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Thermo-mechanical finite element analysis of die-entry temperature and stamping speed in hot stamping of 22MnB5 box-shaped parts

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Abstract

Hot stamping is widely used to produce ultra-high-strength automotive components; however, its coupled thermo-mechanical nature makes forming quality highly sensitive to process parameters. This study investigates the hot stamping of a 22MnB5 steel box-shaped part using a thermo-mechanical coupled finite element model in ABAQUS. Temperature-dependent material behavior, friction, and interfacial heat transfer were considered in the simulation. Forming quality was assessed by thinning tendency, strain uniformity, and temperature distribution under die-entry temperatures of 800–950 °C and stamping speeds of 50–200 mm/s. The results indicate that corner and fillet transition regions are the most critical areas for thinning and strain localization, while sequential tool contact causes temperature non-uniformity. A process window is recommended of 850–900 °C and 100–150 mm/s is provided for stable forming of the 22MnB5 part.

Keywords: Hot stamping; 22MnB5 steel; Finite element simulation; Process window; Thermo-mechanical coupling

1. Introduction

Hot stamping has become an important manufacturing process for producing ultra-high-strength steel components in the automotive industry, particularly for lightweight and crashworthy body structures. [1][2][10] In this process, a heated blank is formed and rapidly cooled in the die, which enhances formability during deformation and imparts high final strength after quenching. [17][18] Due to the strong interaction among deformation, friction, contact pressure, and interfacial heat transfer, hot stamping is a coupled thermo-mechanical process, making forming quality highly sensitive to process parameters. [13][16]

For box-shaped thin-walled parts, non-uniform deformation is more likely to occur in corner and fillet transition regions, where constrained material flow and intensive tool contact promote thinning, strain concentration, and temperature non-uniformity. [8][28][29] Thermo-mechanical finite element simulation therefore provides an effective means to analyze process sensitivity and reduce dependence on costly trial-and-error experimentation. [12][16][18]

In the present study, a thermo-mechanical coupled finite element model of a 22MnB5 steel box-shaped part is established in Abaqus to examine the effects of die-entry temperature and stamping speed. [3][4][7][30] Their effects are assessed through multiple quality indicators, including thickness reduction, strain distribution, minimum forming

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temperature, and temperature-field uniformity, and a practical process window is finally proposed for stable forming. [4][5][15]

2. Literature Review

Hot stamping has been widely investigated as an effective process for producing ultra-high-strength steel components with improved formability during forming and high strength after die quenching.[11][14] Existing studies show that the process response is governed by the coupled effects of temperature, deformation, contact pressure, friction, and cooling during heating–forming–quenching.[19][21][23] For thin-walled box-like parts, the corner and fillet transition regions are particularly prone to thickness reduction and strain concentration due to constrained material flow and simultaneous stretching-bending deformation. [28][29]

Thermo-mechanical finite element simulation is a widely used tool for analyzing thickness variation, strain evolution, and temperature distribution in hot stamping, since full-scale experimental trials are costly and time-consuming.[12][18] Previous studies have emphasized that simulation accuracy depends strongly on the description of temperature-dependent material behavior and tool–blank interfacial heat transfer.[20][21][24] In particular, the interfacial heat transfer coefficient is known to vary with contact pressure and contact condition, making it a key factor in predicting local cooling behavior and thermal non-uniformity during forming.[20][22][23] These simulation approaches are especially useful for comparative parameter studies and trend evaluation under consistent modeling assumptions.[13][18]

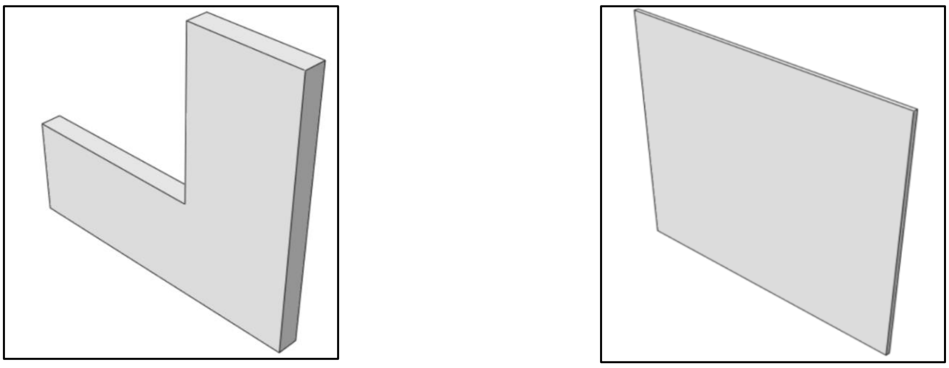
Selecting process parameters in hot stamping involves multiple factors, including temperature, speed, transfer conditions, cooling intensity, and friction-related effects. [18][27][31] Among these variables, die-entry temperature and stamping speed are especially important in practice because they directly influence deformation resistance, heat loss during forming, and the stability of the final thermo-mechanical response.[5][6] Previous research has applied sensitivity analysis, finite element comparison, and response surface based optimization to improve forming quality and identify suitable operating conditions.[15] However, from an engineering viewpoint, a practical process window is often more useful than a single optimum point because it allows more stable production under normal process fluctuations.[17][18] Based on this background, the present study focuses on the integrated effects of die-entry temperature and stamping speed on the forming behavior of a 22MnB5 box-shaped part and proposes a practical window using multiple quality indicators.[6][15]

3. Methodology

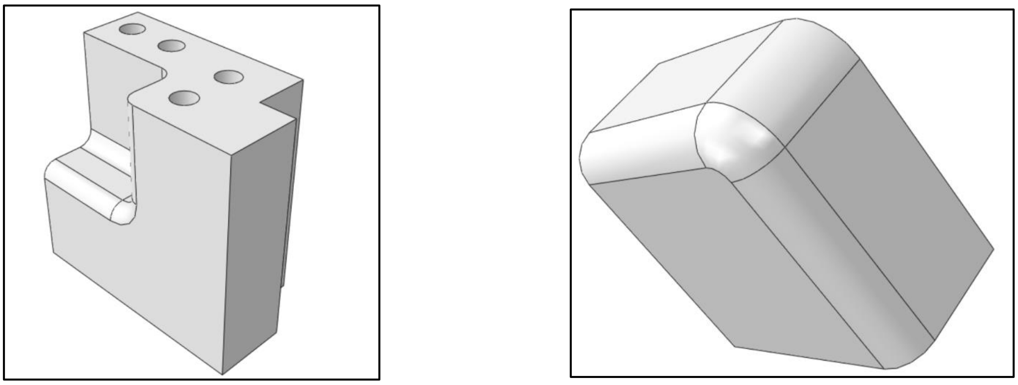
This section describes the thermo-mechanical coupled finite element (FE) model, simulation procedure, process parameter design, and evaluation indicators used to assess the hot stamping quality of the 22MnB5 box-shaped part. [16][19]

