1. Introduction

Hot stamping of boron steel has become more and more popular in the last decades due to the increasing demands for the vehicle lightweight and crashworthiness improvement. Hot stamped components are manufactured by heating sheets to austenitization in a gas furnace, and then simultaneously forming and quenching in a die set, which has an advantage on the improvement of formability and decrease of springback.1) In recent years, more stringent requirements for the vehicle crashworthiness bring new challenges that the hot stamped components should possess different mechanical properties in different regions. A partial region of the components should have an increased tensile strength to preserve the structural integrity under high dynamic load, whereas the other region should own an increased elongation to improve the capacity of energy absorption.2)

For the purpose of tailoring the microstructure and mechanical properties of hot stamped components, some derivative forming processes developed from the conventional hot stamping have emerged. Tailored welded blanks (TWBs) and tailored rolled blank (TRBs) were employed to manufacture the components with gradually changed properties in hot stamping.3–7) These two methods increase the costs of the tailored blank production and put forward higher requests for the tool design. The hot stamping using the tailored die quenching was developed, and it changed the mechanical properties of components at different regions by the various cooling rates.8–12) This method does not need changes on the blank production process, but it increases the complexity of the mold design and reduces the production efficiency. Using an additional annealing was a new method for producing tailored components as well, by which a soft zone at the components can be acquired after hot stamping.13) The partial annealing method is easier to be applied on the traditional hot stamping line, but annealing tends to result in the decrease of the part’s forming precision.

Likewise, partial austenitizing that heating the different regions of blank to different temperatures was a feasible process to obtain a tailored component. The high-temperature region of blank is heated above the final austenite phase transformation temperature Ac, to form a complete martensite microstructure after hot stamping. The blank in low-temperature region is heated below Ac temperature, to form a mixed microstructure of ferrite, pearlite and martensite with higher elongation. Hot stamping using partial heating is more easily accomplished in the industrial practice without the need for changing the original hot stamping equipment, and it can also guarantee the forming precision of the part. However, only a few investigations on the hot stamping using partial heating were put forward. Mori et al.14) and Liang et al.15) investigated the hot stamping using resistance heating to produce components with tailored properties, but the partial blank was unheated resulting in the decline of...
formability. These investigations mainly adopt rapid resistance heating, and it is necessary to investigate the feasibility of using the more common furnace to fulfill hot stamping by partition heating.

Heating process parameters are very crucial for hot stamping using partition heating, which determines the distribution of different mechanical properties of components. Naderi et al.\(^{16}\) presented an improved process named the semi-hot stamping for the MSW1200 steel to enhance the formability. Mori\(^{17}\) investigated the warm and hot stamping of high strength steels SPFC440, 590Y, 780Y and 980Y, which verified the feasibility of hot stamping at a lower temperature. Zhou et al.\(^{18}\) analyzed the effect of hot stamping parameters such as austenitization temperature, soaking time, deforming temperature and cooling rate on the microstructure and mechanical properties of cold-rolled 22MnB5 steels. Liu et al.\(^{19}\) investigated hot formation quality of BR1500HS at different hot stamping parameters, and found that forming temperature and tool temperature can influence microstructure and mechanical properties of components. Hidaka et al.\(^{20}\) researched the effect of heating rate, heating temperature and cooling conditions on the microstructural evolution of carbon steels in hot stamping, and proposed the favorable operational conditions. However, the relationship of heating condition with mechanical properties in both high and low temperature regions are still in lack, which is helpful for providing theoretical guidance for hot stamping using partition heating. Furthermore, the requirements for the tensile strength and elongation of the tailored part in high and low temperature regions are different, but it is lack of quantitative researches to obtain the optimum heating process parameters in both high and low temperature regions. This paper aims at performing a systematic investigation on the influence and optimization of heating parameters for hot stamping using partition heating, which can provide a guidance for hot stamping of tailored parts.

In this paper, the effects of heating temperature and heating time on the mechanical properties and microstructure of 22MnB5 steel were investigated by conducting the hot stamping simulation experiment using a flat die. Afterwards, the response surface models for tensile strength and elongation as a function of heating parameters in both high and low temperature regions were established, and the optimization of heating parameters was conducted using multi-objective sorting genetic algorithm NSGA-II. At last, taking an M-shaped part as a research case, the hot stamping using partition heating was performed according to the optimal heating parameters.

