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Numerical simulation of springback of medium-thick plates in local hot rolling

XIE Dong, ZHAO Yao, DONG Hongbao

School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract: [Objectives] In order to understand the factors of springback in the local hot rolling of medium-thick steel plates, **[Methods]** a 3D thermal-elastic-plastic analysis is conducted to investigate the factors affecting the amount of springback. Through a series of numerical analyses, the influence of deformation temperature, temperature field distribution, plate size and local loading are examined. **[Results]** The results show that when the deformation temperature exceeds a certain level at which material yield stress begins to decrease significantly, the springback will reduce markedly with the increase in temperature. Due to the distribution characteristics of the deformation area, the influence of temperature distribution on springback where the local deformation scale is larger is dominated by the three dimensions of temperature field distribution. Changes in the length and width of the plate have a certain influence on the springback, in which changes to the length of a plate where the local deformation scale is larger have a more obvious influence on springback. The springback of the plate decreases with the increase of local loading. **[Conclusions]** The results of this study can assist in the optimization of parameters in the automatic hot rolling of thick plates, while also haveing a basic guiding effect on the further study of springback in the local hot rolling of thick plates.

Key words: medium-thick plate; hot rolling; springback; numerical simulation; Finite Element Method (FEM)

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0 Introduction

As modern ship construction is tending to be of large scale, digitalized, and automated, and steel plates for hulls are prepared with larger sizes and processed with more complicated techniques, it is of important significance to summarize processing and forming laws of steel plates[1]. Generally in engineering applications, steel plates with thicknesses of 4.5-25 mm are named medium-thick plates[2]. In terms of traditional techniques, cold bending is mostly adopted for larger deformation of medium-thick plates[3], but a large amount of springback after the cold bending of steel plates severely influences the precision of formed components. High-temperature forming techniques for steel plates can greatly improve performance and effectively reduce springback, and therefore, the research on springback laws of steel-plate forming under high temperatures has become the focus of attention.

Hot rolling of plates is a new forming method. Neugebauer et al.[4] generalized key problems to be solved in hot rolling of plates, and pointed out that the major challenge of the hot rolling faced was to determine suitable forming temperatures. Yanagimoto et al.[5-7] conducted experimental research on basic characteristics of hot rolling of high-strength thin plates, and found out that springback was greatly reduced when temperatures of plates in forming areas were above 750 ℃. Liu et al.[8] numerically simulated

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Authors: XIE Dong, male, born in 1993, master candidate. Research interest: hot rolling of ship hull plates. E-mail: 15927279416@163.com

ZHAO Yao (Corresponding author), male, born in 1958, professor, doctoral supervisor. Research interest: static and dynamic responses of ship structures. E-mail: yzhaozzz@hust.edu.cn

DONG Hongbao, male, born in 1991, Ph.D. candidate. Research interest: rolling of curved surfaces of ship hull plates. E-mail: hbdongnaoe@hust.edu.cn

the hot rolling of steel plates with super-high strength and concluded that thermal effect was a major factor to cause springback of steel plates. At present, most of the studies on hot-rolling technologies, both at home and abroad, focused on thin plates used in automobile and aerospace fields[9], and very few of them aimed at medium-thick plates for ship construction. For most studies on hot rolling of plates, analysis was conducted based on the condition of overall heating on the plates, while springback analysis of steel plates under the condition of local heating was still a blank. In practical engineering applications, as to forming technologies of medium-thick plates for ships, the technique of local heating has lower energy consumption but better operability, compared with that of overall heating, and in addition, it is able to reduce springback and loading force to a certain extent, compared with the pure cold-rolling technique. Springback control in local hot rolling of medium-thick plates for ships will directly influence shipbuilding efficiency. As local hot rolling is a three-dimensional complicated forming technique with big deformation and also a complicated thermal-mechanical coupled deformation process with integrated nonlinear factors such as geometrical parameters, materials, and boundary conditions[10], it is extremely complicated to conduct pure theoretical analysis on the local hot rolling and difficult to accurately and efficiently apply the technique to practical production. The traditional experimental research takes a lot of time, but numerical simulation can be used to better solve such problems.

This paper aimed to study the local hot rolling of medium-thick plates for hulls to analyze factors influencing springback of hot rolling. Firstly, a steel plate used in the experimental research was heated locally to obtain the target temperature field on the plate. After that, the temperature was kept unchanged and local loading was conducted in the heating zone of the plate, with a specific loading system, to produce local plastic deformation. As the loading increases, deformation of the plate gradually increases as well, and when the target shape was formed, the plate was placed in the air for natural cooling. Finally, unloading was done to finish the loading process. Then, ABAQUS software was used to numerically simulate the local hot rolling of the plate and the simulation method was verified through comparison of the simulation results with experimental results; in addition, various factors influencing springback during the hot rolling of plate were analyzed respectively based on the simulation method. At last, relations between various influence factors and springback were obtained according to calculation results.

1 Numerical model

This paper planned to use the ABAQUS software to numerically simulate hot rolling of medium-thick plates for hulls. As the bend forming of medium-thick plates involves complicated nonlinear problems such as big elastoplastic deformation, contact between moulds and steel plates, and springback after unloading, implicit algorithms with higher stability were adopted, which could produce more precise results in simulating springback, compared with explicit algorithms.

Loading of hot rolling involved in this research is a thermal-mechanical coupled process. As stress and deformation exert little influence on thermal conduction, sequential coupling was adopted to improve calculation efficiency in the thermal-elastoplastic analysis through the simulation model, ignoring influences of stress-strain fields on the temperature fields during deformation.

1.1 Finite element model

As steel plates with a thickness of 20 mm are commonly used in shipbuilding, this paper adopted rectangular plates of 20 mm in thickness as the forming plates, with plate lengths L and widths W as variables.