3.1. Geometry and FE Model

A box-shaped thin-walled part was selected as the research object to represent typical enclosure-type geometric features, including corners, fillets, and wall transitions, which are prone to localized deformation during hot stamping. [8][14] To reduce computational cost while preserving the essential deformation characteristics, a symmetric quarter model was adopted in ABAQUS. [5][16]



(a) Blank holder **(b) Blank**



(c) Die **(d) Punch**

Figure 1 Four components of the 1/4 model of the box-shaped part for hot stamping

3.2. Material Properties and Thermal Conditions

The blank material used in the simulations is 22MnB5 steel, a common choice for hot stamping due to its excellent strength and formability. [9][19] To capture the coupled effects of temperature, strain, and strain rate during deformation, the Johnson-Cook constitutive model was applied. This model is particularly effective for high-temperature processes like hot stamping, as it accounts for the material's behavior under varying strain rates and temperatures. [16][25] The flow stress is defined as:

$$\sigma = (A + B\varepsilon^{n})(1 + C ln \dot{\varepsilon}^{*})(1 - T^{*m}) \quad (1)$$

where σ is the flow stress, ε is the equivalent plastic strain, $\dot{\varepsilon}^{*}$ is the normalized strain rate, T* is the normalized temperature, and *A, B, C, n,* and *m* are material constants. [25] The Johnson-Cook model was selected for its ability to represent temperature-dependent material behavior and its relevance to processes like hot stamping, where both temperature and strain rate can vary significantly. [3][9]

3.2.1. Constant physical properties

Table 1 Material properties of 22MnB5 used in simulation.

Physical property	**Symbol**	**Value**
Elastic modulus	E	190 GPa
Coefficient of thermal expansion	α	11.6×10^{-6} (1/K)
Poisson's ratio	ν	0.30

3.2.2. Temperature-dependent thermo-physical properties

Table 2 Temperature-dependent thermo-physical properties of 22MnB5.

Temperature (°C)	**Density (kg/m³)**	**Specific heat (J/kg·K)**	**Thermal conductivity (W/m·°C)**
25	7800	460	32.3
300	7800	410	34.5
500	7800	420	35.7
700	7800	430	36.5
800	7800	440	37.1
850	7800	450	37.5
900	7800	460	37.8
950	7800	470	38.0

3.3. Contact, Friction, and Heat Transfer

In this study, the interaction between the tool and the blank is modeled utilizing surface-to-surface contact with a Coulomb grinding law. This approach expects a steady contact coefficient between the die and the blank, which simplifies the simulation. [20][27][31] However, this simplification may not completely capture the varieties in friction that happen in real-world scenarios, such as changes in oil conditions or the wear and tear of the tools over time.

For heat transfer, we utilize a pressure-dependent heat transfer coefficient, which reflects how the pressure at the tool-blank interface influences the effectiveness of heat transfer. [20][21][23] Whereas this strategy is effective for simulating the cooling behavior, it assumes a constant cooling rate. In reality, the cooling rate can vary throughout the stamping process due to variables like fluctuations in tool temperature or the behavior of cooling fluids.

Assumptions

- The tools are considered as rigid bodies, maintained at room temperature throughout the process, meaning we don't account for any potential tool distortion or temperature changes.
- The material of the blank is accepted to be homogeneous and isotropic, meaning we treat it as having uniform properties over its whole structure, without considering defects or varieties that might exist in a genuine material.
- Tool distortion is neglected, meaning we expect that the tools don't experience critical changes in shape during the forming process.

Limitations

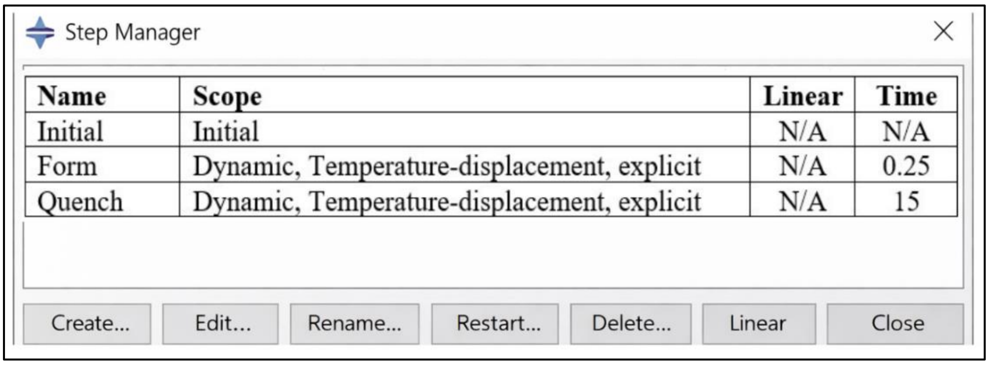
- **Tool wear,** which could alter friction and heat transfer characteristics over time, is not considered in this model. In a real-world scenario, wear can significantly affect both the friction and cooling processes.
- The cooling model used here does not capture the full complexity of heat transfer during the stamping process. Factors like the roughness of the tool surface or changes in the cooling rates due to varying fluid dynamics are not accounted for.
- Material property variations in the blank are not considered in the model, even though in practical applications, the properties of the material may change due to its initial state or processing history.

