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Parametric analysis of warm forming of aluminum blanks with FEA and DOE

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Abstract: The effect of temperature distribution on warm forming performance was investigated for 5083-O (Al-Mg) sheet metal blanks. Combined isothermal/non-isothermal FEA with design of experiments tools were used to predict appropriate warm forming temperature conditions for deep drawing and two-dimensional stamping cases. In the investigated temperature range of 25−250 ℃, the formability of Al-5083 alloy is found to be greatly dependent on the temperature distribution of the die and punch. To achieve increased degrees of forming, different temperature levels should be assigned to the corner and body of the die and punch. And the optimal temperature distributions for warm deep drawing and warm two-dimensional stamping are not identical.

Key words: Al-5083 alloy; warm forming; deep drawing; finite element analysis

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1 Introduction

Warm forming of lightmass materials has been investigated as an alternative manufacturing process to achieve higher formability compared with forming at room temperature due to a substantial increase in material ductility[1−8]. SHEHATA et al[1] carried out the tensile experiments of Al-Mg alloys under warm temperature conditions (20−300 ℃), and reported a remarkable increase in elongation with increasing temperature and decreasing strain rate. LI et al[3] also investigated uniaxial ductility of aluminium sheet experimentally and showed that the enhancement of strain rate sensitivity with increasing temperature accounted for the ductility improvement at elevated temperature. Additional information on the previous research efforts can be found in Refs.[3,9,10]. On the other hand, few analytical studies have been conducted on warm forming[4,9] to bring about useful predictive design tools mostly due to the non-uniform temperature distribution in the warm forming system.

Determination of optimal temperature for warm forming of sheet material is necessary to achieve the desired increased formability of complex part shapes and improved process robustness, and increased productivity. Experimental trial-error methods to determine and design temperature distribution on tooling and blank are not practical and impossible to use for all cases due to high cost, lengthy time and lack of experience. Thus, numerical simulations and analytical models are needed. Because of complex interactions between material, tooling, process and equipment parameters, implicit analytical models are only good for simple shapes and a narrow range of circumstances. Finite element analysis method was employed to validate and investigate process design for simple warm forming cases such as deep drawing[4, 9, 11]. However, for complex and large parts (such as body closure panels, structural frame parts in the automotives), FEA also has limitations in terms of computational time and accuracy in addition to lack of proper material and friction models. Due to the nature of the warm forming process, non-isothermal FEA models involving coupled thermo-mechanical analyses are required. Particularly for large parts (such as doors, hood, deck lid), large number of elements, nodes and contacts are necessary to lead to computationally long, inefficient and inaccurate results that sometime may take days. Since determination of an optimal temperature distribution usually requires multiple FEA runs, consequently non-isothermal FEA for warm forming becomes a very inefficient, expensive, and unknown in accuracy. KIM et al[10, 12] proposed an alternative FEA approach for warm forming analysis, which significantly

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reduced the number of simulations and the required simulation time. This approach is simply based on combined DOE/Isothermal/Non-Isothermal FEA runs where only a few non-isothermal FEA needs to be performed for validation at the end of the proposed procedure. The effectiveness of this method has been verified by comparison with experimental results[4, 10, 12].

There exist, in general, three numerical approaches that can be taken to determine optimal temperature distribution in warm forming: 1) Combined non-isothermal FEA/DOE approach would offer accuracy at the expense of costly and lengthy simulations, particularly for 3-dimensional large part cases. All warm forming system elements (blank, die, punch, etc) are divided into heating zones. Each zone is handled as a design factor in a DOE. This approach require non-isothermal FEA, hence, can be very lengthy especially for large parts. 2) Regional temperature levels of the blank can be considered design factors without considering heating the tooling. For this case, isothermal FEA can be used because the conduction heat transfer at the interface can be ignored. The determined temperature distribution on the blank can, then, be mapped onto the tooling regions in a non-isothermal FEA for validation analysis. With this approach, we can achieve accurate results rapidly. 3) Other optimization techniques such as adaptive controlled FEA, neural networks, and genetic algorithm can be tried to find the optimal heating mode for the warm forming process as reported in literature for various process parameters[13−15]. However, their applications can be limited if not impossible because of a large number of variables (nodes and elements). In this work, approaches 1) and 2) are presented and compared for deep drawing and 2D stamping models. The experimental validation of the FEA simulations as described in this work was done by KIM[5].