During the processing and manufacturing of curved plates for ships, plates are commonly bent and plastically deformed through loading systems. Table 1 shows dimensions of the loading system used in this paper, and Fig. 1 shows a local schematic diagram of the loading system, mainly including sketches of a punch and a support. In the figure, t refers to the plate thickness.

Both the press point of the punch and the heating center shown in Fig. 1 were at the central point of

Table 1 Geometric dimensions of loading system

Parameter	Value
Radius of punch r_u /mm	117
Half width of punch l_u /mm	60
Turning radius of punch R_u /mm	200
Radius of support $r_{d'}$ /mm	162
Great-circle radius R_d /mm	95.6
Small-circle radius $R_{d'}$ /mm	20
Effective half width $l_{d'}$ /mm	100
Half width of support l_d /mm	118

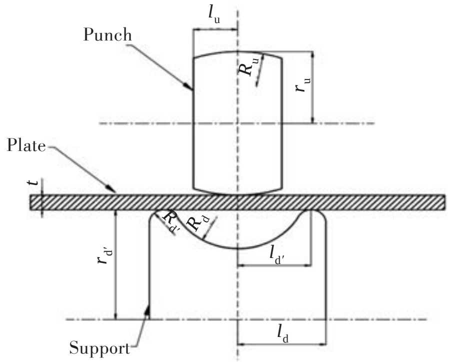


Fig.1 Schematic diagram of section shape of loading system

the plate. In view of the symmetry of both the model and the load, the finite element model of 1/4 of a plate was adopted for all calculations and analyses to improve calculation efficiency. Fig. 2 shows the selected solid elements for model calculation of the plate. Because the plate had a bigger deformation area, uniform meshes of the plate model were generated. The punch and the support were considered as rigid bodies, without considering about their deformation.

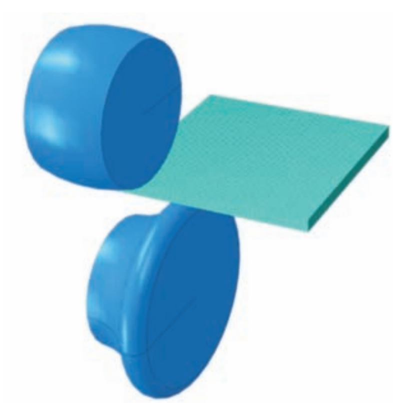


Fig.2 Finite element model

1.2 Material properties of plates

During the numerical simulating calculation, SS400 low-carbon steel plate, commonly used for hulls, was selected, with its thermal physical properties as listed in Table 2[11].

Table 2 Thermal physical property of plate

Temperature/ ℃	Density/ ($kg \cdot m^{-3}$)	Thermal conductivity/ ($W \cdot m^{-1} \cdot ℃^{-1}$)	Specific heat/ ($J \cdot kg^{-1} \cdot ℃^{-1}$)
25	7.8	60	461
200	7.76	51	491
400	7.72	43	543
600	7.68	36	677
700	7.66	32	818
767	7.65	30	102
800	7.64	29	759

A bilinear hardening model based on the von Mises yield criterion was adopted for the simulation of the plate, which simulated the true stress-strain curve by bilinear fitting, as shown in Fig. 3. As during machining, the plate forming through bending is actually a process of elastoplastic nondestructive deformation. Only parameters related to yield stress and work hardening of the plate were considered in the simplified model, and thus Young's modulus E, tangent modulus E_t, and yield strength σ_y became the most important parameters influencing mechanical properties of the material. Table 3 lists parameters of mechanical properties of the plate under different temperatures.

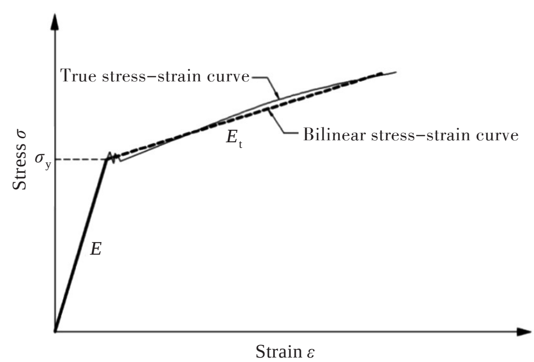


Fig.3 Constitutive relationship of material

Table 3 Thermal mechanical property of plate

Temperature/ ℃	Young's modulus E /GPa	Poisson's ratio μ	Coefficient of thermal expansion $/K^{-1}$	Yield stress σ_y /MPa	Tangent modulus E_t /GPa
25	209	0.3	1.2×10^{-5}	300	10
100	202	0.31	1.24×10^{-5}	300	10
200	195	0.32	1.28×10^{-5}	290	10
300	187	0.33	1.32×10^{-5}	270	9
400	175	0.34	1.36×10^{-5}	220	9
500	162	0.35	1.40×10^{-5}	170	8
600	150	0.36	1.42×10^{-5}	100	8
700	125	0.37	1.44×10^{-5}	40	6
800	95	0.38	1.46×10^{-5}	30	2

1.3 Verification of accuracy of the numerical simulation method

In order to verify the accuracy of the applied numerical simulation method, this paper numerically simulated the experiment, by Yanagimoto[5], on hot-rolling V-bending of high-strength thin plates, with material parameters and model sizes same as those in Yanagimoto's experiment. Fig. 4 shows the comparison between numerical results and experimental ones.

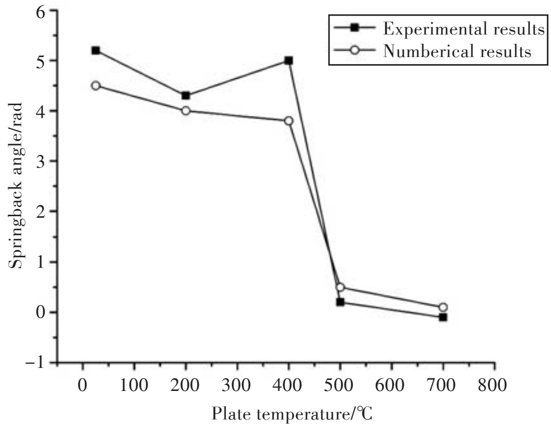


Fig.4 Comparison of results between numerical simulation and experiment

From Fig. 4, it can be seen that springback angles from both numerical and experimental results basically match, with generally consistent trends, despite of some local differences. Therefore, it is believed that the proposed method in this paper is accurate and effective for simulating the hot rolling of steel plates.