3.3.1. Simulation Steps and Boundary Conditions

The hot stamping process was simulated using a coupled temperature-displacement explicit dynamic analysis in ABAQUS. [16][30] Two analysis steps were defined: (i) the stamping step and (ii) the holding/quenching step. The stamping time was related to stamping speed through the forming stroke distance, as expressed by:

$$T \times V = 25\ mm \qquad (2)$$

where ***T*** is the stamping time and ***V*** is the stamping speed. In the reference case, ***V=100mm/s***, giving a stamping time of ***0.25 s***. The holding/quenching time was fixed at ***15*** s to represent die quenching after forming. The initial die-entry temperature was assigned to the blank as a predefined temperature field, while the tools were initialized at room temperature. [16]



Name	Scope	Linear	Time
Initial	Initial	N/A	N/A
Form	Dynamic, Temperature-displacement, explicit	N/A	0.25
Quench	Dynamic, Temperature-displacement, explicit	N/A	15

Figure 2 Setting of the analysis steps

3.4. Evaluation Indicators (Quality Metrics)

To evaluate forming quality and process stability, thickness, strain, and temperature indicators were used. [6][15]

The thinning rate was defined as:

$$\eta = \frac{t_0 - t}{t_0} \times 100\% \qquad (3)$$

where t represents the thickness after deformation, t_0 represents the initial thickness, $\eta<0$ indicates thickening, and $\eta>0$ indicates thinning. The thinning rate was used as a primary indicator of crack risk in critical regions.

Strain localization was assessed using the equivalent stress/strain-related field response from the FE results. The equivalent stress is expressed as:

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]} \qquad (4)$$

where σ_1, σ_2 and σ_3 are the three principal stresses. In addition to local strain concentration, strain uniformity was evaluated comparatively across parameter cases using the field distribution trends extracted from the simulations. Temperature evolution was examined through minimum temperature and temperature-field uniformity at the end of stamping and at the end of holding/quenching. [20][21]

3.5. Parameter Design for the Study

Two key controllable process parameters were investigated: die-entry temperature and stamping speed. [4][15] Their levels were selected to cover typical hot stamping ranges and to enable comparative evaluation of their effects on thickness, strain, and temperature responses.

Table 3 Process Parameter Scheme

Parameter Category	Fixed Parameter	Variable Parameter
Die-entry temperature study	Stamping speed: 100 mm/s	Die-entry temperature: 800°C, 850°C, 900°C, 950°C
Stamping speed study	Die-entry temperature: 900°C	Stamping speed: 50 mm/s, 100 mm/s, 150 mm/s, 200 mm/s

4. Results and Discussion

4.1. Baseline Forming Behavior

The baseline simulation results show that the thermo-mechanical response of the box-shaped part is clearly non-uniform. Thickness reduction is mainly concentrated in the corner and fillet transition regions, where stretching and bending occur simultaneously under constrained material flow. [18][24] These zones therefore represent the critical locations for thinning risk and forming instability. The thickness field, measurement path, extracted thickness curve, and thickness variation rate curve are shown in Figures 3–6.

