Research on hot stamping and forming technology of variable strength hot stamping of high-strength steel inone mold with multiple partitions

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In this study, we conducted an investigation into the multi-zone variable-strength hot stamping and forming technology within a single die. This investigation encompasses the crucial technologies of simulating and analyzing variable-strength (Tailored temperature process) hot stamping and forming, die design, part development, and testing. We have undertaken extensive research and development in these areas. The research involves analyzing part data and material requirements for simulating variable-strength hot stamping and forming, determining zoning requirements for mold design and development, and conducting trial production and testing of variable-strength hot stamping and forming parts. The simulation analysis includes hot stamping forming simulation analysis and forming simulation/mold temperature control and cooling analysis of the mold, with a focus on part data, material requirements, and part performance requirements. Additionally, we have developed a variable strength forming die and the associated heating and cooling system. Multiple batch prototyping with varying process conditions was carried out, and the fundamental mechanical properties of the parts were tested. Furthermore, the paper discusses the key aspects of material and processing development in the high-temperature zone of the variable strength forming die.

Keywords: High-strength steel; Hot stamping and forming; Variable strength forming; Forming simulation; Materials and testing.

1. Introduction

Variable-strength hot stamping and forming technology is extensively employed in automobile manufacturing to fabricate body parts with superior mechanical properties and intricate shapes. This optimization of the body structure enhances automobile safety performance and reduces the extent of collision damage [1]. High-strength steel hot stamping technology has experienced rapid development worldwide, particularly in China, where it is primarily applied in the manufacturing of high-strength steel plates for automobiles [2]. In order to achieve variable strength designs for parts, hot stamping and forming technology has been studied to adjust process parameters, such as heating temperature and cooling rate, for high-strength steel plates with varying strength levels. This enables the realization of strength differentiation in different regions of the parts, thereby enhancing the stiffness and fatigue resistance of the parts [3]. Recent research literature indicates that application deve lopment for multi-die variable strength hot

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stamping and forming technology has prompted the demand for efficient engineering methods [4].

Furthermore, achieving Tailored Properties typically involves controlling the internal structure or properties of the material to meet specific engineering requirements. Material properties can be tailored by regulating aspects such as organization, physical properties, and chemical properties. For high-strength steel plates, the steps to achieve Tailored Properties include material design, customized temperature treatments, local mechanical property modulation, and forming and processing.

The primary focus of this paper is on the method of achieving multiple strength partitions on a part without altering the material, achieved through special tooling design without the use of spliced plates, differentially thick plates, or altering the heating equipment of the blank.

2. Variable strength hot stamping and forming simulation analysis

2.1. *Part data and material requirements*

Variable strength forming part shape and size, see Figure 1 shows. The part approximates a U-shaped part with a flange. One of the A area for the hard zone, B1 and B2 is a soft zone, T1 and T2 is a hard - soft transition zone. The material composition of the variable-strength molded part is shown in Table 1, and the mechanical property requirements for the different zones are shown in Table 2.

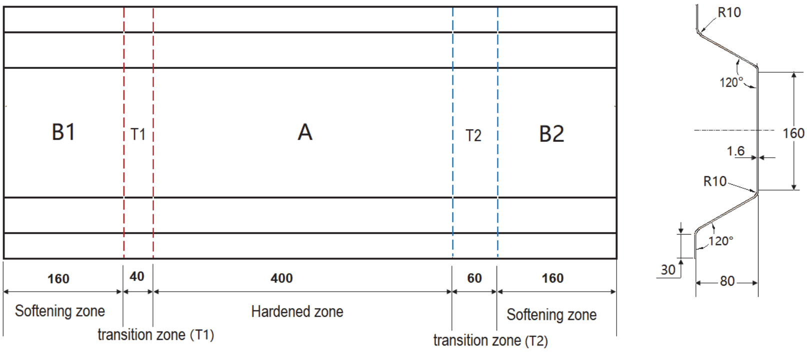

Fig. 1 Diagram of a one-mold 3-section variable strength forming part and definition of partition parameters

Table 1 Chemical Composition of 22MnB5 steel (wt%)

C	Mn	P	S	Si	Al	Ti	B
0.2-0.25	1.1-1.4	<0.25	<0.008	0.15-0.35	>0.015	0.02-0.05	0.002-0.005

Table 2 Mechanical Property Requirements for Variable Strength Forming Parts

No.	**Part strength zone**	**Target data requirements**
1	Harden Zone	Tensile strength ≥ 1300MPa, yield strength ≥ 950MPa, A50 ≥ 6%
2	Soft Zone (Two)	750MPa ≤ tensile strength ≤ 850MPa, A50 ≥ 13%
3	Transitional zone (Two)	Length 40mm and 60mm, hardness between hard and soft areas