1.4 Loading process and springback definition

A complete loading process for a medium-thick hull plate in this paper was as follows:

1) Heat a selected plate at room temperature, and stop heating when the target temperature is reached;

2) Keep the position of the support unchanged, align the punch with the plate center, and then apply force until the defined press amount of the plate is reached;

3) Cool the plate naturally to the room temperature, and then lift the punch to unload.

Deflection of the plate before and after unloading was used to describe springback. Springback was evaluated by *SB* with a definition as shown in Fig. 5. In this figure, h_0 refers to the deflection of the maximum press center, while h_1 is the residual deflection of the same point after unloading. If deflection of the press center before and after unloading has no change, that is, $h_1 = h_0$, SB=0; if the deflection of the press point becomes 0 after unloading, that is, $h_1 = 0$, SB=100%. The calculation of springback is given by Formula (1):

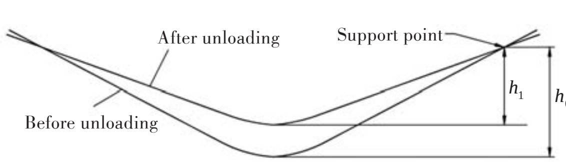


Fig.5 Definition of springback

$$SB = (h_0 - h_1)/h_0 \times 100\% \qquad (1)$$

2 Numerical simulation and result analysis

Based on current research results on local hot rolling of medium-thick plates for hulls, as well as relevant engineering practice, it can be concluded that major factors influencing plate deformation include temperature of integrated forming, distribution of local temperature fields, plate size, and magnitude of local loading. This paper studied respective relations between above factors and springback through numerical calculation based on control variables.

During the calculation, parameters about mechanical and thermal physical properties of plates under different temperatures were integrated into the ABAQUS finite element model by referring to stress and strain data of the plates under different temperatures, and local heating of plates was analyzed by calling the subprogram of a Gaussian semi-ellipsoidal heat source, which was written in FORTRAN language; then, node-temperature information from the thermal analysis was imported into the model for structure stress analysis to obtain material properties under different temperatures and conduct corresponding stress analysis, so as to complete the whole thermal-mechanical coupled simulating calculation; finally, node temperatures from the thermal analysis were imposed as body loads for subsequent analysis of structural stress to finish the whole numerical simulating calculation.

2.1 Influences of temperature on springback under isothermal condition

Plate forming temperature is the major factor that distinguishes hot rolling from cold rolling. To study the relation between plate forming temperature and final springback, hot rolling under isothermal condition should be studied at first. An SS400 low-carbon steel plate with a size of 600 mm × 600 mm × 20 mm was heated wholly to obtain different temperatures *T*, namely, *T*=25, 100, 200, 300, 400, 500, 600 and 700 ℃. Under the isothermal condition, simulating calculation of local loading was conducted, in terms of a press amount of 10 mm, to comparatively analyze springback and maximum loading force under different temperatures.

From Fig. 6, we can find that under the condition of isothermal forming, when the plate temperature is between room temperature and 400 ℃, the forming temperature exerts little influence on springback; when the forming temperature reaches about 400 ℃, as the temperature increases, springback starts to decrease greatly; when the forming temperature is 700 ℃, springback is reduced to about 1/3 of that at room temperature.

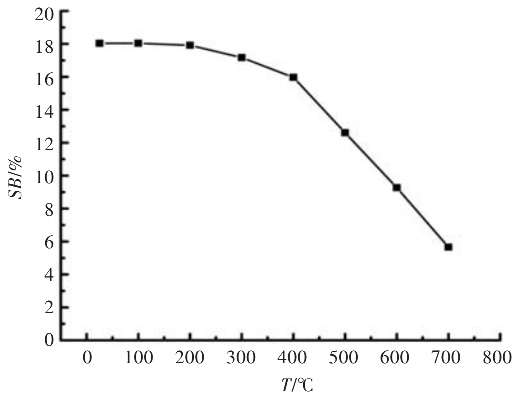


Fig.6 Relationship of springback and forming temperature of plate

It can be seen from Fig. 7 that when the forming temperature increases to 400 ℃, the plastic strain distribution of the plate and relevant values have little difference from those at room temperature, while when the temperature increases to 500 ℃ and 700 ℃, plastic strain distribution of the plate remains almost unchanged, but relevant values increase significantly. According to Fig. 8, when the forming temperature exceeds a certain value, if it continues increasing, changes in the yield stress of the material will make plastic deformation of the plate increase rapidly, under the same total deformation, resulting in a drop in the proportion of elastic deformation in the total deformation and thus a corresponding rise in the proportion of plastic deformation in the total deformation. After unloading, springback due to release of the elastic strain is also reduced significantly.

From Fig. 9, it can be seen that as for the same press amount of the plate, the higher the forming temperature is, the smaller the loading force of the punch is, which means lower forming pressure is required. This is because higher temperature leads to smaller yield stress, easier plastic deformation and better forming property of the material.