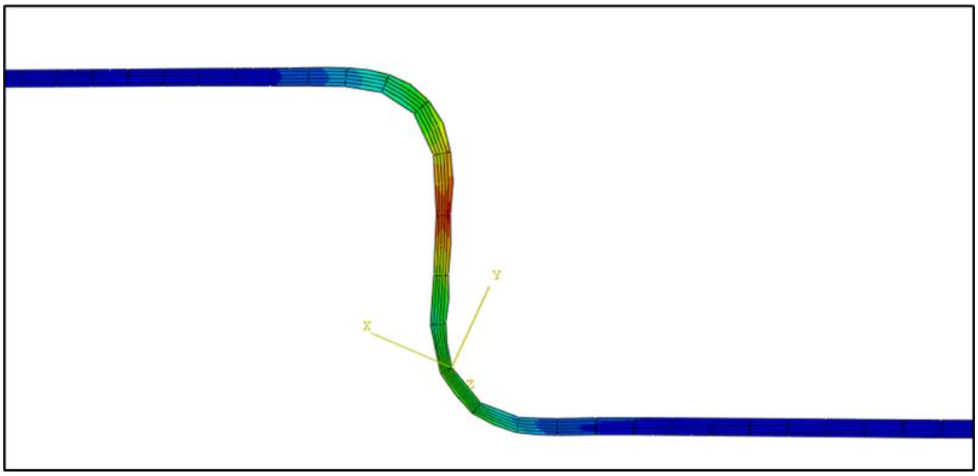


Figure 3 Thickness distribution characteristics

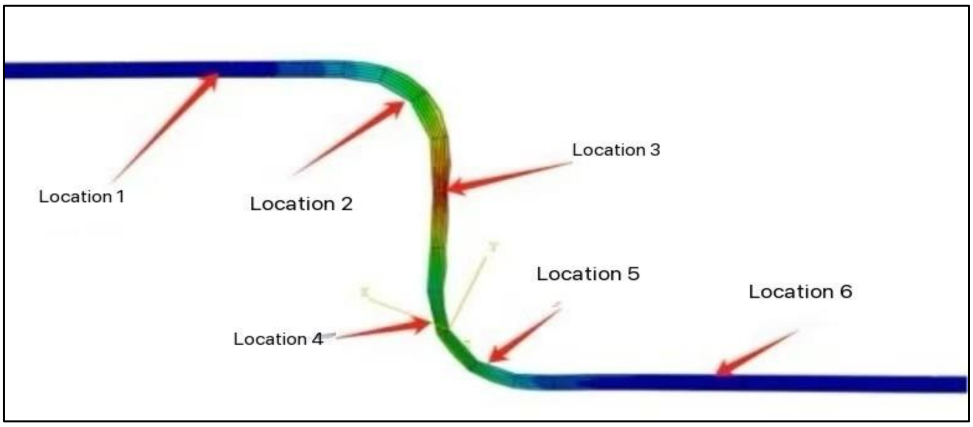


Figure 4 Determination of the path

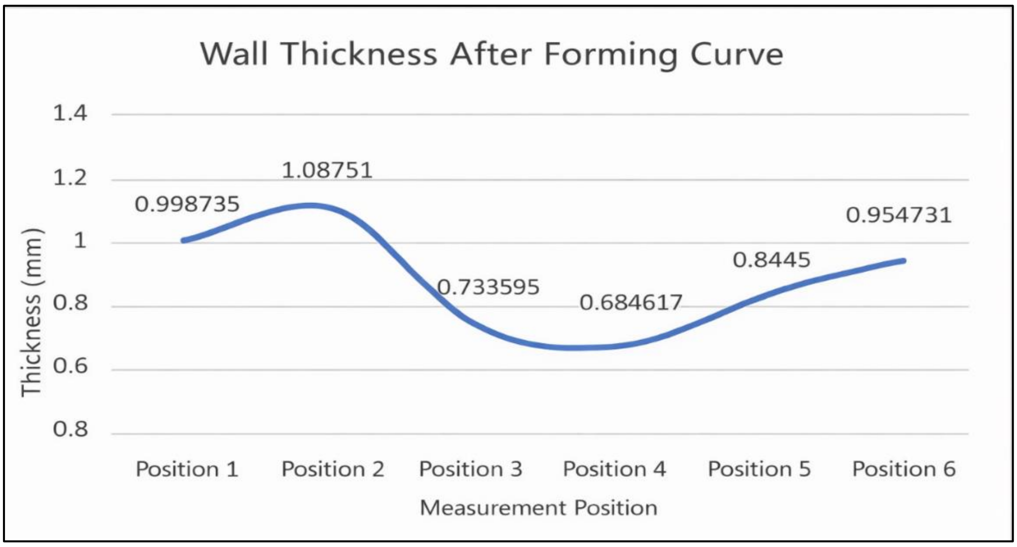


Figure 5 Thickness curve after forming

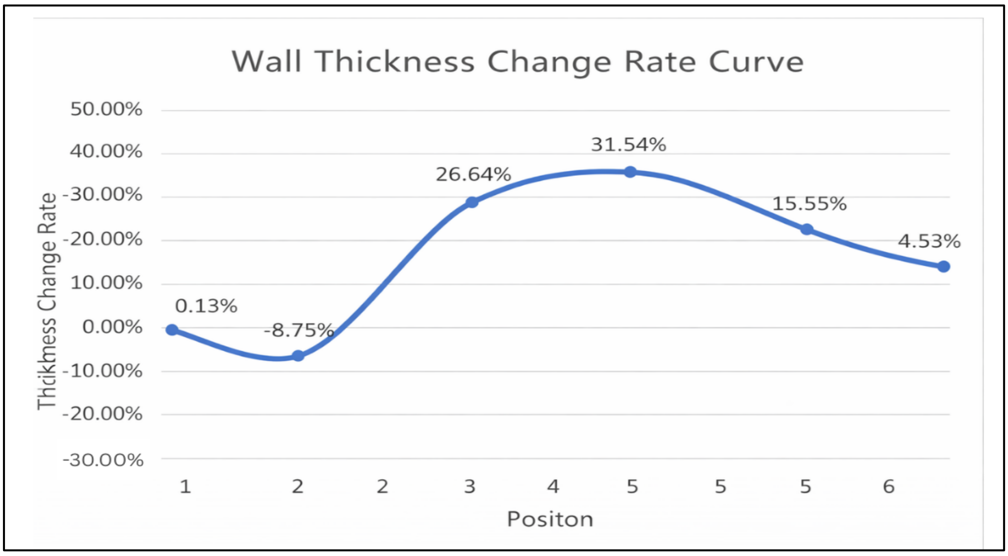
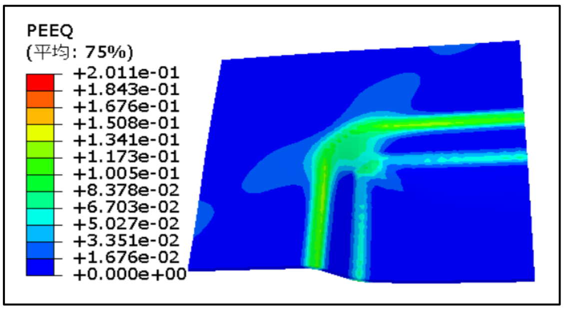
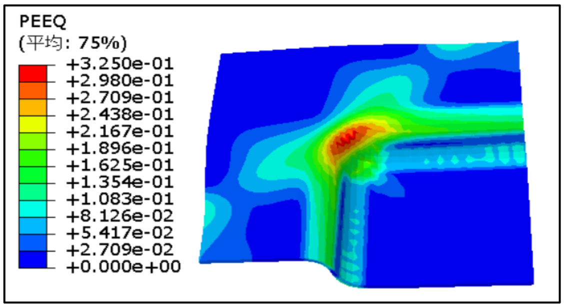


Figure 6 Thickness variation rate curve

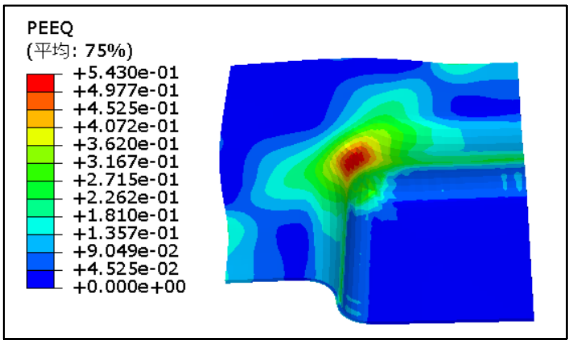
The strain field shows a similar localization pattern. Equivalent plastic strain is higher in the corner/fillet and early-contact regions, indicating that the locations of strain concentration are consistent with the thinning-sensitive zones. [17][24] Figure 7 further shows that the deformation pattern is established during the stamping stage and remains essentially unchanged during the holding and quenching stage.