2.2. *Forming simulation analysis*

The mechanical property requirements of variable strength formed parts are shown in Table 2. The material modeling for the hot stamping simulation is based on the 22MnB5 standard material database model. Hot stamping forming process simulation model, see Figure 2. hot stamping forming simulation focuses on the mechanical properties of the soft zone and the mechanical properties of the transition zone with the hard zone, using the simulation of the forming process as follows:

- Material: 22MnB5 AlSi coated plate, plate thickness 1.6mm
- Sheet heating process: room temperature -890 °C (120 seconds) - holding 930 °C (210 seconds)
- Mold temperature setting: hard zone A module (water cooling): 25-35°C. Soft zone hot block temperature, 400°C, 450°C and 500°C for calculation and simulation.
- Forming holding process: when other conditions remain unchanged, the mold closing time is 5s, 15s,and 18s, respectively, to predict the tissue transformation and mechanical properties of the soft zone.

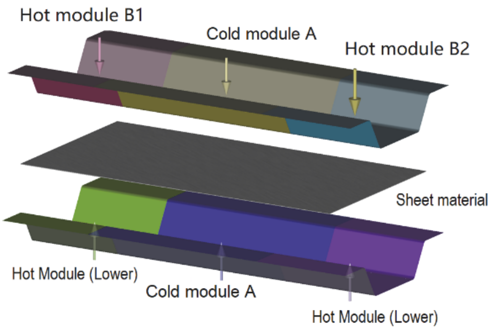

Fig. 2 Model for forming simulation of variable-strength parts

2.3. *Forming process and simulation results analysis*

Taking the lowest soft zone temperature of 400°C and the hard zone temperature of 20°C as examples, the simulation results can predict the mechanical properties obtained between the specified process goals. Under the temperature field forming conditions illustrated in Fig. 3, the distribution of martensite content in different parts of the component is depicted in Fig. 4. A more detailed breakdown reveals the percentage of bainite distribution in different parts of the component, as shown in Fig. 5. Figure 6 illustrates the Vickers hardness in different regions, indicating that the flange side is cooled earlier, leading to a slightly higher martensite content and greater hardness than the side walls of the component. The bottom closed mold contact and compression force are more uniform, resulting in almost entirely martensitic content and the highest Vickers hardness.

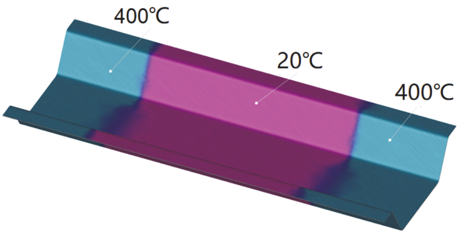

Figure 3 temperature distribution of the part after molding and holding

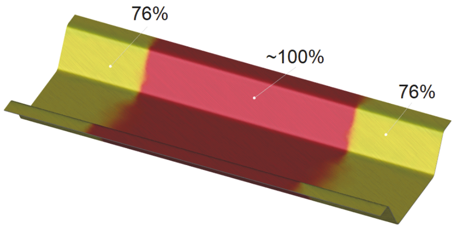

Figure 4 martensite content distribution in different parts of the part

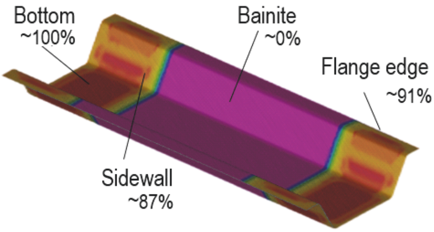

Fig. 5 Distribution of bainite content of parts under set process conditions

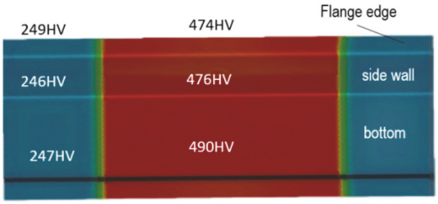

Fig. 6 Predicted Vickers hardness of different parts

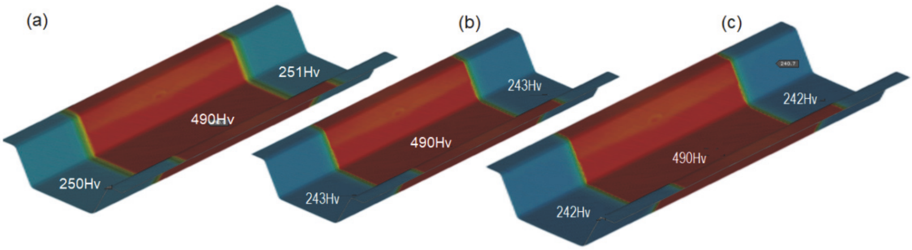

Fig. 7 Predicted Vickers hardness for different holding times: a) holding time 5 seconds; b) holding time 15 seconds; c) holding time 18 seconds.

