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EXPERIMENTAL PLATFORMS AND DIE DESIGN FOR THE HOT STAMPING PROCESS

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Abstract. *A finite element model for simulating the hot stamping process was constructed to investigate the influence of the process parameters on the product formability in the present study. In order to construct the hot stamping finite element model, the material properties of boron steel at various high temperatures with different strain rates were first obtained by the empirical approach with the use of the JMatPro software. An experimental apparatus for the determination of friction coefficients and an experimental platform for measuring the contact heat transfer coefficient at elevated temperatures were both developed in the present study. With the constructed finite element model, the die design for hot stamping of a U-hat channel was investigated. Three different forming processes: bending without blank-holders, drawing, and bending with counter-pad, were designed and simulated by the finite element method. The formability of the boron steel sheet 15B22 resulted from different forming processes was examined. In order to validate the finite element analysis, the proposed hot stamping dies were manufactured and the hot stamping process for the U-hat part was implemented. The* *consistency between the finite element simulation results and the experimental data confirms the accuracy of the finite element analysis on the hot stamping of a U-hat part.*

Keywords: *Hot stamping, Experimental Platform, Finite element analysis, Die design, Friction, Heat transfer coefficient*

1 INTRODUCTION

In order to develop a lightweight vehicle for carbon exhaustion reduction, the hot stamping process has been widely used in the automotive industry to manufacture structural parts. In the hot stamping process, the boron steel sheet is first heated up to about 930 ℃ with phase changed into austenite microstructure. The hot steel sheet is then formed and subsequently quenched in the stamping dies. In the quenching process, the hot steel sheet is cooled rapidly in the closed dies, and the microstructure is transferred from austenite to martensite as the cooling rate reaches the critical cooling rate. Because of the complex manufacture process which couples the mechanical-thermal-metallurgy mechanism, it is difficult to predict the forming defects and the final product strength. Therefore, applying the finite element analysis to facilitate the tooling design for the hot stamping process is required, and the effects of the process parameters on the formability and strength of the product parts can also be examined. Although the formability of steel at elevated temperature is superior to that at room temperature, the forming defects, such as fracture and wrinkle, could still occur if the die design is not appropriate. In addition, the contact condition between the formed part and die surface could affect the efficiency of the subsequent die quenching process. Different from the conventional stamping process, the die cooling system in the hot stamping die design plays an important role to assure the final product strength. The design of cooling water channels needs to consider both the cooling efficiency and the machining cost.

In order to establish a suitable finite element model for simulating the hot stamping process efficiently, three important process parameters, such as the material properties of boron steel at elevated temperature, the coefficient of friction between sheet and die surface at elevated temperature, and the heat transfer coefficients at the sheet-die interface and between water channel and die structure, are required to be determined by experiments. In the field of friction coefficient research, Geiger et al. (2008) conducted friction coefficient measurement and calculation with the use of circular cup extension experimental approach in combination with theoretical derivation, and the obtained friction coefficient was between 0.4-0.6. Yanagida et al. (2010) carried out friction tests by conducting the flat stretch experiments, and discussed the impact of stretching speed, contact pressure and sheet temperature on friction coefficient. Ghiotti et al. (2014) studied the friction properties and wear characteristics of galvanized sheet and discussed the friction coefficient of galvanized sheet and aluminum silicon sheet. Among the process parameters of the hot stamping, the contact heat transfer coefficient is one of the important parameters which affect both the sheet formability at high temperature and the part cooling rate afterwards. Merklein et al. (2008) investigated the contact heat transfer coefficient of 22MnB5 steel at different contact pressure. It shows that the contact heat transfer coefficient becomes larger as the contact pressure increases. Tondini et al. (2009) examined the contact heat transfer coefficient of Usibor 1500 steel with various tool materials at different contact pressures. The results indicate that the tool material may affect the heat transfer coefficient. Salomonsson et al. (2009) discussed the contact heat transfer coefficient of Usibor 1500P and 22MnB5 steels. They found that the contact heat transfer coefficient might be affected by the contact pressure and varied through the contact time. Merklein and Svec (2013) further investigated the contact heat transfer coefficient between the blank and warm tools. The results could be used for the analysis of tailor blank application. In the study of the finite element analysis for hot stamping, Yu et al. (2011) studied the influence of the friction coefficient on the formability of B-pillar. Long et al. (2012) also used finite element soft-ware to examine the formability of a hot-stamped B-pillar. He proposed an optimum die design to improve the formability of the B-pillar. Xing et al. (2010) also employed the finite element analysis to examine the effects of the process parameters on the formability in hot stamping.