2 Temperature distribution for warm deep drawing of Al5083- isothermal FEA/DOE approach

Figs.1 and 2 show schematic diagrams of deep drawing model with four temperature zones on the blank that are considered design variables. Three different temperature levels (25, 137.5 and 250 ℃) are assigned to each region for the design of experiments. An aluminum-magnesium alloy sheet (5083) of 1 mm-thickness was used for the blank material. Elastic-plastic properties of this material at different temperatures and different strain rates were obtained from NAKA[4], and validation of the FE model for this problem was previously conducted by KIM[10,12]. Process parameters used in the FEA are presented in Table 1. The entire FE model was built using thermally-coupled four-node bi-linear axisymmetric element (CAX4RT). Isothermal simulations (neglecting heat transfer between tooling and blank) were performed using ABAQUS/standard.

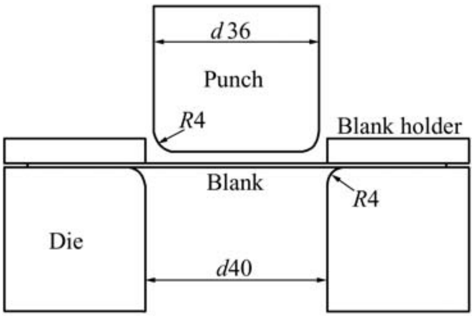

Fig.1 Schematic diagram of deep drawing FEA model

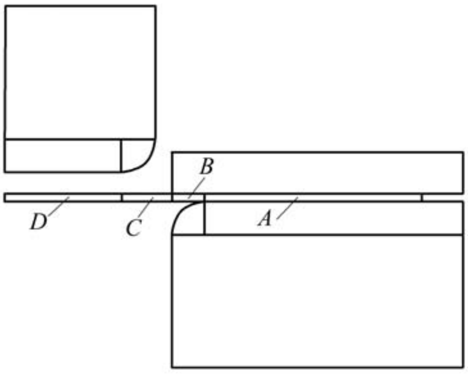

Fig.2 Schematic diagram of temperature zone partition for isothermal deep drawing

Table 1 Process parameters used in experiments and simulations

Punch speed/(mm·s^{-1})	Pressure on blank holder/ MPa	Friction coefficient	Sheet material
2.5	2	0.1	JIS-A5083P-O

In order to reduce the number of simulations and achieve an efficient analysis, the Response Surface Method was applied. Using this method, the number of required FEA runs/tests was reduced from 81 to 27 for a four-factor and three level case. The amount of material drawn successfully into the die cavity (part depth) at the failure time is considered to be a measurement of drawability. Time of failure is assumed to be when there is a 30% thinning in the blank material based on practical industrial practice.

As shown in Table 2 and Fig.3, temperature region *C* (punch corner) has the greatest effect on part depth, and next are region *A* (holding zone) and interaction *C***D* (punch corner and face). To achieve the highest formability, temperature region *A* (holding zone) should be heated to high temperature level (250 ℃), and other regions of the blank should be kept at low temperature (25 ℃). The recommended temperature levels are summarized in Table 3. Based on the main effects and interactions, a regression model can be obtained as

$$Y=9.342\,8+1.378\,5X_1-1.920\,6\,X_3-1.486\,0\,X_3^2+1.096\,4\,X_3\,X_4+\varepsilon \quad (1)$$

where X_1 is a coded variable for A, X_3 is a coded variable for C, X_4 is a coded variable for D, Y is the blank depth and ε is the residual. If t_A, t_C and t_D denote the natural variable temperature, then the coded variables are

$$X_1=(t_A-137.5)/112.5,\ X_2=(t_B-137.5)/112.5 \quad (2)$$

$$X_3=(t_C-137.5)/112.5,\ X_4=(t_D-137.5)/112.5 \quad (3)$$

According to the regression model, the predicted maximum blank depth is 12.25 mm. The actual simulation result is 12.64 mm. The prediction error is only 3.18%.