The simulation results for different holding times ranging from 5 sec to 18 sec under the same molding conditions are depicted in Figure 7. In Fig. 7a, the Vickers hardness of soft zone B1 is 250Hv, A zone is 490Hv, and B2 zone is 251Hv at a holding time of 5 s. At a holding time of 15 s, B1 and B2 zones exhibit a hardness of 243Hv, while A zone maintains a hardness of 490Hv, as shown in Fig. 7b. When the holding time is extended to 18 seconds, as shown in Figure 7c, the A zone exhibits a hardness of 490Hv, while B1 and B2 zones both display a hardness of 242Hv. The model's calculation results indicate that a minimum holding time of 5 seconds has already achieved the desired outcome. Furthermore, extending the holding time will result in a more uniform hardness in the soft zone.

3. Variable-strength hot stamping and forming mold design and development

3.1. *Module design of the mold*

In line with the requirements for the planning of the variable strength hot stamping experiment, the mold is designed with three modules: the middle A hard zone module and the B1 and B2 soft zone modules at its two ends, as depicted in Fig. 8. The soft zone is heated by the heating rods integrated into the module, while the hard zone is equipped with a cooling water channel. Temperature sensors are installed in each zoned module and are controlled by a multi-point temperature detection and heating control system. To minimize the dissipation of heat from the soft zone heat module, a ceramic heat-insulating pad is positioned directly between the heat module and the bottom plate of the mold, and a lightweight adiabatic material is applied outside the heat module for insulation. These measures are implemented to reduce energy loss from the heat module. The connection of the cold module of zone A with the heat modules of B1 and B2 involves a small gap on the mold surface and a larger gap under the mold surface to minimize heat conduction between the cold and hot modules, thereby facilitating the mechanical properties of the transition zones T1 and T2 between the hard and soft zones of the variable-strength molded parts.

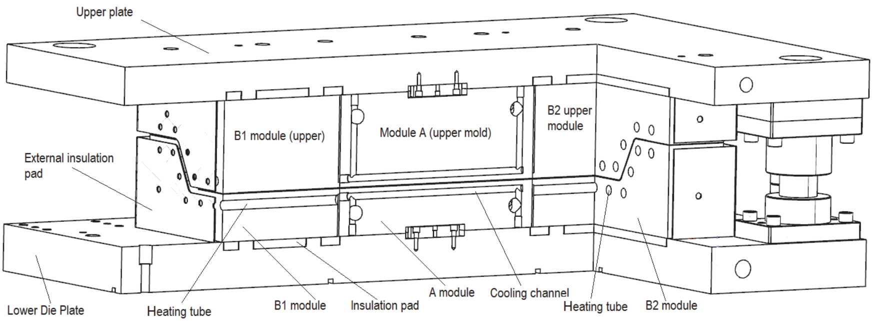

Fig. 8 Structure of hot stamping experimental mold with one die and three temperature zones

3.2. *Development of heating and cooling system for variable strength forming molds*

Based on the simulation results, the cooling water channel of the A zone module is designed to be longitudinally arranged by water, with water being channeled out from the front and rear ends of the upper and lower pads of the mold. For the B1 and B2 soft zone modules, electric heating tubes are arranged along the cross-section shape of the parts, as shown in Fig. 9a. Each electric heating tube is equipped with a temperature sensor, and the set and real-time temperatures of each heating tube are displayed on the display terminals. Furthermore, multi-point module temperature sensors are employed to continuously record the temperature of the upper and lower modules in the B1 and B2 soft zones, as depicted in Figure 9b. During the hot stamping process, as the mold opens, the surface temperature of the hot module will decrease due to heat dissipation. The heating automatic control system regulates the temperature of the heating tube to compensate for the heat loss during mold opening, thereby maintaining the temperature of the module's die surface for the molding process.

