Research on the thermal deformation rules of patch panels of high-strength steel body structural parts during the heating process

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The objective of this research is to examine the deformation of the patch plate sheet of high-strength steel body structural components during the heating process to address the specific requirements of hot-stamped high-strength steels, which are extensively utilized in the automotive industry. By analyzing the temperature differential between the patch plate and the main plate in the heating process, as well as thermal stress and other influencing factors, a numerical simulation model was developed to investigate the deformation behavior of the patch plate sheet under various heating processes. The experimental findings indicate that warpage deformation occurs during the heating process of the patch plate sheet, and its extent is influenced by the heating temperature, heating method, and material properties. The study concludes that in the actual production process, the thermal deformation of the patch plate sheet should be minimized by mitigating the temperature differential between the heating of both sides of the patch plate and employing gradual sectional heating, in order to enhance production efficiency and quality.

Keywords: High-strength steel; Hot stamping; Patch plate; Heating process; Warpage simulation.

1. Introduction

The investigation of the deformation during the heating process of the patch plate sheet of high-strength steel body structural components is a crucial area of study [1]. High-strength steel is extensively utilized in the automotive industry, and its exceptional strength and good toughness contribute to the robustness of the body structure, thereby enhancing the vehicle's safety performance [2]. Patch plate hot stamping technology can achieve comprehensive toughness of body components by incorporating "patches" in different areas, and it offers the advantages of a simple process and cost-effectiveness [3]. However, during the application of heat to the patch plate and the main plate, the limited contact area between the two results in uneven heat transfer, leading to disparate stress distribution between the patch plate and the main plate, and ultimately causing thermal deformation. In the heating process, a temperature disparity between the patch plate and the main plate generates thermal stress. As the heating process progresses, the thermal stress gradually intensifies, and upon reaching a certain threshold, it induces plastic deformation of the patch plate and the main board, thus triggering the thermal deformation of the patch plate sheet during the heating process. This type of heating-induced deformation significantly impacts the transport reliability of the patch plate sheet in the roller-heating furnace.

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Therefore, conducting an in-depth investigation into the deformation during the heating process of the patch plate sheet of high-strength steel body structural components holds great significance.

2. Body structure parts and materials

2.1. *Material properties of patch plate*

Through an analysis of the physical and mechanical properties of high-strength steel, including the modulus of elasticity, coefficient of thermal expansion, and yield strength, the aim is to comprehend its deformation characteristics during the heating process. Patch plates are utilized in body structural components such as the A-pillar, B-pillar, and the rapidly evolving laser-spliced plate door ring structural components. This study focuses on the main plate thickness of the A-pillar, which is 1.6 mm, and the patch plate thickness of 1.4 mm. Both the main plate and the patch plate are composed of 1500 MPa AlSi coated plates.

2.2. *Welding of base plate and patch plate*

During the spot welding process of the base plate of hot-stamped parts made of high-strength steel, the welding parameters, including current, time, and pressure, are meticulously selected based on the material and thickness of the patch plate and the base plate to ensure welding quality. In consideration of the structure and welding requirements of hot-stamped parts, a well-planned welding sequence is implemented to mitigate welding deformation and stress concentration. Spot welding the patch plate of hot-stamped parts made of high-strength steel is an effective welding method to enhance the quality and performance of stamped parts. In practical applications, appropriate welding parameters and processes should be chosen based on specific conditions. Figure 1 depicts an example of the model of the A-pillar base plate and the patch plate of the welded sheet.