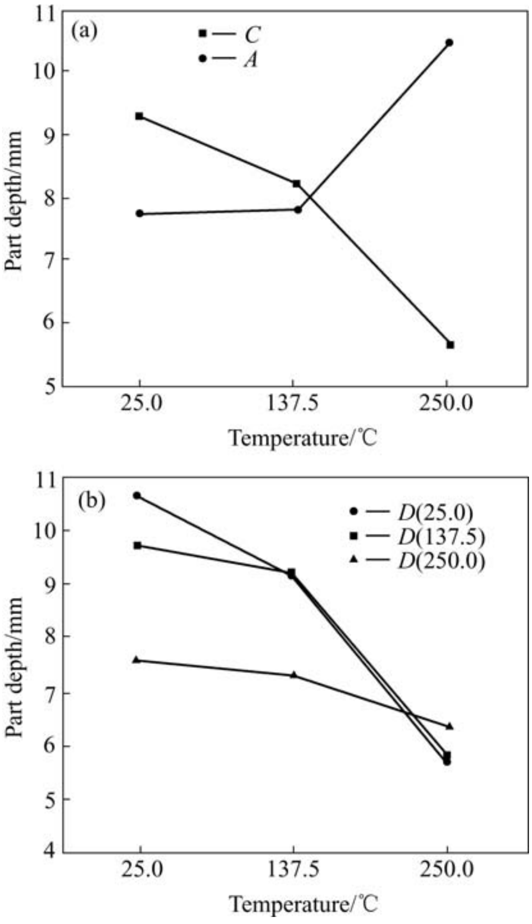

Fig.3 Main effects(a) and interactions ($C\times D$) (b) of isothermal deep drawing

Table 2 Main effects and interactions based on isothermal deep drawing DOE

Term	Importance	Effect	Term	Importance	Effect
C	1	−3.8	*B*C*	8	−1.57
*C**C	2	−3	*B*	9	−1.4
A	3	2.76	*A*A*	10	−1.36
*C*D*	4	2.19	*D*	11	−1.3
A**D*	5	−1.8	*B*D*	12	1.01
*B*B*	6	−1.6	*A*B*	13	−0.9
D**D*	7	−1.6	*A*C*	14	−0.9

Table 3 Recommended temperatures for isothermal deep drawing(℃)

Region	*A*	*B*	*C*	*D*
Temperature	250	25	25	25

3 Temperature distribution for warm deep drawing of Al-5083 non-isothermal FEA/DOE approach

In order to find the appropriate temperature distribution on the tooling components for improved formability, the second approach, Non-isothermal FEA/DOE, is performed on the same deep drawing model. In this approach, the conduction heat transfer between the blank and tooling components is included in the analysis by running thermo-mechanically coupled FEA. The heat conductance coefficient is determined according to the experimental result (1 400 W/(m·K)) by TAKUDA[11]. As shown in Fig.4(a), the tooling is divided into the following six regions: *A*—Punch face; *B*—Punch corner; *C*—Blank holder; *D*—Blank; *E*—Die corner; *F*—Die face. Due to the large number of factors, only two different temperature levels (i.e., 25 ℃ and 250 ℃) were assigned to these regions. The blank temperature (*D*) was assumed to be at the initial temperature and heat transfer is allowed between blank, tooling and surroundings (ambient temperature 25 ℃).

Using the fractional factorial design with resolution Ⅵ, one replicate, 1/2 fraction and one block, 32 simulations are performed, and the effects of each factor are investigated. As presented in Table 4 and Fig.4(b), results of statistical analysis show that the most important factor is *B* (temperature at the Punch corner), and it should be kept at room temperature while *C* (temperature at the Blank holder) and *F* (temperature at the Die face) should be at 250 ℃. The recommended temperature condition is listed in the last row of Table 4. The maximum deformed depth of the blank under these conditions is 65.25 mm.

As a conclusion, the recommended temperature condition from Isothermal FEA (Table 3) and non-isothermal FEA (Table 4) are the same but the part depths differ for the same temperature conditions due to