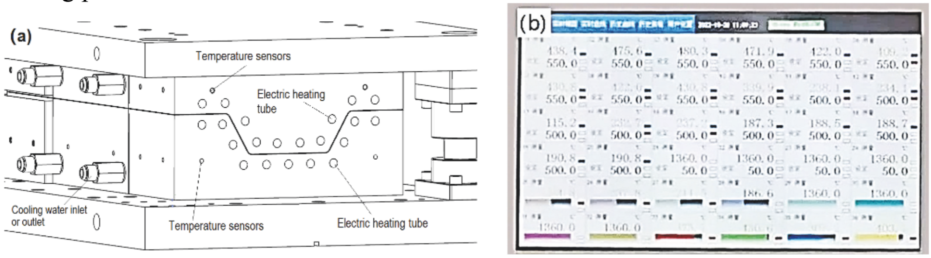

Fig. 9 Electric heating pipe and temperature detection system: a) Arrangement of temperature measuring thermocouple; b) Temperature monitoring and displaying system of heat module heating

4. Trial production and testing of variable-strength hot-stamped molded parts

4.1. *Tensile strength test of variable strength hot stamped parts*

In order to simplify the description, the test is based on the tensile experimental data of the standard sampling of hot stamping and forming parts with B1/B2 soft zone temperatures of 400°C, 450°C and 500°C, as shown in Table 3.

Table 3 Tensile strength test results of formed parts under different soft zone mold temperatures

Module Heating process (AlSi coated sheet)	Maximum tensile strength of soft zone B1/B2 (MPa)	Elongation after fracture (%)	Maximum tensile strength of hard zone A (MPa)	Elongation after fracture (%)
B1/B2 - 400°C	842	13.5	1350	10.2
B1/B2 - 450°C	793	13.8	1380	10.8
B1/B2 - 500°C	787	15.2	1430	9.2

When the process conditions involve high module temperature in the soft zone, the A zone meets the requirements of tensile strength ≥1300MPa and A50≥6%, while the B1/B2 soft zone is close to the target requirements with a tensile strength ≤750MPa and A50≥13%. Tests indicate that further increasing the die temperature of the soft zone can lead to a reduction in the tensile strength of the soft zone. However, this would result in excessively high mold heating energy consumption and have a greater impact on the service life of the hot mold.

4.2. *Hardness test of transition zone of variable strength hot stamped parts*

From the test data in Figure 10, it is observed that for the variable strength molded parts with a preset 40mm transition zone, the actual transition zone ranges between 35-48mm, while for the preset 60mm transition zone, the actual transition zone ranges between 55-63mm. The hardness changes exhibit a linear trend, which aligns with the requirements of the strength transition zone from the hard zone to the soft zone. The test results indicate that at a soft zone module temperature of 500 °C, the uniformity of the parts is better, thereby confirming the conclusion drawn from static tensile experiments that 500 °C is the optimal temperature.

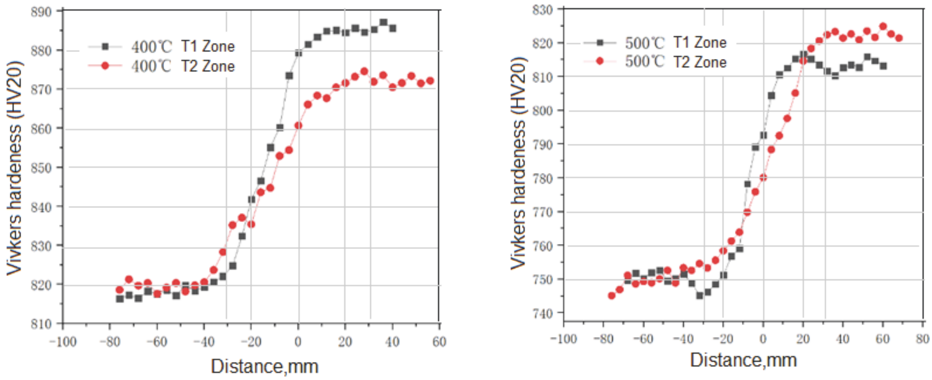

Fig. 10 Soft zone mold temperature and hardness test of transition zones T1 and T2: a) Soft zone mold temperature 400°C; b) Soft zone mold temperature 500°C.

4.3. *Organization analysis of hard and soft zones of variable strength hot stamped parts*

The metallographic structure of the hot stamped formed parts in different sections is analyzed as depicted in Fig. 11. The organization in the soft zone is primarily ferrite + bainite (F+B), while the strengthened part of zone A consists mainly of full martensite. The sidewalls in zone A exhibit slightly different tissue phases based on the mold closing time and compression force. Additionally, Figure 11c illustrates the appearance of bainite + martensite organization in the sidewall of the hard zone.