Based on springback analysis of SS400 medium-thick hull plates under the condition of isothermal forming and according to research on springback laws of other steel materials under heating conditions by Yanagimoto et al.[5-7] and Liu et al.[8], it can be concluded that in practical engineering applica-

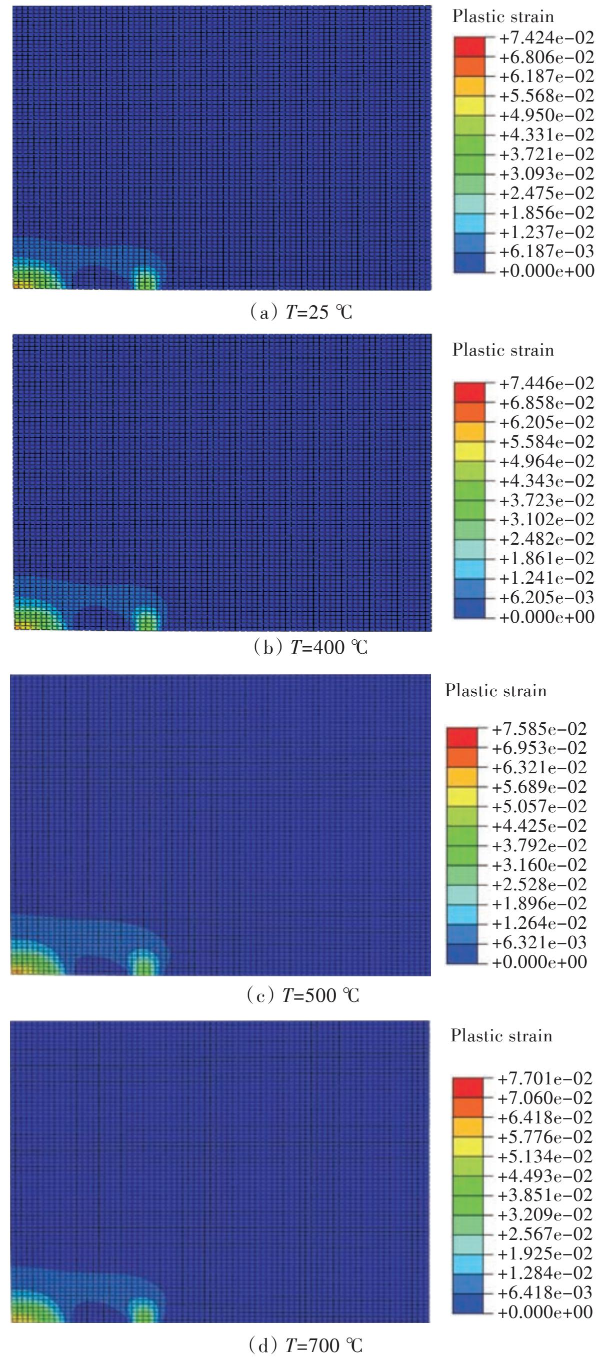


Fig.7 Contours of plastic strain of plate under different forming temperatures

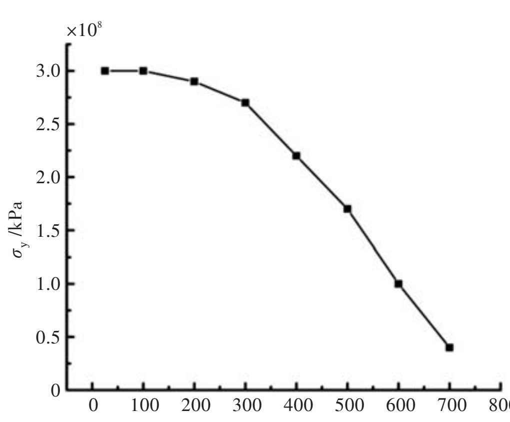


Fig.8 Relationship of yield stress and forming temperatures of plate

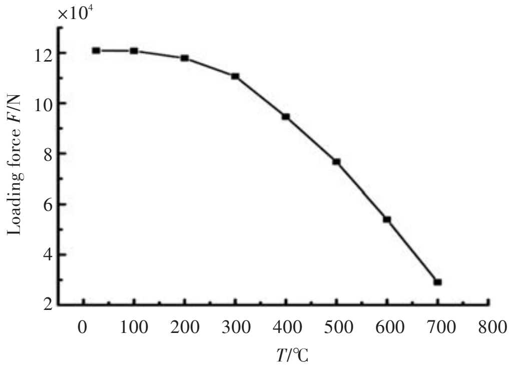


Fig.9 Relationship of loading forces and forming temperatures

tions, yield stress of a wholly heated plate starts to decrease greatly after the plate temperature reaches a certain point, and the plate forming under this temperature can significantly reduce the final springback and the required loading force, compared with cold rolling at room temperature.

2.2 Influences of temperature distribution under non-isothermal condition

Medium-thick steel plates for hulls are generally prepared with bigger sizes, and thus large-scale high-power devices are necessarily required in order to heat such plates wholly to reach certain temperatures. However, it is difficult to apply such devices in practical projects as they consume higher energy and occupy larger space. Therefore, overall heating is more applicable to plates with smaller sizes, while as to large medium-thick steel plates for hulls, local heating is more feasible, which means non-isothermal forming.

In the following, the influences of temperature distribution on springback of bent plates, under the condition of local heating will be analyzed. Local heating was conducted at the center of a steel plate with the same size and type as those mentioned in Section 2.1, and after the target temperature field was obtained, simulating calculation of local loading was conducted in terms of a press amount of 10 mm. Fig. 10 shows the typical temperature distribution after local heating, which is a temperature field obtained from the thermal analysis using a Gaussian semi-ellipsoidal heat source, with the upper surface center of the plate as the heat source center. This temperature field has the following basic characteristics: the maximum temperature is at the heat source center; the temperature gradually decreases from the upper surface to the lower one, along the thickness direction; the temperature gradually decreases outwards from the heat source center, along the plate surface.

