it takes merely 3.1s from the initiation of the holding quench to the maximum sheet temperature dropping to 100°C. This represents a 74.19% reduction compared to the time required for conventional hot stamping with indirect water cooling.This remarkable efficiency is attributed to the jet impingement-cooled hot stamping process, featuring a lower initial sheet temperature and a larger temperature difference between the die and the sheet. Fig.8c illustrates the thickness variation in the formed part. In comparison with conventional hot stamping, the maximum thinning rate is reduced by 24.72%, and the utilization of LN2 contributes to a shortened forming time by enhancing local cooling through the gap between the plate and the die.

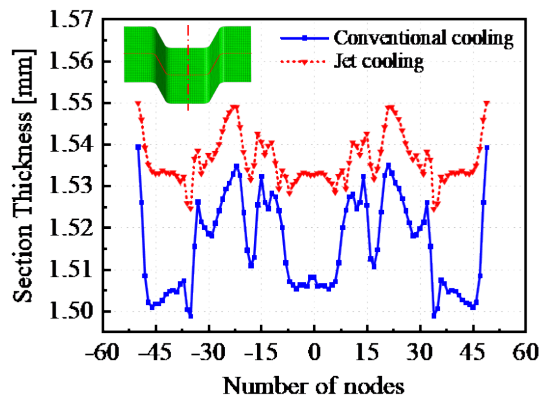


Conventional cooling Jet cooling

(a)



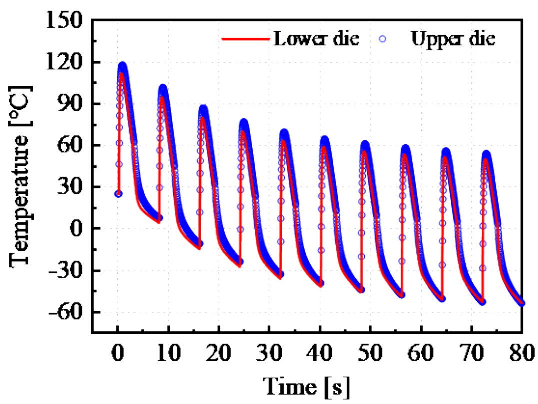
(b)



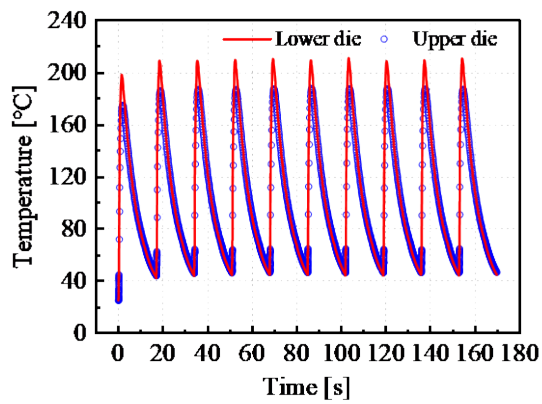
(c)

Fig. 8 Comparison of different cooling methods regarding (a) Temperature variation at the collection point (b) Thickness distribution (c) Thickness cloud

Fig. 9 illustrates the temperature variation at the point where the highest temperature occurs on the die over ten forming cycles with different cooling methods. In all cases, the initial temperature of the die at the first hot stamping was 25°C. The LN2 jet impingement-cooled die in Fig. 9a stabilizes after 10 cycles, with the maximum temperature difference in the upper die reaching 108.65°C and the maximum temperature difference in the lower die reaching 104.19°C in the 10th cycle.



(a)



(b)

Fig. 9 Variation of die temperature over 10 stamping cycles using the method of (a) Jet cooling (b) Conventional cooling

On the other hand, the conventional hot stamping die in Fig. 9b tends to stabilize after 2 cycles. In the 10th cycle, the maximum temperature difference is 166.05°C for the upper die and 140.50°C for the lower die.Comparatively, the LN2 jet impingement cooling die achieves a reduction of 34.57% and 25.84% in the maximum temperature difference of the upper and lower dies, respectively, compared to the conventional hot stamping die. This demonstrates the effectiveness of the LN2 jet impingement cooling die in reducing the maximum temperature difference and mitigating thermo-mechanical fatigue.

Conclusion and future works

A novel in-die LN2 injection impingement cooling forming method is proposed to enhance forming performance, efficiency, and extend die service life. The forming effect was simulated, verified, and compared with the conventional hot stamping method. This method effectively improves part forming quality and increases forming efficiency. The main conclusions are as follows:

- The application of LN2 impingement cooling to regulate the sheet temperature during the forming process can significantly reduce the sheet thinning rate from 6.31% to 4.75%. This indicates a notable improvement in material formability. Further enhancements in formability are achievable with more sophisticated control of the jet parameters.
- Jet impingement cooling during the forming stage contributes to a decrease in the initial temperature during the holding and quenching stage. This reduction results in a 74.19% decrease in holding time and an overall reduction in the hot stamping cycle by 52.35%.
- The efficient heat transfer performance maintains the die at a consistently lower temperature throughout the process, reducing the temperature difference by 57.40 ℃ in the upper die and 36.31℃ in lower die, compared to conventional hot stamping. This leads to decreased thermo-mechanical fatigue of the die, effectively extending the service life of the die.

In this paper, only numerical simulation is performed, and experimental validation should be carried out subsequently.As a future perspective, the advanced LN2 jet impingement cooling die is expected to feature a more intricate structure, necessitating more precise control of the cooling system for accurate management of zones and time intervals. The optimal initial holding temperature should be determined through experimental means to prevent a reduction in sheet formability and the need for excessive forming force.

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