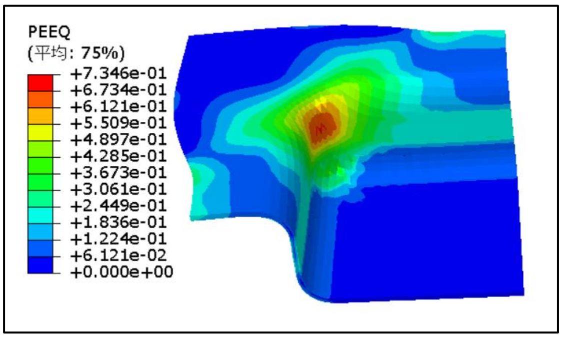
Stamping at 0.10 s



Stamping at 0.15 s

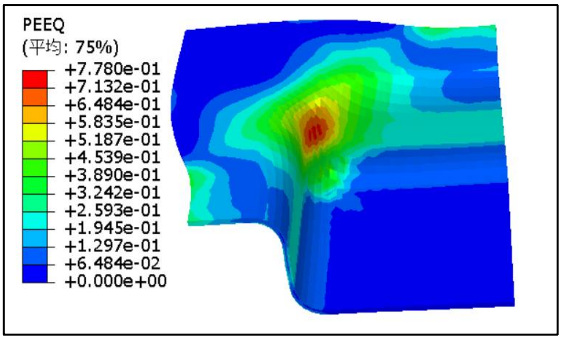


Stamping at 0.20 s

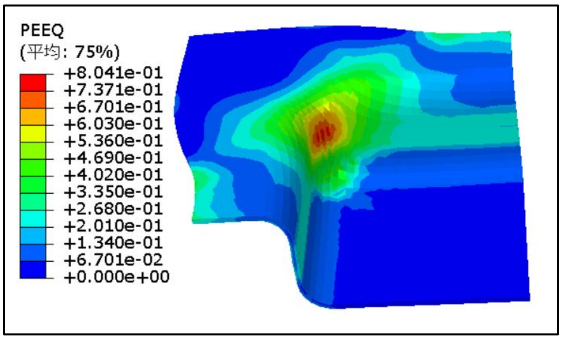


Stamping at 0.25 s

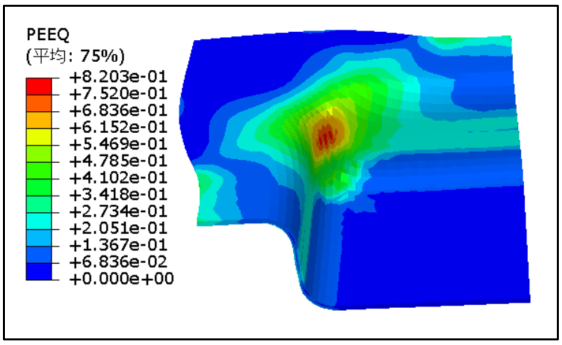
(a) Strain field contour plots at different times during the stamping stage



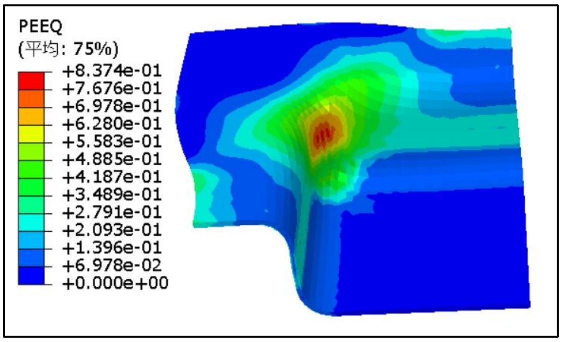
Holding and quenching at 4 s



Holding and quenching at 8 s



Holding and quenching at 12 s



Holding and quenching at 15 s

(b) Strain field contour plots at different times during the holding and quenching stage

Figure 7 Strain field contour plots during stamping and holding at different times

The temperature field is non-uniform due to variations in the tool-blank contact sequence and contact pressure. [21][22] Regions contacting the tools earlier cool faster, producing thermal gradients across the blank. Since deformation resistance is temperature-dependent, this temperature non-uniformity contributes to uneven material flow. [19][23][25] Overall, the baseline results confirm that thinning, strain localization, and temperature gradients should all be considered in evaluating process stability. [15][18]

4.2. Effect of Die-entry Temperature

Die-entry temperature affects both deformation capability and thermal stability during hot stamping. [17][19] The thickness variation results in Figure 8 indicate that temperature has a measurable influence on the maximum and minimum thickness change rates. When the die-entry temperature is too low, the blank loses formability more quickly during contact cooling, which increases the tendency for localized thinning. [18][24] In contrast, excessively high temperature may intensify thermal gradients during early tool contact. [20][23] As a result, an intermediate temperature range gives a more favorable thickness response.

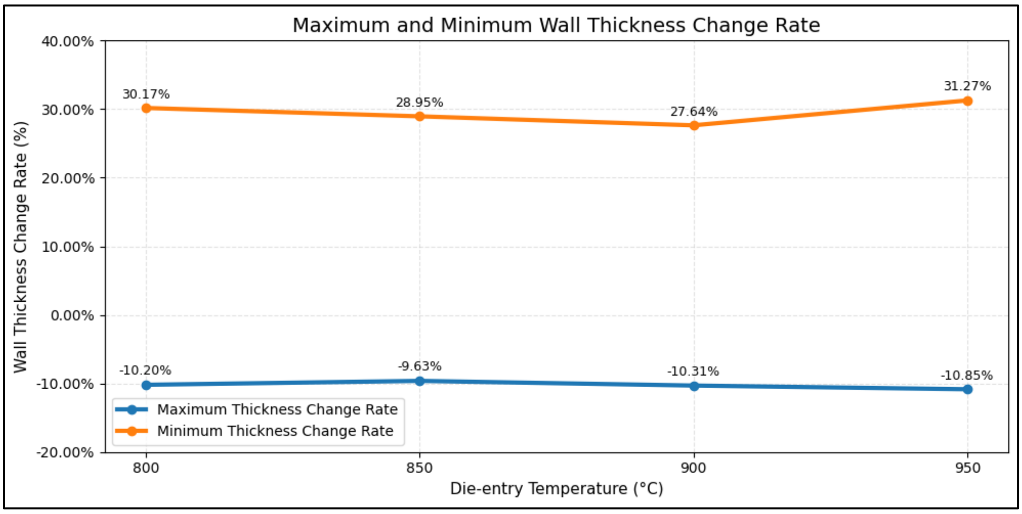


Figure 8 Maximum and minimum thickness variation rates under different die-entry temperatures

The strain uniformity curves in Figure 9 show that die-entry temperature also affects the overall deformation stability of the blank. A moderate temperature level provides a better balance between maintaining sufficient ductility and avoiding strong thermal non-uniformity. [15]