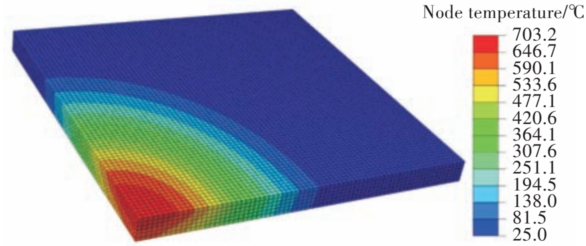


Fig.10 Typical temperature distribution of finite element model

According to the above conclusion that springback of SS400 low-carbon steel plates will not change obviously until temperatures exceed 400 ℃, zones with temperatures of above 400 ℃ were defined as high-temperature zones in this paper. Based on characteristics of the local temperature field shown in Fig. 11, parameters of a and b were used to describe temperature distribution of the high-temperature zone on the upper surface of a plate, where a is the lengthwise diameter and b is the widthwise diameter of the high-temperature zone.

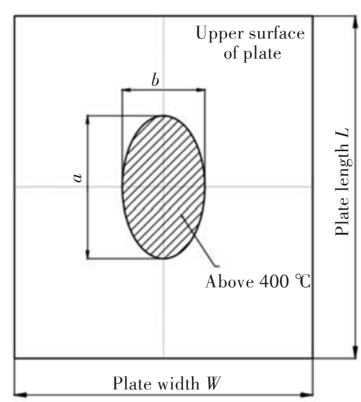
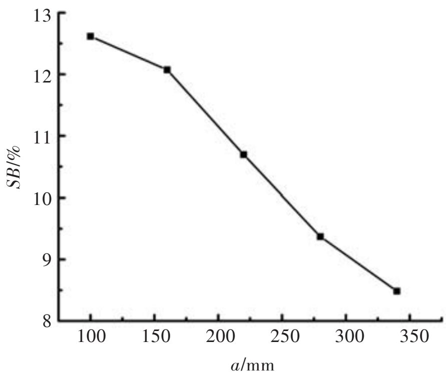


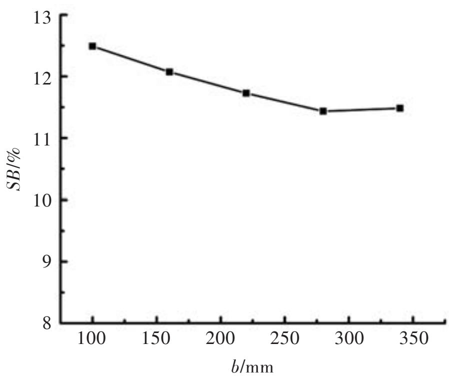
Fig.11 Schematic diagram of high temperature zone of plate

During the analysis, the central temperature of the upper surface of the plate was fixed at 700 ℃, while that of the lower surface was fixed at 500 ℃. Temperature fields with different a and b were obtained accordingly by changing heating parameters. Influences of temperature distribution along the plate surface on springback were studied through simulating calculation of local loading. Figs. 12-14 show detailed analysis results.

From Fig. 12 we can see that, in the case of b = 80 mm, that is, in the case of fixed temperature distribution along the width direction of the plate, as a increases, the lengthwise high-temperature zone enlarges and springback decreases rapidly; in the case of a = 80 mm, that is, in the case of fixed temperature distribution along the length direction of the plate, as b increases, the widthwise high-temperature zone enlarges but springback changes slightly.



(a) Relationship of the lengthwise diameter of the high-temperature zone and springback



(b) Relationship of the widthwise diameter of the high-temperature zone and springback

Fig.12 Relationship of springback and distribution in high temperature zone

Fig. 13 shows contours of stress distribution of 1/4 scaled plate under a local bending load at room temperature. It can be seen from Fig. 13 that the distribution range of local stress along the length direction of the plate is bigger than that along the width direction. At this moment, deformation of the plate under the local bending load has the following characteristics: the deformation area is mainly distributed along the length direction of the plate, while it is smaller along the width direction vertical to the length direction of the plate.

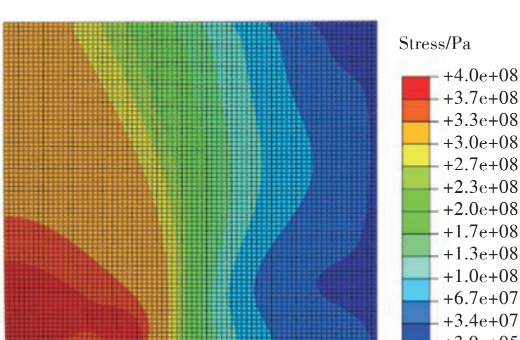
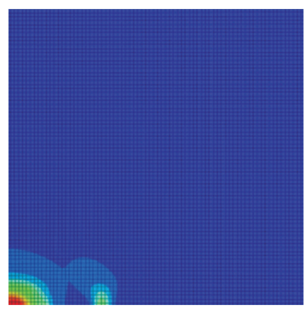
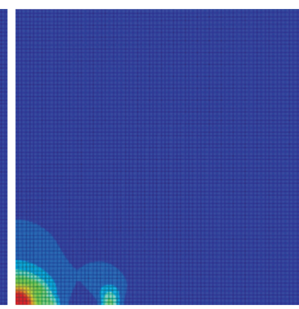


Fig.13 Contour of stress distribution of 1/4 scaled bending plate under room temperature

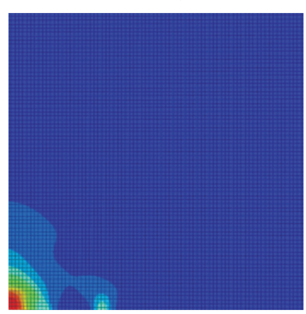
Fig.14 shows contours of plastic strain of plates formed under different temperatures. From Figs. 14(a)–14(d), it can be seen that when the area of the high-temperature zone along the length direction of the plate increases, influenced by changes of the plate temperature, the plastic component of the plate deformation increases significantly and the final springback decreases rapidly. However, as the plate has a narrower area for big deformation along its width direction, changes in the area of the high-temperature zone in this direction have limited influences on the deformation area. From Figs. 14(e)–14(h), it can be seen that when the area of the high-temperature zone along the width direction of the plate increases, the plastic component of the plate deforma-