In this paper, a finite element model for simulating the hot stamping process was constructed to investigate the effects of the forming processes on the product formability. In order to construct the hot stamping finite element model, the material properties of boron steel at various high temperatures with different strain rates were first obtained by the empirical approach with the use of the JMatPro software. An experimental apparatus for the determination of friction coefficients and an experimental platform for measuring the contact heat transfer coefficient at elevated temperatures were both developed in the present study. The values of the friction coefficient and contact heat transfer coefficient under various die contact forces and at different temperatures, which are required in the hot stamping finite element model, were then obtained from the experiments conducted with the developed experimental platforms. With the constructed finite element model, the die design for hot stamping of a U-hat channel was investigated. Three different forming processes: bending without blank-holders, drawing, and bending with counter-pad, were designed and simulated by the finite element method. The formability of the boron steel sheet 15B22 resulted from different forming dies was then examined. In order to validate the finite element analysis, the proposed hot stamping dies were manufactured and the hot stamping process for the U-hat part was implemented.

2 THE MATERIAL PROPERTIES

The boron steel has been widely used in the hot stamping process. In the present study, the 15B22 steel was adopted. In order to obtain the material properties of 15B22 steel at different elevated temperatures with various strain rates, the tensile tests at high temperature are usually performed. However, numerous experiments are required to conduct in various high temperatures for obtaining a complete set of material properties. Instead of performing high temperature tensile tests, the material properties calculated by the JMatPro were adopted as an alternative.

The material properties of 15B22 steel including flow stress, elastic modulus, thermal conductivity, heat capacity, etc. were calculated by the JMatPro software in the present study. The flow stresses at different temperatures with various strain rates were also calculated. Fig. 1 displays the flow stresses in the temperature range between 600 ℃ and 900 ℃ with strain rate of 1 s^{-1}. While the various flow stresses obtained with strain rates from 0.01 s^{-1} to 10 s^{-1} at temperature 800 ℃ are shown in Fig. 2.

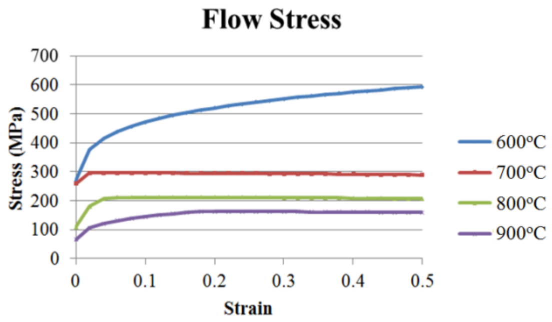


Figure 1. The calculated flow stresses with different temperatures at strain rate 1 s^{-1} by JMatPro software

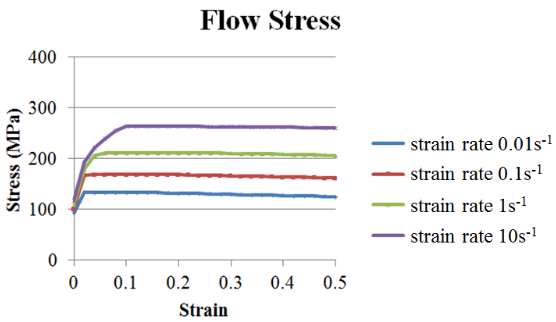


Figure 2. The calculated flow stresses with different strain rate at temperature 800℃ by JMatPro software

3 THE EXPERIMENTAL PLATFORM FOR CONTACT HEAT TRANSFER COEFFICIENT

The contact heat transfer coefficient is one of the major parameters in the hot stamping process which affect directly the heat transfer behaviour between the blank and tools. Moreover, it is also an essential parameter to be used in the finite element model for the hot stamping analysis.