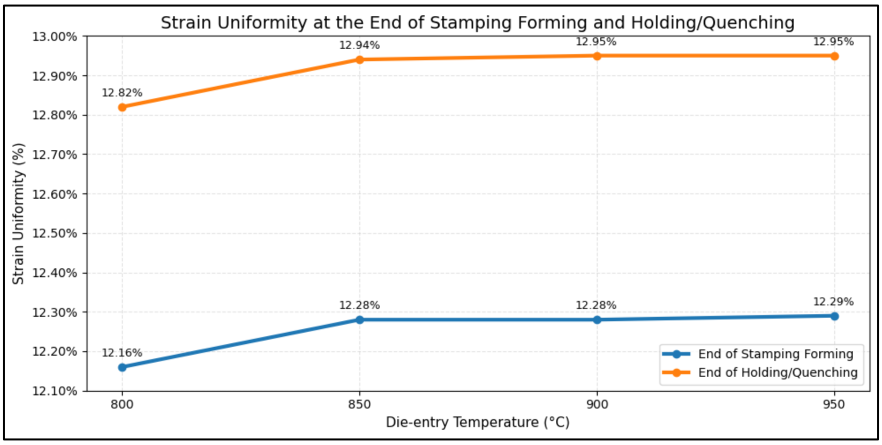
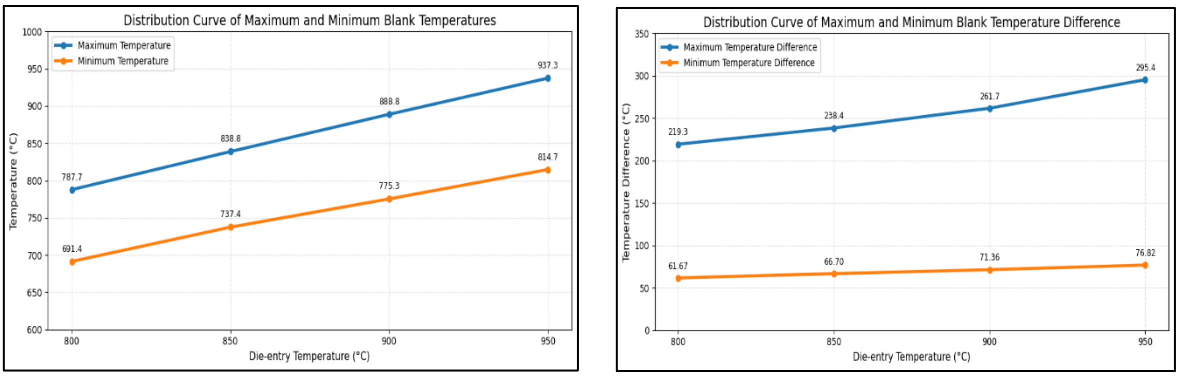


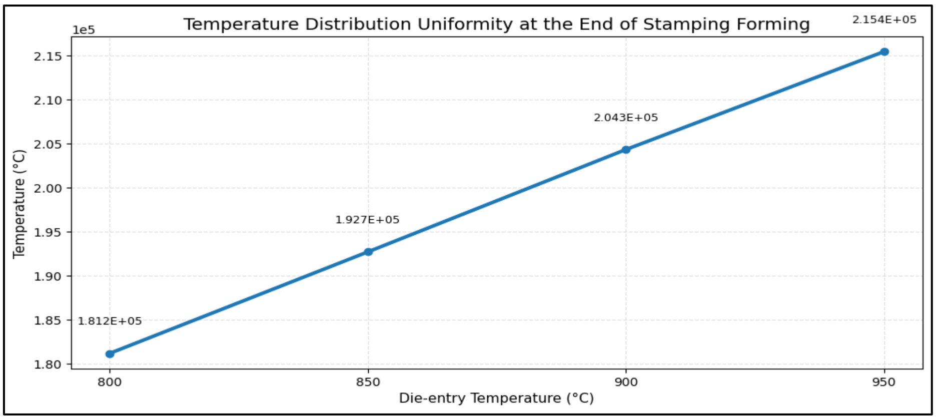
Figure 9 Strain uniformity curves of the blank at the end of stamping and holding and quenching under different die-entry temperatures



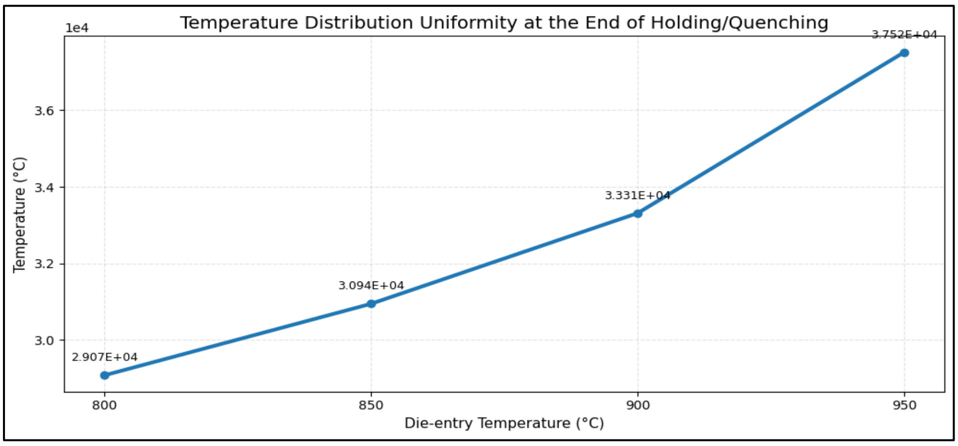
(a) End of stamping **(b) End of holding and quenching**

Figure 10 Maximum and minimum temperature curves of the blank under different die-entry temperatures

The maximum and minimum temperature curves in Figure 10 increase with die-entry temperature, as expected from the higher initial thermal state of the blank. However, the temperature uniformity curves in Figure 11 indicate that higher die-entry temperature does not necessarily lead to better thermal stability, because stronger early-stage contact cooling can increase spatial temperature differences. [20][23]



(a) End of stamping



(b) End of holding and quenching

Figure 11 Temperature uniformity curves at the end of stamping and holding and quenching under different die-entry temperatures

Considering thickness response, strain stability, and temperature-field behavior together, the results indicate that a die-entry temperature range of 850–900 °C provides the best overall balance for the present box-shaped part. [15][18]

4.3. Effect of Stamping Speed (50–200 mm/s)

Stamping speed alters the forming time and directly impacts both deformation rate and heat loss during the stamping stroke. [16][19] Figure 12 shows that speed variation leads to noticeable differences in thickness change rate. Very high speed increases thinning tendency in the critical regions, whereas a moderate speed range gives a more stable thickness response. [15][24]