### 2. Hot Stamping Simulation Experiment

#### 2.1. Material Description

The uncoated cold-rolled strip of 22MnB5 steel with a thickness of 1.6 mm was employed in this study, which is produced by Shougang Group. The chemical compositions of 22MnB5 steel are listed in Table 1 and its initial microstructure consists of ferrite and pearlite.

#### 2.2. Experimental Equipment and Test Procedure

In order to investigate the effect of heating temperature and soaking time on the mechanical properties of blank, the experimental equipment as shown in Fig. 1, was applied to mimic the practical temperature history of blank in hot stamping. It mainly consists of a digital-controlled electric furnace and a circular flat die set. The electric furnace is used to heat the blank to different temperatures. The flat die is used to simulate the quenching process in hot stamping. The tools made of steel H13 are two cylinders with the same height of 35 mm, and the diameter of the upper and lower die is 55 mm and 85 mm, respectively. The effect of deformation on the mechanical properties of blank is not considered in the experiment. The flat die set is installed on the work platform of a hydraulic press, and consists of an upper die, a lower die, locating pins and springs. The locating pins plays a role of positioning the blank. The springs prevent the blanks from contacting with the lower die to ensure the blank not cooled quickly before the dies closing.

Different combinations of heating temperature and heating time are chosen in the experiment and given in Table 2. There are two groups of tests that need to be conducted: group A is for investigating the effect of heating temperature, and group B is for investigating the effect of heating time. The blanks were heated in the furnace which reached

![Table 1. Chemical compositions of the 22MnB5 steel.

| Elements | C | Mn | Si | P | S | Cr | Ti | Al | B | Ni |
|----------|---|----|----|---|---|----|----|----|---|----|
| wt%      | 0.23 | 1.3 | 0.3 | 0.02 | 0.005 | 0.35 | 0.05 | 0.03 | 0.003 | 0.013 |

![Table 2. Hot stamping simulation experiment arrangement.

| Test groups | Heating temperature (°C) | Heating time (min) |
|-------------|--------------------------|--------------------|
| A           | 700/725/750/775/800/825/850/900/950/1000 | 5                  |
| B           | 900                       | 1/1.5/2/3/5/10/20   |

![Fig. 1. Experimental equipment of hot stamping simulation experiment.

![Fig. 2. Dimensions of circular plate (unit in mm) and specimens for tensile test and microstructure observation.](image)
the preset temperatures. When the blank was soaked for a set time, it was quickly taken out from the furnace and transferred to the flat die. The transferring time of 4 s was strictly controlled and an infrared thermal camera was used to monitor the blank temperature before the dies were closed. The blank was clamped by the dies for 15 s, and the holding pressure provided by the press is about 3 MPa.

The diameter of the circular plate used in the experiments is 52 mm, as shown in Fig. 2. After the quenching process, the circular plate was cut into three tensile specimens, which were used to measure the tensile strength and elongation of as-quenched specimens by a tensile testing machine at room temperature. The mean values of tensile strength and elongation were calculated by taking three measurements. Square samples with the length of 5 mm were cut to observe the microstructure and measure the Vickers hardness. The microstructure specimen was grounded, polished and etched in 4 vol% nital, and then observed using a scanning electron microscope (SEM). The Vickers hardness was averaged by taking five measurements under the loading force of 500 N.

3. Results and Discussion

3.1. Effects of Heating Temperature

The tensile strength and elongation of as-quenched specimens that were heated at different temperatures for 5 min are shown in Fig. 3(a). When the heating temperature increased from 700°C to 900°C, the tensile strength increases with the increasing heating temperature. The tensile strength is only 543 MPa when the specimen is heated at 700°C, whereas the tensile strength of the as-quenched specimen heated at 900°C reaches up to 1 596 MPa. The tensile strength decreases with the heating temperature increasing from 900°C to 1 000°C and it reduces to 1 431 MPa at the heating temperature of 1 000°C. The variation of elongation with heating temperature presents an opposite trend that the elongation firstly decreases and then increases with the increasing heating temperature. The maximum value of 30.8% occurs when the specimen is heated at 700°C and it is only 11.8% when heated at 900°C. As shown in Fig. 3(b), the Vickers hardness increases at first and then decreases with the increasing heating temperature. It reaches up to the maximum value of 472 Hv when the heating temperature is 900°C and the minimum value of 158 Hv occurs when the specimen is heated at 700°C. It can be concluded that different mechanical properties can be obtained by adjusting the heating temperature, therefore hot stamping parts with tailored properties can be realized by heating sheets to different temperatures in different regions.