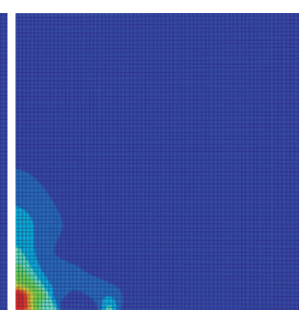
(a) a=50 mm, b=80 mm



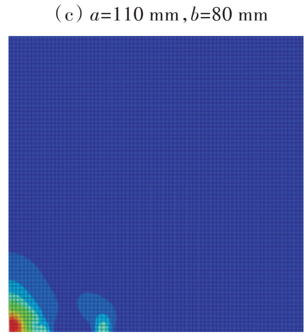
(b) a=80 mm, b=80 mm



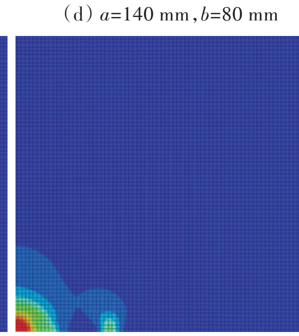
(c) a=110 mm, b=80 mm



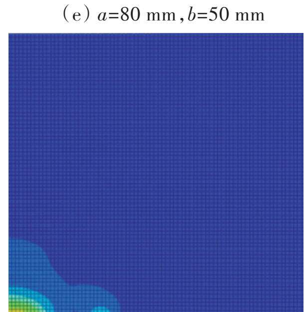
(d) a=140 mm, b=80 mm



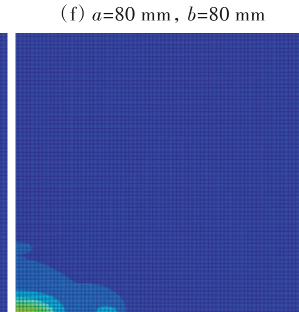
(e) a=80 mm, b=50 mm



(f) a=80 mm, b=80 mm



(g) a=80 mm, b=110 mm



(h) a=80 mm, b=140 mm

Fig.14 Contours of plastic strain distribution of plates under different temperatures tion is less changed and therefore, the final springback is slightly influenced.

In order to study the influences of temperature distribution along the thickness direction of plate on springback, based on the characteristic of the temperature field, which is that the high-temperature zone is located at the plate center, the temperature difference between centers of upper and lower surfaces of the plate was used to indicate temperature distribution along the thickness direction. The central temperature of the upper surface was fixed at 700 ℃, with both a and b being set as 160 mm, to keep the temperature distribution of the upper surface basically unchanged. Different temperature fields, *BT*, at the center of the lower surface of the plate were obtained by adjusting heating parameters, namely, *BT*= 200, 300, 400, 500, and 600 ℃. Then, simulating calculation was conducted through local loading to study how temperature distribution along the thickness direction of the plate influences the springback. Fig. 15 shows relevant calculation results.

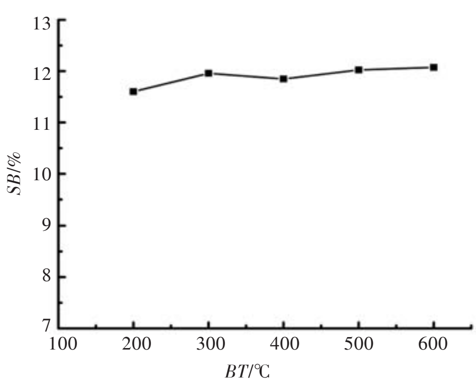


Fig.15 Relationship of springback and temperature distribution across the plate

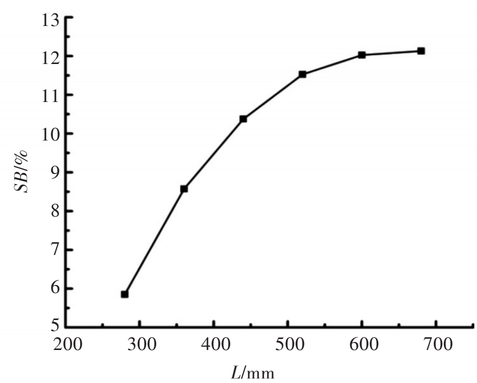
It can be seen from Fig. 15 that changes in temperature distribution at the plate center along the thickness direction have little influences on springback, under the condition of local heating. By analysis, the reason is as follows: as to local hot rolling of a medium-thick hull plate, plastic deformation mainly occurs at the outer layer of such a plate, and changes in material properties of the outer layer are the major factor influencing the proportion of plastic deformation in the overall deformation, which is finally manifested as the fact that the temperature distribution along the plate surface is the dominant factor influencing springback, while that along the thickness direction has little influence on springback.

2.3 Influences of plate size on springback

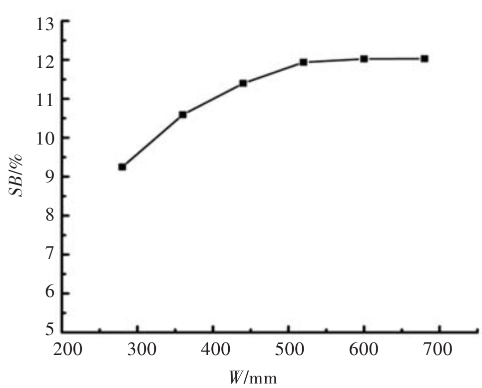
In practical engineering applications, plate sizes for hulls are determined according to specific conditions, so plate size is an important factor to be considered as well. This paper mainly studied medium-thick steel plates and focused on influences of plate lengths and widths on final springback in the case of unchanged plate thickness. Under the same heating conditions, simulating calculation was respectively conducted through local loading of plates with a thickness of 20 mm, in terms of lengths *L* and widths *W* as listed in Table 4. Fig. 16 and Fig. 17 show relevant results.