The value of contact heat transfer coefficient depends on the contact pressure between die and sheet. In this paper, the contact heat transfer coefficients with different contact pressures were measured by the experimental apparatus, as shown in Fig. 3. In the experimental apparatus, a sheet specimen is placed between upper and lower tools. The contact pressure exerted by the upper and lower tools to the sheet specimen is powered by the MTS-810 tensile test machine. The thermal couples are inserted into the sheet specimen and tools, respectively, for measuring the temperature evolution paths. The inverse calculation method is then adopted to calculate the contact heat transfer coefficient based on the temperatures measured.

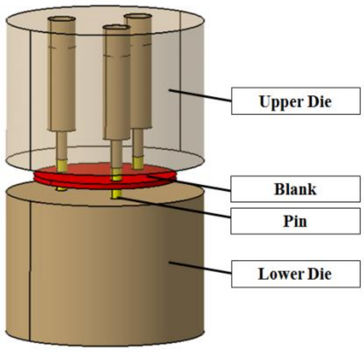


Figure 3. The illustration of contact heat transfer coefficient experimental platform

The average contact heat transfer coefficients obtained with different contact pressure are shown in Fig. 4. It is seen in Fig. 4 that the contact heat transfer coefficient increases from about 300 W/m^2℃ to about 2600 W/m^2℃ as the contact pressure increase from 0 MPa to 40 MPa. It also reveals that the contact pressure has a significant effect on the contact heat transfer coefficient.

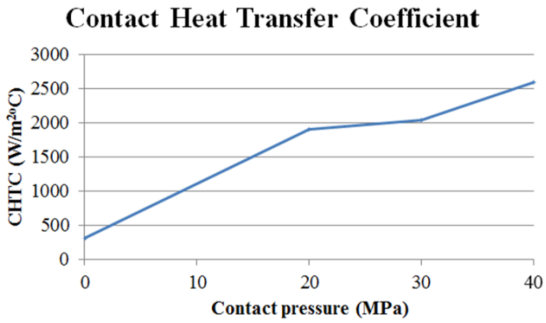


Figure 4. The average contact heat transfer coefficient with different contact pressures

4 THE ANALYSIS OF A HOT STAMPED LAB-SIZE B-PILLAR

In order to examine the efficiency of the contact heat transfer coefficient obtained from the experiments and the validity of the finite element model constructed to simulate the hot stamping process, a hot stamping process for manufacturing a lab-size B-pillar was designed and implemented. Since the effect of die contact pressure on the heat transfer coefficient and the cooling rate is the major concern in the present study, the hot stamping dies without cooling channels were designed.

4.1 The finite element model

The finite element model for the hot stamping of a lab-size B-pillar without cooling system was established, as shown in Fig. 5. The sheet thickness is 1.2 mm. The finite element analysis is performed with the use of the PAM-STAMP 2G software. In the finite element simulations, the initial temperature of the blank is 930 ℃, and the transfer time of the sheet from the furnace to the press is 4 seconds. Various die forces were specified in the finite element simulations, respectively, to examine the effect of the die forces on the part cooling rate.

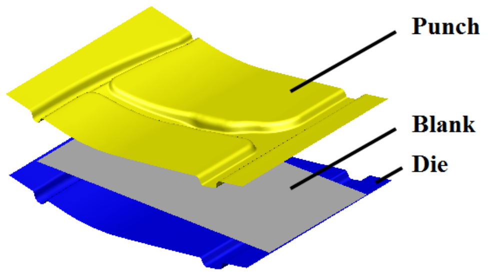


Figure 5. The finite element model of a lab-size B-pillar

4.2 The temperature analysis for the transfer process

In the experiment design, the sheet specimen was heated up to 930 ℃ in the furnace and then was transferred to the press in 4 seconds. In the finite element simulation, the initial temperature of the sheet blank was also set as 930 ℃ and the heat loss by the convection with air and the high temperature radiation during the sheet transfer process was considered. The simulation result of the temperature variation of the sheet blank in the transfer process is shown in Fig. 6. It is observed that the temperature of the blank drops from 930 ℃ to 810.6 ℃ within 4 seconds. The simulation result of the temperature distribution of the sheet blank at the end of transfer process is shown in Fig. 7. A uniform temperature distribution is noted in Fig. 7.

In order to validate the temperature prediction by the finite element simulation, the temperature variation of the sheet blank during the transfer process in the actual experiment was also recorded by using a thermal camera. The recorded temperature distribution after 4 seconds is shown in Fig. 8 by thermal images. It is seen in Fig. 8 that the temperature distribution of the sheet blank is quite uniform with a value about 800 ℃. It indicates that the finite element simulation result of the sheet blank temperature is well consistent with the experimental data.