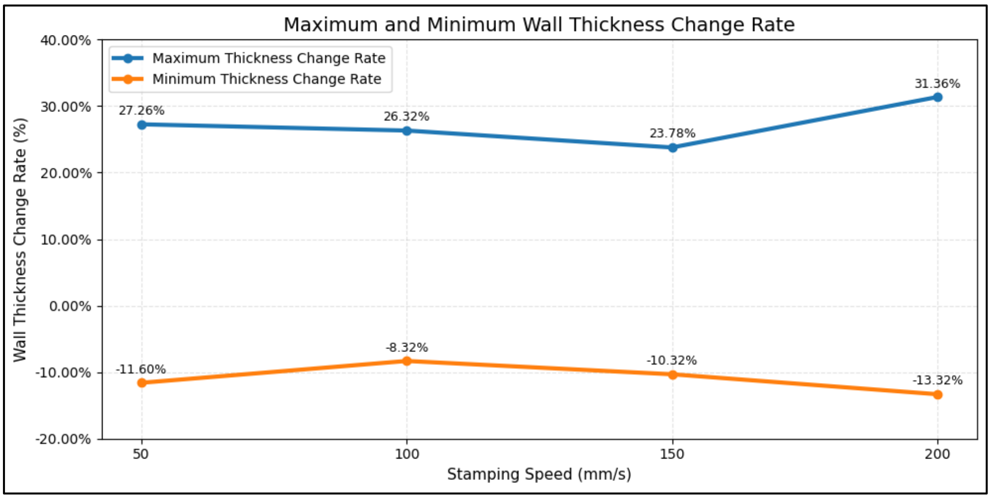
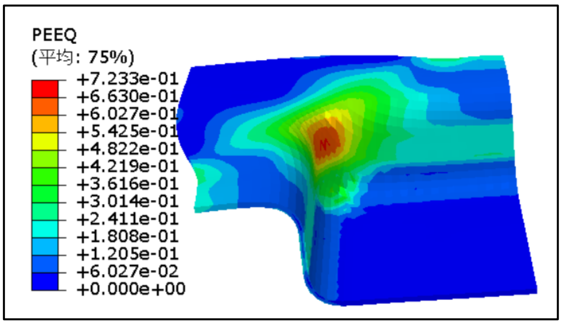
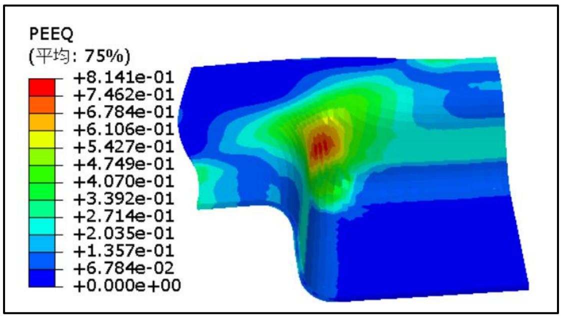


Figure 12 Maximum and minimum thickness variation rates of the blank under different stamping speeds

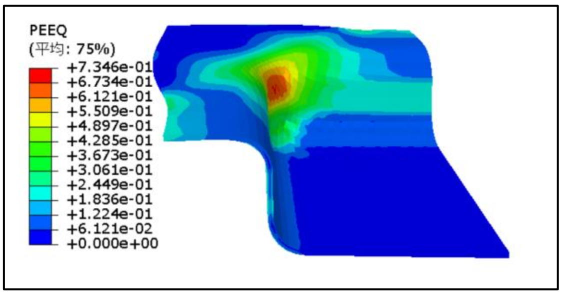
The strain field contours in Figure 13 confirm that stamping speed influences deformation uniformity. Although all cases show localization near the same geometric regions, the overall deformation pattern becomes less stable under extreme speed conditions. [17][18]



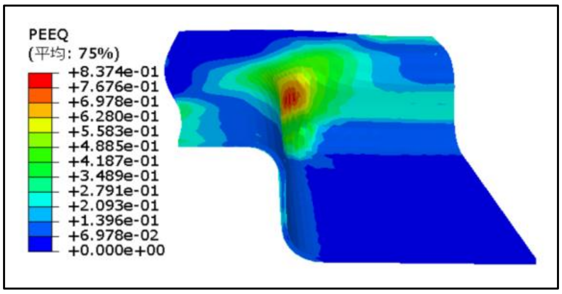
(a1) End of stamping at 50 mm/s



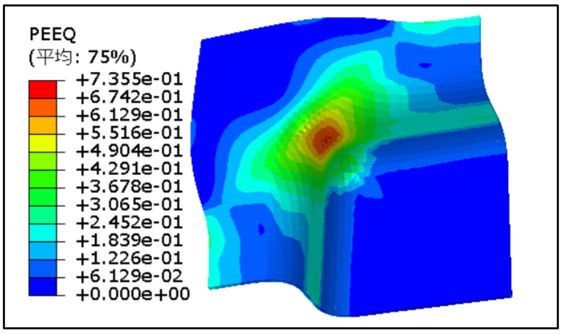
(a2) End of holding and quenching at 50 mm/s



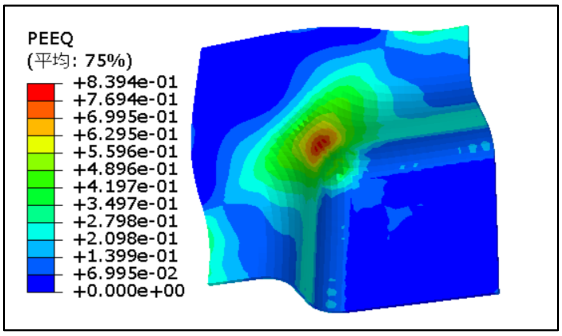
(b1) End of stamping at 100 mm/s



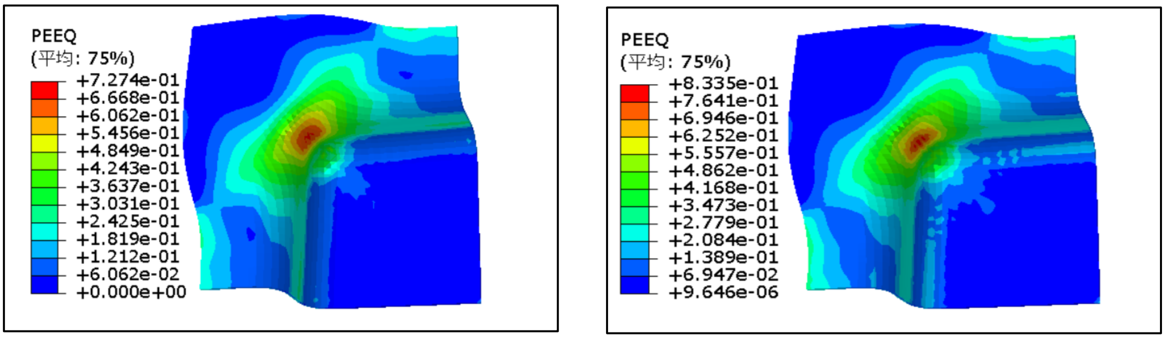
(b2) End of holding and quenching at 100 mm/s