The microstructures of as-quenched specimens heated at different temperatures for 5 min are shown in Fig. 4. When the heating temperature is 700°C, the microstructure consists of ferrite and pearlite, indicating that the specimen has barely austenitized at 700°C. Because of the lower strength of ferrite and pearlite, the specimen owns lower tensile strength but higher elongation at 700°C. When the heating temperatures are 750, 800 and 850°C, the microstructures are the mixtures of martensite and ferrite. The content of martensite increases with the increasing heating temperature. The martensite owns higher strength, so the tensile strength of specimens increases with the increasing martensite content. The microstructure is full lath martensite when the heating temperature is above 900°C, but the dimension of lath martensite distinctly increases with the increase of heating temperature, which leads to the decline of tensile strength.

3.2. Effects of Heating Time

The tensile strength and elongation of as-quenched specimens heated at 900°C for different time are shown in Fig. 5(a). With the heating time increasing from 1 min to 2 min, the tensile strength increases with the increasing heating time. The tensile strength is only 1 030 MPa when heated for 1 min, but it reaches up to 1 633 MPa when the heating time is 2 min. When the heating time increases from 2 min to 20 min, the tensile strength gradually decreases, and it is 1 483 MPa when the specimen is heated for 20 min. The elongation firstly decreases and then increases with the increasing heating time. When the heating time is 1 min, the elongation reaches up to the maximum value of 16.4%, and it is only 10.8% when the heating time is 2 min. It can be seen from Fig. 5(b) that the Vickers hardness rapidly increases from 210 Hv to 487 Hv when the heating time increases from 1 to 1.5 min. This is because the temperature of the blank heated for 1 min is 765°C lower than Ac3, so the blank has not been fully austenitized. The blank heated for 1.5 min reached 895°C above Ac3, and it is enough for austenitization by heating for several seconds when the temperature exceeds Ac3. So the sheet is fully austenitized and owns higher hardness. The Vickers hardness reaches the maximum value of 492 Hv when the soaking time is 2 min, and then it decreases with the increasing heating time. It
It can be figured out that hot stamping parts with tailored properties can be also realized by adjusting heating time in different regions of sheets.

The microstructures of as-quenched specimens heated at 900°C for different time are shown in Fig. 6. When the heating time is 1 min, the microstructure is a mixture of ferrite and martensite, indicating that a partial of ferrite has not been transformed to austenite due to too short heating time. The existence of the untransformed ferrite results in the decline of tensile strength and Vickers hardness. When the heating time is above 3 min, the microstructure is complete martensite, but the martensite lath gradually grows with the increasing heating time, which leads to the decline of tensile strength.

4. Multi-objective Optimization of Heating Parameters

4.1. Response Surface Modeling

The hot stamping simulation experiment has verified the feasibility of using partition heating to obtain the tailored properties of parts in hot stamping. The sheet region requiring high tensile strength should be heated to a higher temperature, whereas the other region requiring high elongation should be heated to a lower temperature. In order to acquire the optimal heating parameters of both high and low temperature regions, response surface models reflecting the relationship between heating parameters and mechanical properties were firstly established. The experiment design was performed before establishing response surface models, as shown in Table 3. According to the relationship of mechanical properties and heating parameters studied...
above, the heating temperature in high-temperature region is set from 800 to 950°C, the temperature from 600 to 750°C is selected in low-temperature region, and the heating time is 2.5, 5, 7.5 and 10 min. The heating parameters adopt full arrangements and the mechanical properties of as-quenched specimens were obtained by tensile testing machine at room temperature.

Based on the testing results, the response surface models are obtained, which can predict the tensile strength and elongation of as-quenched specimens for every particular set of heating temperature and heating time.