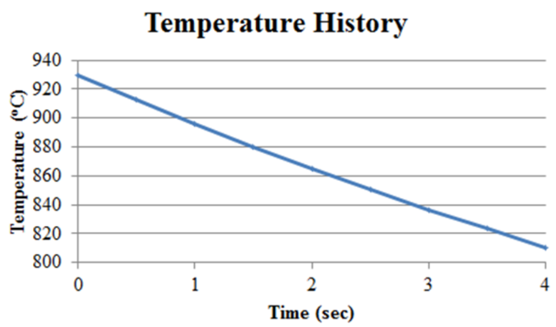


Figure 6. The simulation temperature history of blank in transfer process

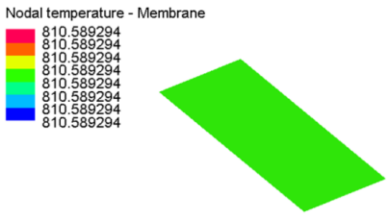


Figure 7. The simulation temperature distribution of blank at the end of transfer process

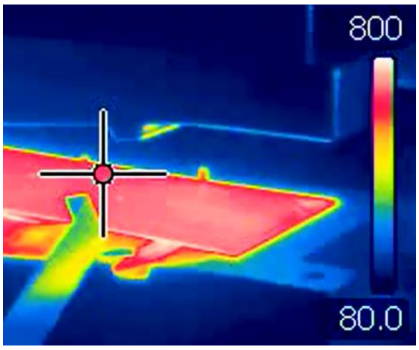
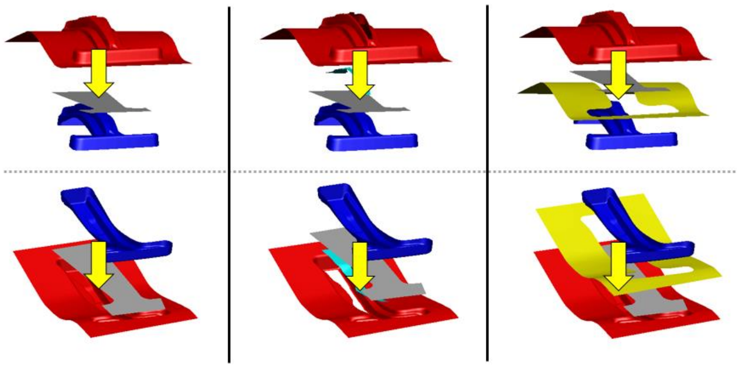


Figure 8. The experiment temperature distribution of blank at the end of transfer process

5 HOT STAMPING DIE DESIGN

For the hot stamping die design, both the formability of the boron steel at elevated temperatures and the cooling rate of the formed part in the quenching process need to be considered. In addition to the die surface design, the forming mechanism is also one of the key factors that affect the formability boron steel. The forming mechanism contains: direct forming, forming with pad, and drawing with blank-holders. Each forming mechanism also has different forming directions including forward direction forming (punch upside) and reverse direction forming (die upside). Fig. 9 illustrates various forming mechanisms for stamping a B-pillar which was used as a benchmark in Numisheet 2008 (2008). The upper three types shown in Fig. 9 are of reverse direction forming.

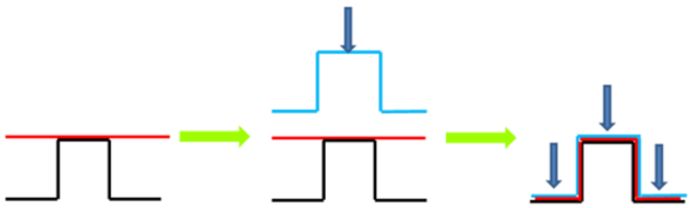


(a)Forming (b)Forming wiht pad (c)Drawing with holder

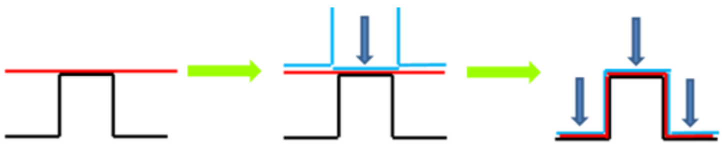
Figure 9. Various forming mechanisms of Numisheet 2008 benchmark B-pillar (2008) [11]

It is to be noted from Fig. 9 that the formability of blank sheet may be affected by the non-flat contact between blank and tool after the blank is positioned by gravity due to forward or reverse direction forming. However, this phenomenon may not occur as the blank and die are in well-flat contact as in U-hat tool model shown in Fig. 10.