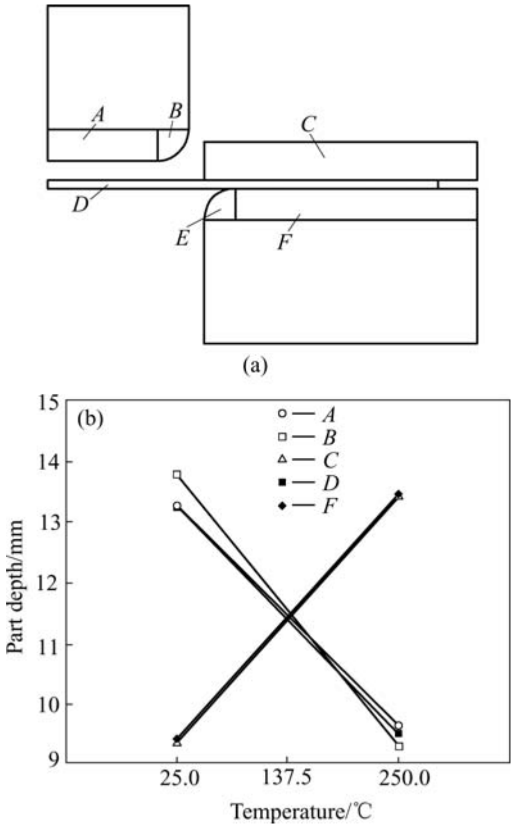

Fig.4 Temperature zone partition for non-isothermal deep drawing(a) and main effect plot(b)

Table 4 Main effects and recommended temperature conditions as result of non-isothermal deep drawing FEA

Region	Importance	Effect	Recommended temperature/℃
B		−4.84	25
C	2	4.411	250
F	3	4.258	250
D	4	−4.08	25
A	5	−3.96	25
E	6	−2.73	25

the restricted movement of the blank in case of isothermal FEA to prevent excessive movement of the temperature zones in the blank. The isothermal FEA/DOE approach contains some erroneous factors because regional temperature of the blank, not controllable in a real process, is directly assigned and held constant during the forming process. However, as proved in the previous section, relative importance of regions and appropriate temperature levels are reasonably predicted with the isothermal approach, where only temperature zones on the blank are considered, when compared with the non-isothermal FEA. Therefore, the isothermal approach can be used to obtain information at the beginning of a study with less simulation time. Consequently, a few non-isothermal simulations can be conducted to validate and refine the results, and obtain absolute drawability or formability values. As a result, appropriate temperature distribution for a given geometry, part and process condition can be determined with a significantly reduced CPU time. In this two-dimensional drawing case, each isothermal simulation took around 60 min of CPU time while non-isothermal simulations usually took more than 300 min.

4 Temperature distribution for 2D warm stamping-isothermal FEA/DOE approach

The approaches described above are applied to a two-dimensional (2D) stamping model as shown in Fig.5. The process and material conditions are the same as in the deep drawing case. Similar to the previous deep drawing problem, the sheet was divided into seven different temperature regions as illustrated in Fig.5(b). Different temperatures levels (25℃ and 250 ℃) were assigned to each region. Seven factor-two level DOE was performed using the Fractional Factorial Design with resolution Ⅳ, one replicate, 1/4 fraction and one block. Thirty two simulations were required. As shown in Table 5 and Fig.6, the most important factor is the region *F*(punch corner), and next are *C* and *E*. For the best formability, punch corner (*F*) should be kept cold, the blank holder(*A*) and punch face(*G*) should be heated, and other parts should be kept at low temperature. The depth at the recommended temperature is 89.36 mm.

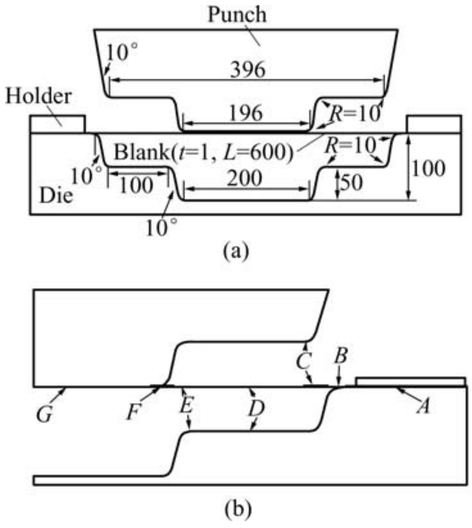

Fig.5 2D stamping model(a) and temperature zone partition for isothermal case(b)

5 Temperature distribution for 2D warm stamping non-isothermal FEA/DOE approach

Several non-isothermal FEA/DOE analyses, considering the conduction heat transfers between the