Table 4 Sizes of the plate in calculation

Plate length *L*/mm	Plate width *W*/mm
280,360,440,520,600,680	600
600	280,360,440,520,600,680



(a) Relationship of plate length and springback

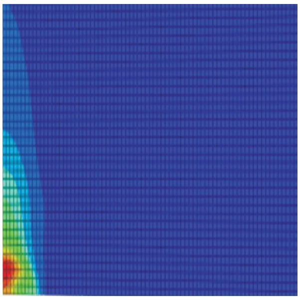


(b) Relationship of plate width and springback

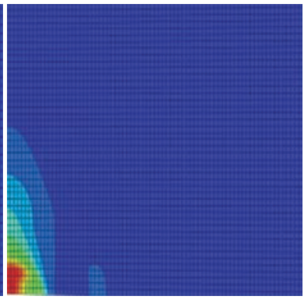
Fig.16 Relationship of springback and plate sizes

From Fig. 16, it can be seen that an increase in either the length or the width of a plate will result in a corresponding increase of springback, and changes of the plate length have bigger influence on springback, compared with those of the plate width. When plate sizes increase to certain values, springback will no longer vary with plate sizes.

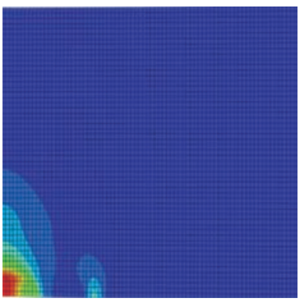
It can be seen from Fig. 17 that in the case of fixed loading force, the bigger the plate sizes are, the larger the deformation areas are, in which elastic de-



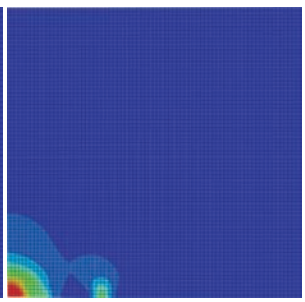
(a) L=280 mm, W=600 mm



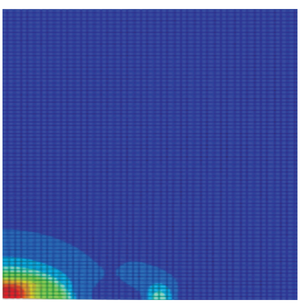
(b) L=360 mm, W=600 mm



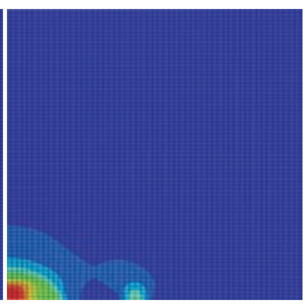
(c) L=440 mm, W=600 mm



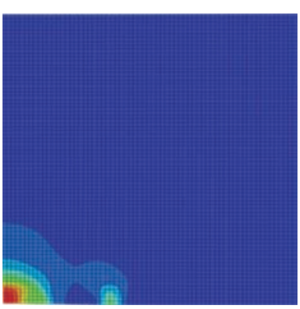
(d) L=600 mm, W=600 mm



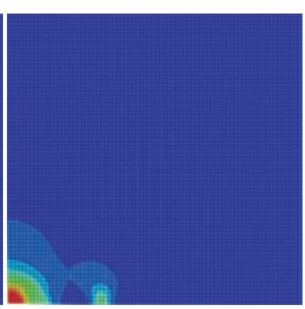
(e) L=600 mm, W=280 mm



(f) L=600 mm, W=360 mm



(g) L=600 mm, W=440 mm



(h) L=600 mm, W=600 mm

Fig.17 Plastic strain distribution of plate with different sizes

formation increases, while the plastic deformation decreases, resulting in a corresponding increase of the final springback. From Figs. 17(a)–17(d), changes in plate length have obvious influences on occurrence areas of plastic deformation but unobvious influences on distribution changes of plastic deformation areas. This is because the loading method of local bending in this paper makes a larger deformation area distributed along the length direction of a plate, resulting in bigger influences of plate-length changes on deformation, which is finally manifested as the fact that changes in plate length have more significant influences on springback. After plate sizes continue to increase, springback hardly changes. This is because local loading has limited effect on plates, and when plate sizes are beyond certain values, further loading fails to deform the increased portions of plates and therefore, no influence will be exerted on the final springback.

2.4 Influences of magnitude of local loading on springback

Based on the simulation model mentioned above and with other conditions kept unchanged, the deflection of the maximum press center, h_0, was used to express different magnitudes of local loading on plates and it was set as follows: h_0 = 6, 8, 10, 12, 14 and 16 mm. Simulating calculation of local heating and loading was conducted respectively, in terms of different deflections, to study the influence of magnitude of local loading on springback. Fig. 18 shows comparison results of plate forming with different magnitudes of local loading at room temperature, and Fig. 19 shows contours of plastic strain of plate cross sections.

From Fig. 18, it can be seen that whether under the room-temperature condition or under the local-heating condition, the bigger the magnitude of local loading is, the smaller the final springback after plate forming is. From the analysis of Fig. 19, the reason is as follows: as the magnitude of local loading increases, the plate deforms more, and plastic deformation of the outer fiber of the plate gradually increases, while elastic deformation decreases accordingly; meanwhile, the pure elastic area near the plate center also gradually undergoes plastic deformation, which makes the total elastic deformation of the plate decrease as the deformation of the plate increases, consequently resulting in the decrease of springback caused by elastic deformation after unloading; however, as the deformation intensifies, the decrease rate of elastic deformation is getting slower