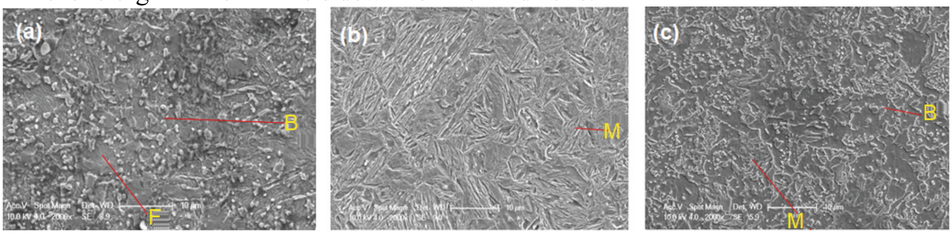

Fig. 11 Organization and strength of hot stamped parts in different zones: a) B1 soft zone organizer is F+B (ferrite+bainite), tensile strength of 734MPa; b) A zone bottom full martensite organization, tensile strength of 1492MPa; c) A zone sidewalls of the bainite + martensite organization, tensile strength of 1249MPa.

The metallographic structure inspection images of the hot-stamped formed parts sampled from different sections are presented in Fig. 11. The organization in the soft zone primarily consists of a ferrite + bainite structure (F+B), while the strengthened part in zone A predominantly exhibits full martensite. The tissue phases in the sidewalls of zone A vary slightly depending on the mold closing time and compression force. Figure 11c illustrates the presence of bainite + martensite organization.

It is evident that in the case of variable strength forming, different parts are subjected to complex temperature zone changes and are influenced by the clamping state. The organization transformation is not entirely consistent, especially in the sidewall where the clamping and contact pressure do not meet the design conditions, resulting in varying mechanical property changes.

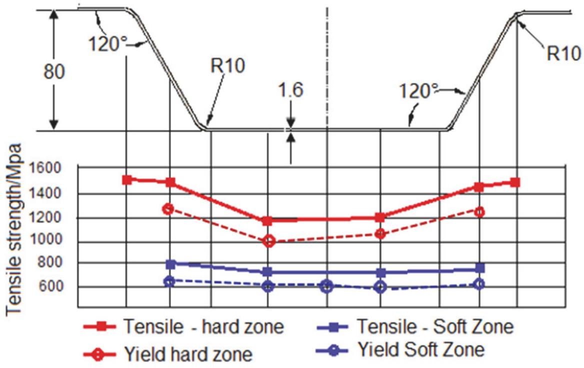

Fig. 12 Diagrams of tensile and yield strength states in hard and soft zones (test data selected from cross-sectional segments of zones A and B1, respectively)

The distribution of tensile and yield strengths in the hard and soft zones of variable strength formed parts is illustrated in Figure 12, showcasing different locations on the same section. It is evident that the fluctuation of tensile strength in the hard zone is more pronounced, while the fluctuation of tensile strength and yield strength in the soft zone at the same cross-section is less pronounced. The cooling rate of the hard zone is influenced by the contact pressure between the sheet and the mold, as well as the positive pressure at the bottom of the U-shaped parts. The insufficient force to overcome the material's deformation resistance during the hardening process is one of the reasons for the non-uniform strength at the bottom of the hard zone. Further research focus is needed to control the consistency of the strength in the hard zone.

5. Conclusion and outlook

This study delves into the one-die-multipartition variable-strength hot stamping and forming technology, conducting an in-depth investigation into the key technologies of variable-strength hot stamping and forming simulation and analysis, mold design, part development, and testing. By extensively analyzing material data, mechanical property requirements, and mold design, a method for achieving multiple strength partitions on a part without the use of spliced plates, differential thickness plates, or heating equipment that alters the blank is realized. Furthermore, experiments and analyses of the simulated forming process confirmed that the expected mechanical property requirements can be met by using 22MnB5 AlSi coated plate sheet with appropriate heating processes and mold temperature settings. A mold structure with sub-module function was designed, and corresponding heating and cooling systems were developed to provide reliable technical support for variable strength hot stamping forming.

During the trial production and testing stage, mechanical property data of each region of the formed parts at different soft zone mold temperatures were obtained through tensile experiments and hardness tests. It was verified that the mechanical properties of the soft and hard zones under specific temperature conditions meet the design requirements.

Additionally, metallographic analysis and mechanical property observation provided reliable data for further research.

The use of Tailored Properties to achieve the rational matching of strength and toughness required for body structure design is an important technology, especially since it can be implemented without changing the conditions of the existing production line equipment. However, the mold heating required to achieve the soft zones of the mold increases the complexity of the mold and raises the requirements for multiple mold materials. This technology is currently facing challenges from the application of laser spliced plates. Lastly, the heating system of the hot module of the mold, which adds additional energy consumption for hot stamped parts, is also a difficult challenge to overcome.

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