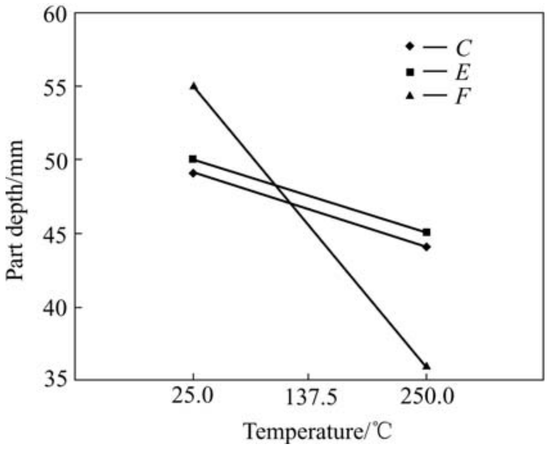

Fig.6 Main effects plot of isothermal 2D stamping

Table 5 Effects and recommended temperature condition for isothermal 2D stamping

Region	Importance	Effect	Recommended temperature/℃
F	1	−16.46	25
C	2	−6.043	25
E	3	−5.895	25
D	4	−2.074	25
G	5	1.481	250
A	6	1.324	250
B	7	−1.058	25

blank and tooling components, were performed to determine the optimal temperature distribution and the results are compared with those of isothermal FEA.

Firstly a seven factor-two level screening DOE was performed as shown in Fig.7(a). The tooling was divided into seven temperature regions (factors). The initial temperature of the sheet blank was considered another factor (*D*). Two temperature levels (25 ℃ and 250 ℃) were assigned to these eight factors. Fractional factorial design with resolution Ⅳ, one replicate, 1/8 fraction and one block was used to perform DOE analysis on these eight factors, two level problem. As summarized in Table 6 and shown in Fig.7(b), punch corner (*B*) has the most significant effect on the part depth, followed by punch face (*A*) and blank (*D*).

Table 6 Main effects of non-isothermal 2D stamping DOE Ⅰ

Region	Importance	Effect	Region	Importance	Effect
B	1	−26.8	*F*	5	−0.64
A	2	−8.71	*C*	6	−0.52
D	3	−6.63	*H*	7	−0.24
G	4	−2.33	*E*	8	−0.06

Usually, blank failure occurred around punch corner (region *B*). However, when the temperature of region *A* is 250℃ and *B* is 25 ℃, a different failure was observed in the middle of blank as shown in Fig.8, which is called ‘*L*’ failure in this work. This is because excessive heating of punch flat region (*A*) softens the material and appears to have negative effect on formability. Therefore, more investigation is required to determine the appropriate temperature levels.

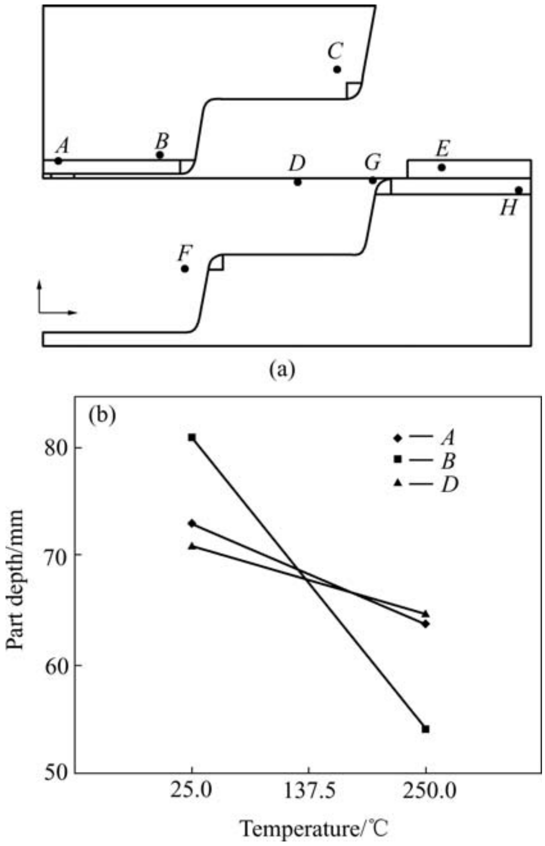

Fig.7 Temperature zones partition for non-isothermal 2D stamping(a) and main effects plot(b)

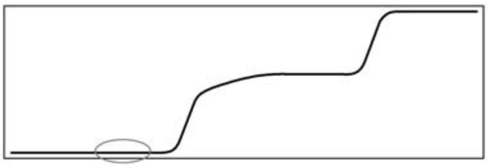

Fig.8 Failure type ‘*L*’(failure occurs near punch flat face)