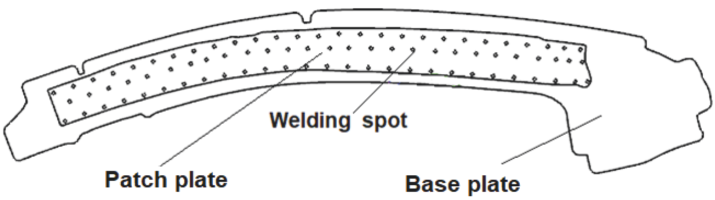

Fig. 1 Body A-pillar patch panel sheet of a car model

3. Modeling and simulation of patch plate temperature difference deformation model

The establishment of a numerical simulation model for the heating process of high-tensile steel patch plate sheet necessitates the consideration of practical factors, such as the heating warpage caused by the thickness disparity between the patch plate and the substrate, the impact of spot welding on shape, the contact pressure between the patch plate and the substrate, as well as the pressure and gap affecting heat conduction between the patch plate and the substrate. Given the previous work related to material modeling and welding issues [4,5], this study will focus on investigating the influence of heating temperature on the warping behavior of the patch plate. The physical properties of the substrate and the patch plate material are analyzed to obtain parameters related to thermal conduction, thermal expansion, residual stress of the material, and environmental conditions of heating. Subsequently, the simulation of the deformation characteristics of the patch plate sheet during the heating process is conducted. The Abaqus simulation software system is utilized to simulate the heating warpage deformation of the hot-stamped patch plate sheet. The schematic diagram of the computational model for the temperature-induced warpage deformation of the patch plate sheet is presented in Fig. 2. The diagram illustrates two distinct deformation modes of the substrate: one involves downward bulging deformation in the area covered by the patch plate, while the other demonstrates linear deformation in the area not covered by the patch plate (as depicted by the linear relationship between the angle β and the warpage height, H, in Fig. 2) [6]. Based on this model, the simulation of temperature difference-induced deformation between the substrate and the patch plate under various heating processes is performed.

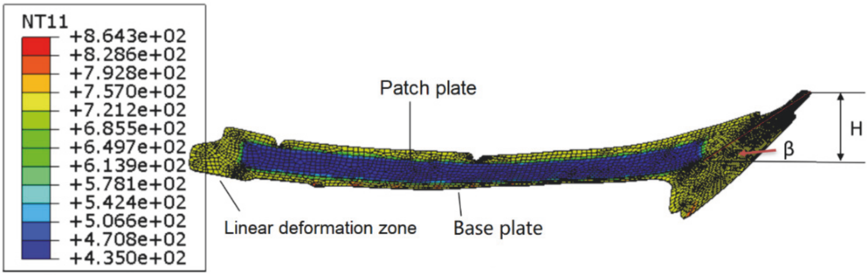

Fig. 2 Schematic diagram of temperature difference thermal deformation between patch plate and main plate

3.1. *Analysis of the temperature difference between the heating furnace temperature and the billet*

In the 3D finite element modeling, the actual production line of the roller bottom heating furnace is considered to be temperature segmented, where the billet travels to different temperature zones with varying heating temperatures. The simulation parameters are also based on the zoned temperature of the heating furnace, serving as the parameter conditions for the simulation, as depicted in Fig. 3a. The variations of NT11 (furnace temperature) and U2 (warping deformation height) over time, from room temperature after 36 seconds of direct heating to 930°C, are illustrated in Fig. 3b.

In conjunction with the aforementioned model and the setup mode of the heating industrial process, the temperature difference and deformation of the sheet under various heating rates are computed. The evolution of NT11 and U2 over time, following 36 seconds of heating from room temperature to 860°C and then to 930°C, is depicted in Fig. 4a. Furthermore, the final variations of NT11 and U2 over time for the patch plate, after 36 seconds of warming from room temperature to 852°C, followed by 36 seconds of warming to 872°C, then continuing to warm to 892°C for 36 seconds, and finally 36 seconds of warming to 930°C, are illustrated in Fig. 4b.