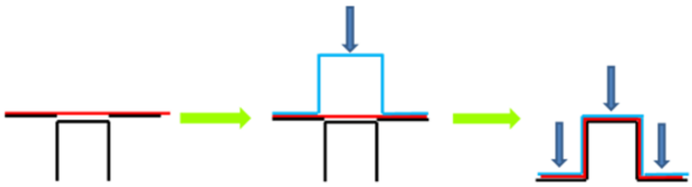
In order to realize the effects of forming mechanisms on the formability of sheet blank, the stamping of U-hat shape and M-shape, which are the cross sections often seen in the hot stamping automotive parts, were examined in this study. Fig. 11 displays the thinning ratio distributions obtained from the finite element simulation results for stamping a U-shape part with different forming mechanisms. From the simulation results, it finds that the forming mechanisms with direct forming and forming with pad does not affect the thinning ratio significantly. However, the forming mechanism in drawing with blank-holders affects the thinning ratio significantly due to the constraint of material flow from blank-holders.



(a)Forming

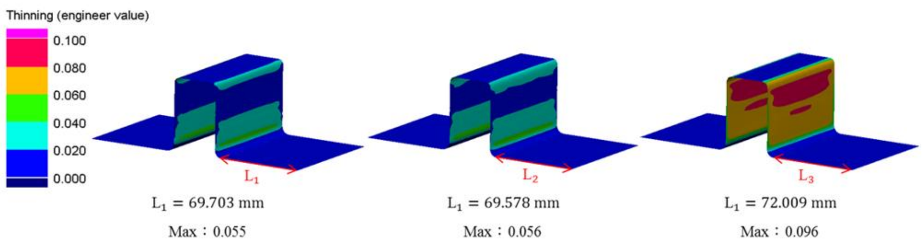


(b)Forming with pad



(c)Drawing with holder

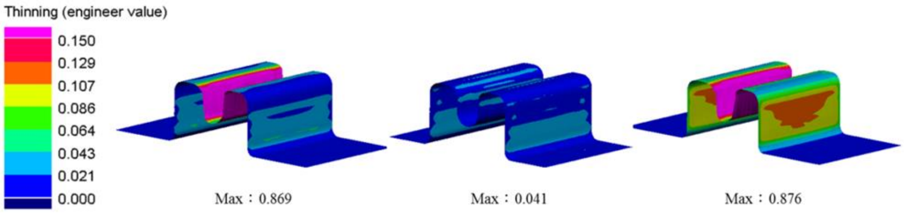
Figure 10. Various forming mechanisms of U-hat shaped tool



(a)Forming (b)Forming with pad (c)Drawing with holder

Figure 11. Analysis results of thinning ratio distribution of U-hat shaped tool

The simulation results of thinning ratio distributions for an M-shape part with various forming mechanisms are shown in Fig. 12. It is found from Fig. 12 that the forming mechanism affects the sheet formability significantly. For the forming mechanisms in direct forming and drawing with holder, the material flow of blank in the center region of M-shape is constrained as the outer side region of M-shape is forming. So, the fracture defects are apt to occurring in the side wall of center region of the M-shape part. However, for the forming mechanism in forming with pad, the blank in the center region of M-shape part is firstly formed and then followed by other regions of the part. It helps for preventing the larger thinning at the center region of the M-shape part.



(a)Forming (b)Forming with pad (c)Drawing with holder

Figure 12. Analysis results of thinning ratio distribution of M-shaped tool

Moreover, the cooling rate of the formed part which directly affects the product strength is the other key point to be considered for the hot stamping die design. In order to control the cooling rate of the formed part, the cooling system design for the hot stamping dies is an important issue. For designing a cooling system for hot stamping dies, the effects of cooling system design parameters including cooling channel diameter, distance between die surface and cooling channel edge, distance between cooling channels, velocity of coolants, etc. on cooling ability need to be investigated. The flat die surface and the U-hat shaped dies are the basic models used to examine the efficiency of the cooling system design. With these models, the database required for the cooling system design can be constructed and applied to the cooling system design for hot stamping tools of automotive structural parts.