For high-temperature region, the models fitting tensile strength and elongation with heating temperature and time are described as Eqs. (1) and (2), respectively.

\[
\sigma_h = -4.46629 \times 10^7 + 1447.88783 \times T + 12281.81653 \\
\times t + 26.43843 \times T \times t - 1.55858 \times T^2 - 955.3862 \\
\times t^2 + 0.014456 \times T^2 \times t + 2.02371 \times T \times t^2 - 1.11612 \\
\times 10^{-3} \times T^2 \times t^2 + 5.5868 \times 10^{-4} \times T^3 + 2.06291 \times t^3
\]  

(1)

\[
\delta_h = 2443.99188 - 7.82043 \times T - 54.1493 \times t + 0.1138 \\
\times T \times t + 8.414 \times 10^{-3} \times T^2 + 1.9112 \times t^2 - 5.998 \\
\times 10^{-3} \times T^2 \times t - 3.5316 \times 10^{-3} \times T \times t^2 + 1.64 \times 10^{-6} \\
\times T^2 \times t^2 - 3.01667 \times 10^{-6} \times T^3 - 2.48 \times 10^{-3} \times t^3
\]  

(2)

For low-temperature region, the models fitting tensile
strength and elongation with heating temperature and time are shown as Eqs. (3) and (4), respectively.

\[
\sigma_t = -30 \times 10^5 + 146.5701 \times t - 2158.75917 \times t^2 + 6.52295 \times T \times t - 0.22973 \times T^2 + 269.6732 \times t^2 - 4.82542 \times 10^{-3} \times T^2 \times t - 0.83088 \times T \times t^2 + 6.2468 \times 10^{-7} \times T^2 \times t^2 + 1.1931 \times 10^{-4} \times T^3 + 0.26531 \times t^3
\]

\[
\delta_t = 387.11913 - 2.84324 \times T + 277.68214 \times t - 0.82818 \times T \times t + 6.1285 \times 10^{-3} \times T^2 - 24.6068 \times t^2 + 6.1778 \times 10^{-4} \times T^3 \times t + 0.073182 \times T \times t^2 - 5.5 \times 10^{-5} \times T^2 \times t^2 - 3.98333 \times 10^{-6} \times T^3 + 0.02296 \times t^3
\]

Where, \(\sigma_t\) and \(\delta_t\) are respectively tensile strength and elongation of as-quenched specimen in high-temperature region, \(\sigma_t\) and \(\delta_t\) are respectively tensile strength and elongation of as-quenched specimen in high-temperature region, \(T\) and \(t\) are heating temperature and heating time, respectively.

The correlation coefficient \(R^2\) is usually evaluated to judge the fitting ability and predictability of the established model. The correlation coefficients of the four response surface models are listed in Table 4. It can be seen that all correlation coefficients are above 0.9, indicating a good predictability.

### 4.2. Effect of Heating Parameters in the High-temperature Region

The response surface representing the relationship of tensile strength with heating temperature and time in high-temperature region is shown in Fig. 7. The tensile strength increases with the heating temperature increasing from 800 to 880°C when the heating time is 2.5 min, but the heating temperature hardly influences the tensile strength when the heating temperature is above 880°C. When the sheet is heated for 5 min, the tensile strength increases and then slightly decreases with the increasing heating temperature, and it reaches up to the maximum value at the heating temperature of around 880°C. This is because that the content of austenite gradually increases with the increase of heating temperature, and the tensile strength is the highest when the austenite content reaches 100%. With the heating temperature continuously increasing, the size of austenite grain is enlarged resulting in the decline of tensile strength. At the heating temperature of 800°C, the tensile strength increases at first and then decreases with the increasing heating time, and it reaches the biggest value when the heating time is 5 min. However, the tensile strength keeps decreasing with the increase of heating time when the sheet is heated at 950°C.

The response surface of elongation of as-quenched specimens in high-temperature region is demonstrated in Fig. 8. It can be seen that the elongation decreases with the increasing heating temperature, and it reaches the maximum when the heating temperature is 800°C. This is attributed to that more untransformed ferrite exists at lower heating temperature, which improves the ductility. When the sheet is heated at 800°C, the elongation decreases with the heating time increasing from 2.5 to 5.5 min. However, it increases with the increasing heating time when the heating time is above 5.5 min, which is attributed to the dual influence of phase fraction and austenite size.