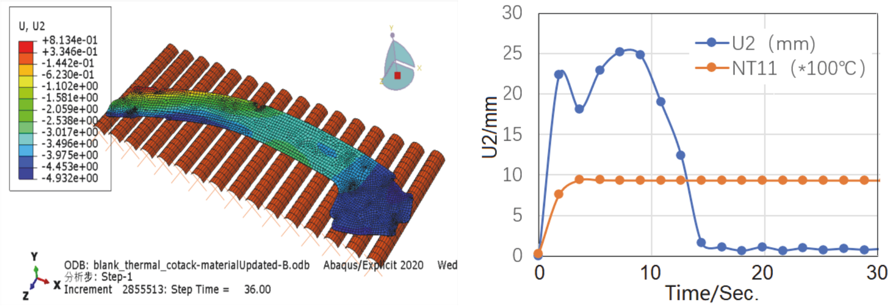

Fig. 3 Deformation analysis of patch plate warpage during warming: a) the state of 3D simulation; b) simulation of warpage deformation height U2 with time during the rise of the sheet from room temperature to 930°C.

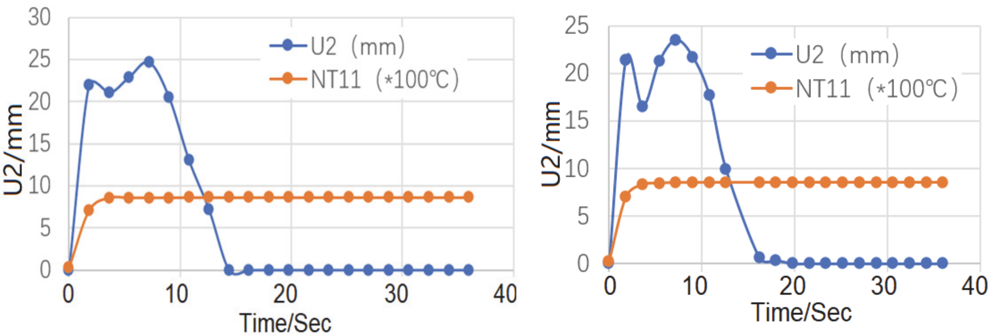

Fig. 4 The process of temperature difference and deformation of the sheet under different heating rates: a) 36s of partitioned heating time, NT11 and U2 of the heating process from room temperature -860℃-930℃ change with time; b) 36s of partitioned heating time, NT11 and U2 of the heating process from room temperature -852℃-872℃-892℃-930℃ change with time.

With three heating processes closely resembling the actual production process, the temperature difference and maximum deformation data of the patch plate sheet are presented in Table 1. The common law of heating-induced deformation of the patch plate sheet is as follows: during the initial 10-second heating period, when the temperature difference between the patch plate and the substrate is between 18-25°C, the patch plate sheet exhibits significant warping deformation. Subsequently, as the temperature difference decreases and the temperature stabilizes, the warping amount steadily decreases and gradually returns to its initial state. This entire process of occurrence and recovery takes only 40 seconds, indicating that the warpage deformation caused by the conveyor axis offset is inevitable at this stage. The warpage alters the contact points of the billet with the rolls, particularly affecting the friction state between the curved plane shape of the patch sheet rolls and the flat plane of the billet, leading to uneven changes. Consequently, this results in variations in the direction and magnitude of the friction force, causing deflection and deviation of the billet during the heating process, which is the most undesirable occurrence during the patch sheet heating process.

Table 1 Temperature difference and maximum deformation of sheet produced by different heating process (patch plate on top)

Heating furnace temperature and time	Max. temperature difference (°C)	Max.Warpage Height（mm）	Corresponding simulation result
Room temperature -930°C, time 36s	35	25.21	Figure 3b
Room temperature -930°C, time 36s	20	24.70	Figure 4a
Room temperature -852°C -872°C -892°C -930°C, 36s per time period	15	23.48	Figure 4b

3.2. *Considering the influence of temperature difference of sheet material on different heating surfaces*

During actual production, when the patch plate is heated and conveyed in the roller bottom heating furnace, it is positioned with the patch facing upward to prevent uneven contact with the rollers, which could cause the patch plate to deviate from its intended forward direction. Furthermore, the heating elements of the furnace are arranged on one side or both sides. However, in this study, the impact of temperature differences arising from unequal thicknesses and areas of the patch plate and the substrate should be considered, with regard to the heating of the sheet from the top and bottom. The temperature difference between the front and back sides of the patch plate, leading to warping, is influenced by different heat exchange coefficients. Therefore, a calculation model is established for the heating of the patch plate from the top and bottom, as shown in Fig. 5. Using this model, different heat exchange coefficients and specific heat capacity parameters of the material are applied to conduct calculations and simulations, analyzing the heating process in actual production.