Secondly, based on the first screening DOE, a Response Surface Method (RMS) was designed as shown in Fig.9(a) with five factors that showed a relatively significant effect on formability selected as design variables. Three temperature levels (25, 137.5 and 250 ℃) were assigned to each factor. As illustrated in Fig.9(b) and Table 7, punch corner (region *B*) and punch face (region *A*) are the most important factors. For the improved formability, 25 ℃ is recommended for the temperature of the punch corner (*B*) and a medium temperature for the punch flat face (*A*). To find the proper medium temperature level, the above simulations were redone using three additional medium temperatures levels 100, 150 and 200 ℃ under the same simulation conditions. The most important regions are found to be punch corner (*B*) and punch flat face (*A*) as predicted in the previous DOE. The recommended temperature is 200 ℃ for the punch flat face (*A*) and 25 ℃ for the punch corner (*B*) as summarized in Table 8. Under these temperature conditions, significant increase of formability was observed. When the temperature level is 200 ℃, the maximum part depth is 97.42 mm, while it is 88.51 mm at 250 ℃.

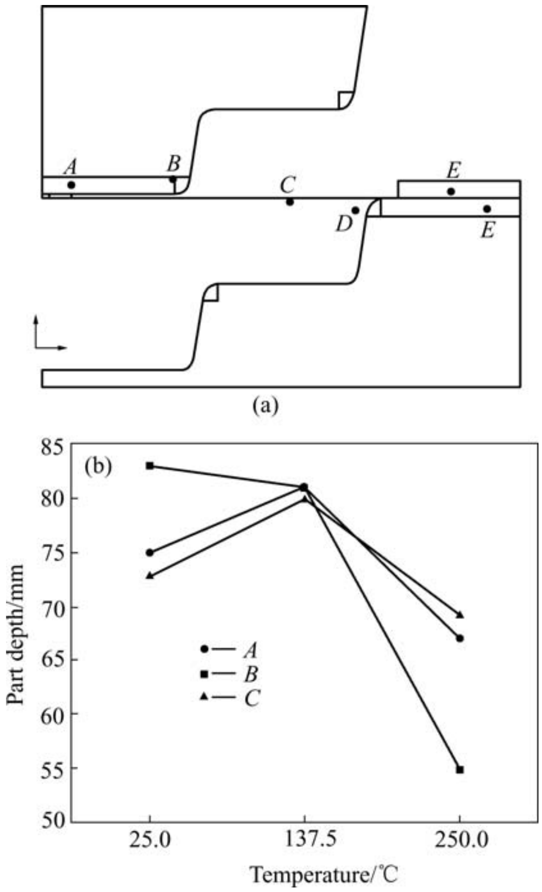

Fig.9 Temperature zone partition for non-isothermal 2D stamping(a) and main effects plot(b)

Table 7 Main effects of non-isothermal 2D stamping with RSM design

Region	Importance	Effect	Region	Importance	Effect
B	1	−14.298	*D*	4	−0.079
A	2	−4.32	*E*	5	−0.008
C	3	−2.71			

The results of the isothermal and non-isothermal methods are quite similar in the trend, although the values of part depth are different. Both of them agree to the following two facts: 1) Punch corner is the most important factor, and it should be kept at room temperature if not cooled down; 2) Punch flat face should be heated to increase the ductility of the material.

Differences between these two approaches may be due to the movement of the defined temperature regions on the blank in case of the isothermal during the process, a limitation of isothermal method. However, the isothermal approach can provide a good estimation of trend in temperature distribution. Additionally, the required simulation time can be significantly reduced compared with the non-isothermal method. Based on the results from the isothermal analysis, few additional non-isothermal simulations could be performed to validate and refine the results.

Table 8 Recommended temperature distribution for 2D stamping

Isothermal/℃				Non-isothermal/℃ (Initial temperature)
Punch	Punch corner	Die corner	Holder	Others
200	25	25	25	25

6 Conclusions

1) Combination of hot blank holder and cold punch gives higher deep drawability for the deep drawing model.

2) Warm punch (instead of hot punch) and cold punch corner appears to increase the formability of the stamping model.

3) Isothermal FEA has some limitations because the blank temperature is mainly determined by the tooling temperature. In reality, it is not a controllable factor. However, this approach could effectively predict the general trend and the relative importance of each factor with less simulation time.

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