### 4.3. Effect of Heating Parameters in the Low-temperature Region

Figure 9 shows the effect of heating temperature and time on the tensile strength of as-quenched specimens in low-temperature region. When the heating temperature varies from 600 to 675°C, the heating parameters have no obvious effect on the tensile strength. This is because that the heating temperature is lower than \(\text{Ac}_1\), so the microstructure of heated blank always consists of ferrite and pearlite. When the heating temperature exceeds 675°C, the tensile strength increases with the increase of both heating temperature and time and it reaches up to the maximum when sheets are heated at 750°C for 10 min. Because the increase of heating temperature and time improves the phase fraction of austenite, which results in the increase of martensite content of the as-quenched sheet.

### Table 4. Multiple correlation coefficient of the established models.

| Model         | \(\sigma_t\) | \(\delta_t\) | \(\sigma_t\) | \(\delta_t\) |
|---------------|--------------|--------------|--------------|--------------|
| \(R^2\)       | 0.979        | 0.909        | 0.937        | 0.908        |

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The response surface displaying the relationship of the elongation with heating temperature and time in low-temperature region is presented in Fig. 10. As can be seen from the figure, the response surface of the elongation presents an opposite tendency with that of the tensile strength. At the temperature range of 600 to 675°C, the elongation reaches the maximum and the value is hardly effected by the heating temperature and time. However, the elongation gradually decreases with the increase of heating temperature and time when the heating temperature is above 675°C.

4.4. Multi-objective Optimization Based on NSGA-II

The optimization aims at obtaining the best combination of heating parameters that will produce hot stamping parts with the desired mechanical properties in both high and low temperature regions. The objects are the response functions of the tensile strength and elongation, which can be described as follows:

\[ f_1(x) = \sigma_h; \quad f_2(x) = \delta_h; \quad f_3(x) = \sigma_l; \quad f_4(x) = \delta_l \quad \ldots \quad (5) \]

The object functions and restricting terms of the optimization process can be formulated as:

\[
F_h = \min(-f_1(x), -f_2(x)) \\
\text{s.t. } 850 \leq T_h \leq 950 \quad 2.5 \leq t_h \leq 10
\]

\[
F_l = \min(-f_3(x), -f_4(x)) \\
\text{s.t. } 850 \leq T_l \leq 950 \quad 2.5 \leq t_l \leq 10
\]

Where, \( F_h \) and \( F_l \) are respectively the object of the optimization in high and low temperature region, \( T_h \) and \( t_h \) are respectively heating temperature and heating time in high-temperature region, and \( T_l \) and \( t_l \) are heating temperature and heating time in low-temperature region, respectively.

NSGA-II proposed by Deb et al.\(^{22}\) is adopted for the multi-objective optimization, which is modified on the basis of NSGA. NSGA-II adopts a rapid non-dominant sorting algorithm, which possesses higher sorting speed and lower computational complexity. The parameters for the NSGA-II program are set as follows: initial population size is 200, crossover probability is 90\%, mutation probability is 10\% and termination generation is 200. After 200 iterations of searching for the optimal solutions, some Pareto optimal solutions in both high and low temperature regions are obtained as shown in Fig. 11. In the multi-objective optimization, ‘optimal’ implies that no objective can be improved without worsening at least one other objective. On the Pareto frontier, the tensile strength and elongation presents a contradicting condition that the increase of tensile strength is accompanied with the decline of elongation. So the optimal tensile strength and elongation can’t increase simultaneously and the compromise solution should be selected according to the actual requirement for properties in high and low temperature regions. In high-temperature region of hot stamping part, higher tensile strength is expected to enhance intrusion resistance, so higher tensile strength should be the first choice. Whereas, higher elongation is required to improve the energy absorption capacity in low-temperature region of the part, so the selection of heating
parameters should be mainly based on the elongation.

As given in Table 5, five optimal solutions are respectively listed in high and low temperature regions based on compromise solutions shown in Fig. 11. In high-temperature region, heating temperature of 885°C and heating time of 4 min are eventually selected for the highest tensile strength of 1 602.8 MPa. In low-temperature region, for the sake of choosing higher elongation, the sheet should be heated at 670°C for 2.5 min.