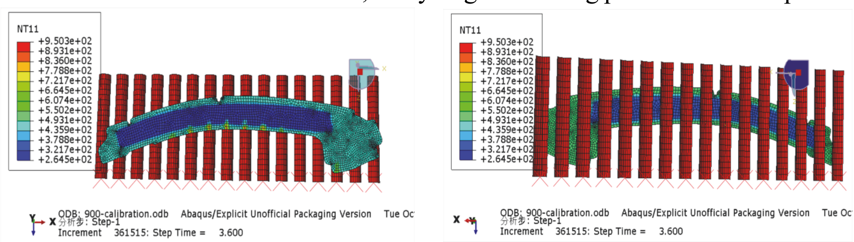

Fig. 5 Simulated setup conditions for simulating the temperature difference between the front and back sides of the patch plate in the heating process: a) Calculation model with the patch plate face up; b) Calculation model with the patch plate face down

Through practical observation and computational analysis, it has been observed that the main factors influencing the warping and deformation of high-strength steel patch plate sheets in the roller-hearth furnace heating process are the shape of the heated sheet and the impact of temperature difference. These factors are the primary causes of warping and deformation of the sheet during the heating process, as well as the bias in movement during the transfer process. The calculated simulation results for the maximum warpage and final warpage height are presented in Table 2.

Table 2 Temperature, temperature difference and deformation of different heating surfaces for single-sided heating

Calculated parameter settings for heating temperature and time	Maximum Warp Height (mm)	Final Warpage Height (mm）
RT-852℃(30s) -872℃(20s)- 890℃(22s)-930℃(134s), Patch face down	21.84	4.89
Rt-852℃(30s)-872℃(20s)-890℃(22s)-930℃(134s), patch facing up	46.84	35.25

Several sets of primary results have been calculated and obtained, and further data merging is presented after comprehensive description, as depicted in Fig. 6 and Fig. 7. The occurrence of surface warpage is observed in the initial phase of the temperature elevation, and before reaching full austenitization, the warpage has almost returned to its pre-heating state. Therefore, the entire heating process, lasting approximately 120 seconds, is considered, with calculations conducted for both the patch plate facing upward and facing downward states. This is done to analyze the relationship between the furnace temperature (NT11), the temperature difference between the front and back surfaces of the sheet (D2), warpage deformation height (U2), and their changes over time.

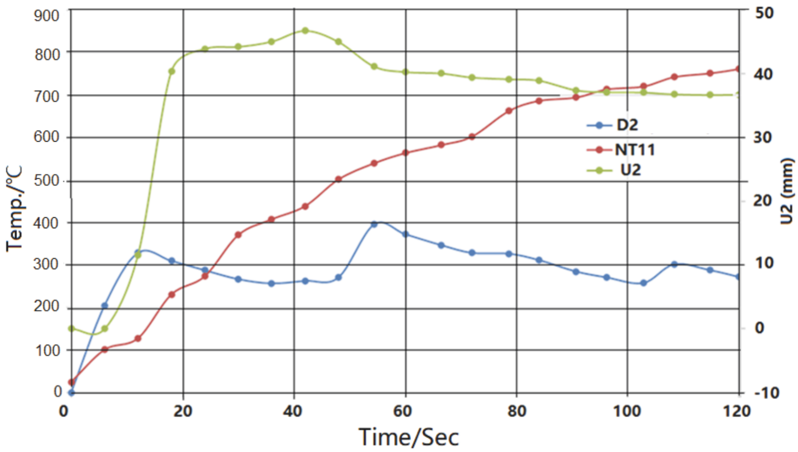

Fig. 6 Time dependent relationship between U2, average NT11, and temperature difference D2 between the front and back when the patch board is facing downwards.