(c1) End of stamping at 150 mm/s



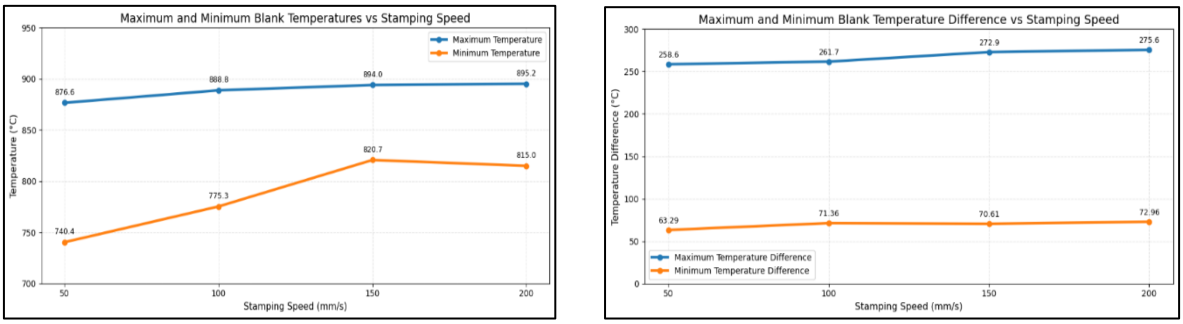
(c2) End of holding and quenching at 150 mm/s



(d1) End of stamping at 200 mm/s (d2) End of holding and quenching at 200 mm/s

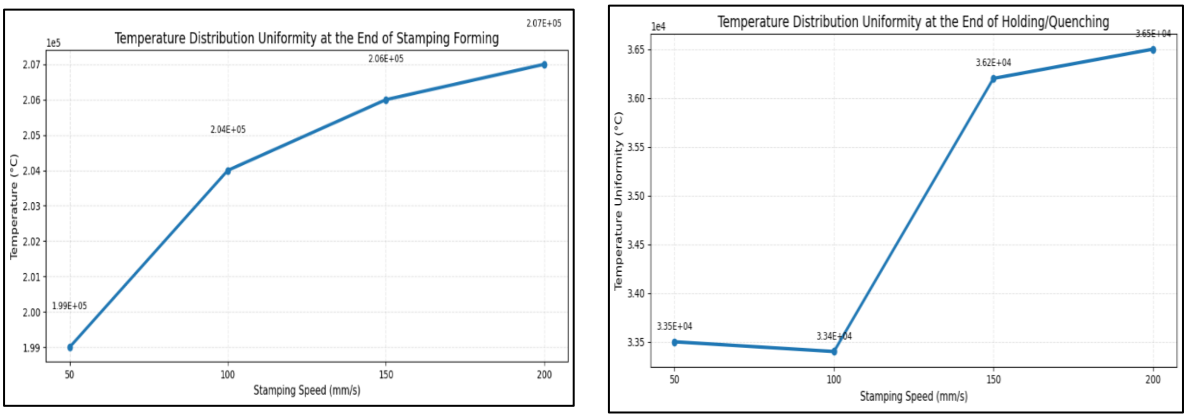
Figure 13 Strain field contour plots at the end of stamping and holding under different stamping speeds

The thermal response is shown in Figures 14 and 15. Increasing stamping speed generally preserves a higher blank temperature at the end of stamping because the contact time is shorter and less heat is lost during forming. [15][19] However, better temperature retention does not necessarily mean better thermal uniformity. The temperature uniformity curves show that high speed can still increase thermal gradients, which may reduce deformation consistency. [21][22]



(a) Stamping stage (b) Holding and quenching stage

Figure 14 Maximum and minimum temperature curves of the blank under different stamping speeds



End of stamping **(b) End of holding and quenching**

Figure 15 Temperature distribution uniformity curves under different stamping speeds

Based on the combined evaluation of thinning tendency, strain stability, and thermal behavior, the results support a practical stamping speed window of 100–150 mm/s. [17][18]

4.4. Integrated Discussion and Process Window Recommendation

The above results show that the hot stamping quality of the box-shaped part is governed by coupled thermo-mechanical behavior.[13] Thinning and strain localization are concentrated near the corner and fillet transition regions, whereas temperature non-uniformity is strongly influenced by contact sequence, heat transfer, die-entry temperature, and stamping speed.[8][24] Therefore, selecting process parameters based on a single indicator is insufficient, and a multi-indicator assessment is required.[15][17][26]

From the integrated comparison, low die-entry temperature or very low stamping speed increases the risk of excessive cooling and reduced formability during stamping, whereas excessively high die-entry temperature or very high stamping speed can worsen thermal or deformation stability in the critical regions. [23] For this reason, a process window is more practical than a single optimum point. [15]

For the 22MnB5 box-shaped part investigated, the recommended process window is as follows:

- **Die-entry temperature: 850–900 °C**
- **Stamping speed: 100–150 mm/s**

This range provides a balanced compromise between thickness safety, deformation stability, and thermal uniformity, and can be used as a practical reference for hot stamping process planning of similar box-like thin-walled structures. [17][18]

5. Conclusion

This paper presented a thermo-mechanical coupled finite element (FE) simulation study on hot stamping of a 22MnB5 steel box-shaped part. The model considered temperature-dependent material behavior, frictional contact, and interfacial heat transfer to evaluate the coupled evolution of deformation and temperature during forming and holding/quenching. The major findings are summarized as follows:

- Thinning and strain concentration mainly localize near corner/fillet transition regions, indicating that these zones govern forming stability for the investigated box-like geometry.
- Die-entry temperature significantly affects both formability and temperature-field stability. Higher initial temperature improves overall deformability but can increase thermal gradients during contact cooling. An intermediate range provides a better balance.
- Stamping speed influences forming quality through the forming time scale and heat loss during deformation. Extremely low speed increases cooling and may reduce formability, whereas extremely high speed may increase localization sensitivity and temperature-field non-uniformity.
- Based on the integrated evaluation of thinning tendency, strain uniformity, minimum forming temperature, and temperature-field uniformity, a recommended process window for the investigated part is provided.
    - die-entry temperature: 850–900 °C;
    - stamping speed: 100–150 mm/s.

The proposed window provides practical guidance for parameter selection in hot stamping of box-like thin-walled parts, particularly where corners and fillet transitions dominate quality risks.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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