6 EXPERIMENT OF HOT STAMPING A U-HAT PART

The die design rules for hot stamping parts were applied to the study of hot stamping a U-hat part by the finite element analysis and the experiments were also conducted to validate the design rules. In order to validate the formability of the hot stamping U-hat part, the forming mechanisms including forming with pad and drawing with blank-holders were discussed in this study. Fig. 13 and Fig. 14 display the thickness distributions obtained from simulation results and experimental data with these two forming mechanisms, respectively. From the simulation results, it reveals that the maximum thickness reduction is 0.05 in drawing with blank-holders and is 0.016 in forming with pad. And it also finds that the maximum error between simulation results and experimental data is about 4%. It shows that the simulation results are well consistent with the experimental data.

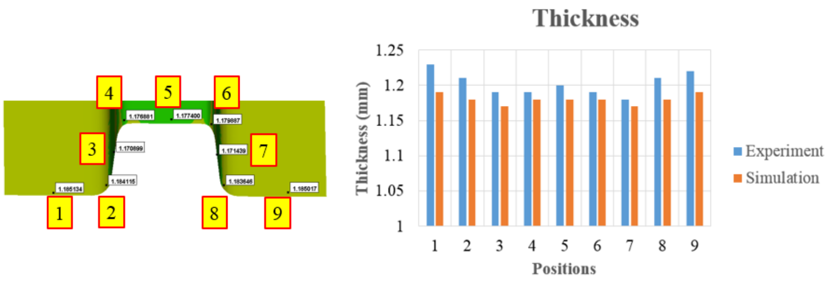


Figure 13. Experimental and simulation results of thickness distribution of U-hat shaped tool in forming with pad mechanism

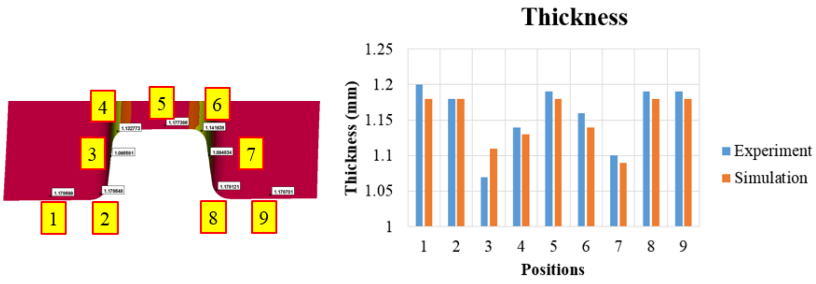


Figure 14. Experimental and simulation results of thickness distribution of U-hat shaped tool in drawing with holder mechanism

7 CONCLUDING REMARKS

The characteristics of the contact heat transfer coefficient and the die design for the hot stamping process was studied with the use of the finite element analysis in the present study. It has been demonstrated that the material properties of boron steel at various high temperatures with different strain rates could also be obtained by using the JMatPro software. The experiment platform for measuring the contact heat transfer coefficient has been constructed as well. The characteristics of contact heat transfer coefficient between 15B22 steel blank and dies were also investigated. As expected, it shows that the contact heat transfer coefficient increases as the contact pressure increases. Using the constructed finite element model, the heat transfer during the hot stamping process was examined. It indicates that the finite element simulation result of the sheet blank temperature is well consistent with the experimental data. The formability for hot stamping of a U-hat channel was also investigated with three different forming processes: bending without blank-holders, drawing, and bending with counter-pad. From the simulation results, it reveals that the forming mechanisms with direct forming and forming with pad does not affect the thinning ratio significantly. However, the forming mechanism in drawing with blank-holders affects the thinning ratio significantly due to the constraint of material flow from blank-holders. It reveals that the forming mechanisms are the important factors which affect the product formability significantly. In order to validate the finite element analysis, the proposed hot stamping dies were manufactured and the hot stamping process for the U-hat part was implemented. The accuracy of the finite element analysis on the hot stamping of a U-hat part was then validated by comparing the simulation results with the data obtained from the experiments.

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