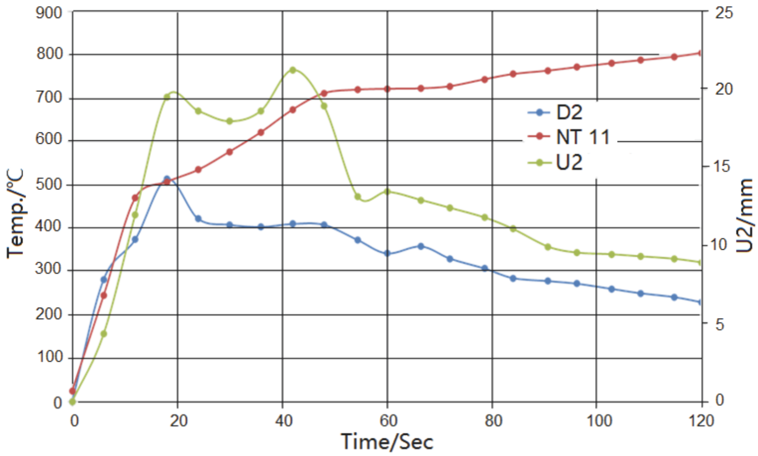

Fig. 7 Time dependent relationship between U2, average NT11, and temperature difference D2 between the front and back when the patch board is facing upwards

3.3. *Analysis of simulation results*

Following calculation, analysis, and practical observation, the influencing factors of warpage deformation in the heating process of the roller-hearth furnace for high-strength steel patch plate sheets have been investigated. The focus was on the impact of the heating process, the shape of the heated plate, and temperature difference on warpage deformation, as well as the plate movement bias caused by warpage deformation in the transfer process. A series of data results have been verified through modeling simulation and actual observation:

(1) In actual industrial production, the patch plate sheet undergoes warpage due to the temperature difference between the front and back sides during the heating process. When the temperature difference between the front and back sides reaches 15-20°C, noticeable deformation occurs due to uneven heating.

(2) Research results indicate that the use of segmented heating can effectively reduce the maximum and final deformation to a certain extent, providing a potential method for mitigating warpage.

(3) A significant difference in warpage height is observed between the heating processes of patch panels facing up and facing down. Simulation results of the heating process with the patch plate facing downward show a final warpage height of 4.89 mm, while the maximum warpage height of the patch plate facing upward is 46.84 mm, and the final warpage height of the entire process is 35.25 mm. Therefore, efforts should be made to reduce the temperature difference between the top and bottom of the plate during the heating process of the patch plate to minimize deformation caused by heat non-uniformity.

4. Conclusion

Following the establishment of the numerical simulation model for the heating process of hot-stamped high-strength steel patch plate sheets in this study, considerations were made for the thickness difference, shape, spot welding, and other factors of the patch plate sheet, and the deformation of the patch plate in the heating process was simulated. By analyzing the relationship between the temperature difference and deformation of the sheet under different heating rates, the law of heating deformation of the patch plate was revealed. The results indicate that the warping deformation of the patch plate is more pronounced when the temperature difference is within 18-25° Cover 40 seconds in the pre-heating period. As the temperature increases and stabilizes, the warpage gradually diminishes and eventually returns to its initial state, occurring within 40 seconds and restoring in approximately 80 seconds. Furthermore, the temperature difference and maximum deformation of the patch panels under different heating processes were analyzed, revealing the significant impact of the temperature difference and heating process duration on the deformation of the patch panels. These research findings offer a theoretical basis for optimizing the heating process of the patch plate in actual production. Adjusting the heating process can reduce the thermal deformation of the patch plate, thereby enhancing the quality and performance of the body structure parts. The study's results are of guiding significance for the process optimization of the heating process of the patch plate sheet for hot-stamped high-strength steel body structural parts, contributing to the improvement of production efficiency and body safety performance in the automotive industry. In conclusion, this study elucidates the influence of the heating process on the deformation of the patch plate sheet, providing valuable insights for enhancing the quality and performance of body structure parts in actual production.

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