5. Verification of Optimal Heating Parameters

In order to verify the accuracy of optimization of heating parameters of boron steel hot stamping in high and low temperature regions, an M-shaped part was hot stamped using the partition heating method. Firstly, the sheet should be heated to different temperatures in different regions. The device of partition heating is shown in Fig. 12(a), and it mainly consists of an electric furnace and a temperature acquisition and monitoring system. Before heating, half of the 22MnB5 sheet with the dimension of 250*190*1.6 mm was placed between two thick iron steels and the other region was put in the air. When the temperature of electric furnace kept 885°C, the whole device as shown in Fig. 12(b) was placed in the furnace. The sheet region in the air was quickly heated to 885°C, but the temperature of the other region increased slowly due to contact with thick iron plate. The temperature of the sheet in high and low temperature regions was monitored by K-type thermocouples contact with the 22MnB5 sheet and temperature acquisition device. The temperature history of the sheet in low and high temperature regions is shown in Fig. 13. In the high-temperature region, the sheet is heated at about 10°C/s to 885°C, and then maintained at 885°C. In the low-temperature region,

| Region         | Heating temperature/°C | Heating time/min | Tensile strength/MPa | Elongation/% |
|----------------|-------------------------|------------------|----------------------|--------------|
| High temperature | 853.3                   | 10               | 1 528.1              | 12.5         |
|                | **884.8**               | **4**            | **1 602.8**          | **11.3**     |
|                | 901.3                   | 3.9              | 1 583.1              | 11.4         |
|                | 916.2                   | 3.9              | 1 560.9              | 11.5         |
|                | 946.9                   | 3.6              | 1 552.8              | 11.6         |
|                | 650                     | 4.5              | 537.4                | 32.5         |
| Low temperature | 660.7                   | 2.7              | 522.1                | 33.9         |
|                | **670.3**               | **2.5**          | **514.9**            | **34.2**     |
|                | 726.6                   | 4.5              | 546.9                | 30.6         |
|                | 743.9                   | 9.9              | 719.6                | 21.2         |

Fig. 12. The temperature monitoring system (a) and setting of sheets partition heating (b).

Fig. 13. The temperature history of the sheet in high and low temperature regions.

Fig. 14. Hot stamping tool (a) and stamped M-shaped part (b).
the sheet was heated at a lower heating rate of 1.6°C/s, and it reached to 670°C after 400 s. When the lower temperature reaches up to 670°C, the sheet was quickly taken out and transferred to the stamping tool.

Figure 14(a) shows the hot stamping tool of M-shaped part, which is installed on the platform of a hydraulic press. The stamping tool mainly consists of upper die, lower die, blank holder and guide pillar. When the heated blank was transferred to the surface of blank holder, the upper die quickly moved down at the stamping velocity of 50 mm/s, and then kept holding for 15 s at the pressure of 5 MPa. As can be seen that the forming quality of hot stamped M-shaped part is good and the oxidation of the part in high-temperature region is apparently more serious.

In order to acquire the mechanical properties of different regions of hot stamped M-shaped part, five specimens were respectively cut to perform tensile testing at room temperature in high and low temperature regions and the location and dimension of selected specimens are shown in Fig. 14(b). Figure 15 shows the tensile strength and elongation of specimens from different locations in high and low temperature regions. It can be seen that an M-shaped part with tailored properties is well realized. The average tensile strength in high-temperature region is 1572 MPa, but it is only 554 MPa in low-temperature region. The elongation also presents distributed properties that the average value is 9.41% and 26.73%, respectively.

6. Conclusions

1) The heating temperature and heating time has an obvious effect on the mechanical properties of as-quenched 22MnB5 sheet by influencing the austenite content and grain size, which makes it possible that using partition heating to achieve tailored properties of hot-stamped parts.

2) The response surface models reflecting the common effects of heating temperature and time on the tensile strength and elongation in both high and low temperature regions are constructed and analyzed. The multi-objective genetic algorithm NSGA-II is adopted to obtain the Pareto solutions in both high and low temperature regions. Heating temperature of 885°C and heating time of 4 min are selected as the optimal parameter in high-temperature region for higher tensile strength, and heating at 670°C for 2.5 min is chosen in low-temperature region for higher elongation.

3) An M-shaped part with tailored properties is hot stamped using partition heating according to the optimal heating parameters. The tensile strength and elongation of part in high-temperature region are 1572 MPa and 9.41%, respectively, whereas the part in low-temperature region owns the tensile strength of 554 MPa and the elongation of 26.73%.

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