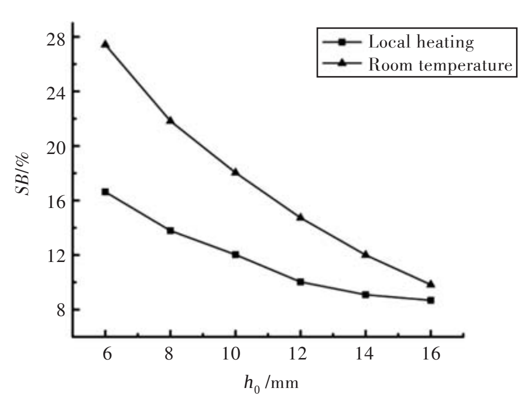


Fig.18 Relationship of springback and the magnitude of local loading

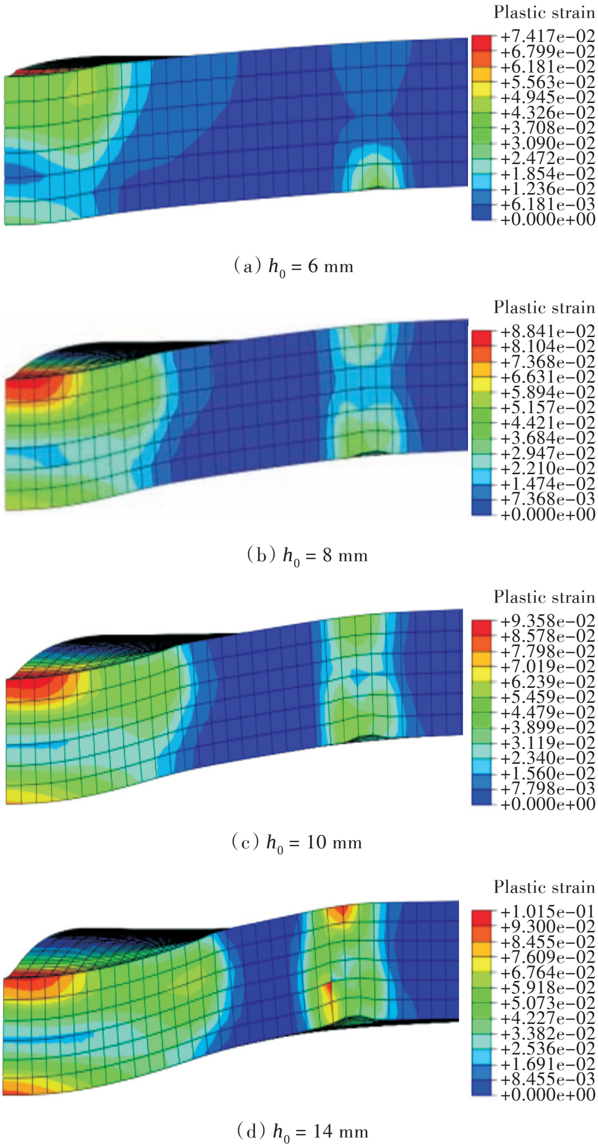


Fig.19 Contours of plastic strain distribution in the cross section of plate under different magnitude of local loading

and slower, making the decrease rate of springback tend to be mild gradually.

From Fig. 18, it can be also seen that different from what happens in the case of loading at room temperature, in the case of local hot rolling, as the magnitude of local loading increases, the decrease rate of springback tends to be mild much faster. This is because under the same degree of deformation, local heating makes a bigger area of the plate deformed plastically and accelerates the plastic deformation of the pure elastic area near the plate center.

3 Conclusions

This paper has established, through numerical simulation, a finite element model for local hot rolling of medium-thick steel plates for hulls, studied factors influencing springback during hot rolling, and analyzed relations between various parameters and springback. Following conclusions have been obtained accordingly:

1) Under the condition of isothermal forming, when the temperature of a plate exceeds a critical point, yield stress of the plate starts to decrease significantly; springback during the plate forming also starts to be reduced drastically, and the higher the temperature is, the smaller the springback is. The critical temperature is related to the material properties of the plate, and different materials lead to different critical temperatures. As for an SS400 low-carbon steel plate, its critical temperature is about 400 ℃, and when the temperature is up to 700 ℃, the springback is reduced to 1/3 of that at room temperature.

2) Under the condition of non-isothermal forming, temperature distribution on the plate surface has bigger influences on springback, and the bigger the area of the high-temperature zone on the plate surface is, the smaller the springback is. In the direction of the larger local deformation range of the plate, the change of the temperature distribution is the dominant factor influencing springback. For local hot rolling, temperature distribution along the thickness direction of the plate almost has no influence on the final springback.

3) Under the same heating conditions and with an unchanged thickness, in a certain size range, the smaller the plate size is, the less the springback after plate forming is. As the local deformation range along the length direction of a plate is larger than that along the width direction, springback is more obviously influenced by changes in the length.

4) Under the condition of bigger magnitude of local loading, the higher the proportion of plastic deformation in the overall plate deformation is, the smaller the springback after plate forming is.

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船体中厚钢板局部热压成形中的回弹仿真分析

谢栋, 赵耀, 董宏宝

华中科技大学 船舶与海洋工程学院,武汉 430074

摘　要:[**目的**]为了研究船体中厚钢板局部热压成形过程中影响回弹的因素,[**方法**]运用三维热弹塑性有限元仿真方法对影响回弹的参数进行研究和分析,通过一系列数值仿真试验考察板材的整体温度、温度场分布、板材尺寸、局部加载量等参数对其成形回弹的影响。[**结果**]分析结果表明,当板材成形温度超过材料屈服应力并达到开始显著下降的温度点时,回弹会随温度的升高而开始大幅度减小;由于变形区域的分布特点,在温度场分布的3个维度中,局部变形范围较大方向的温度分布对回弹的影响占主要部分;加热条件完全相同时,板材长度和宽度方向的尺寸变化对回弹均有一定的影响,其中,局部变形范围较大的板长方向的尺寸变化对回弹的影响更明显,板材回弹随局部加载量的增大而减小。[**结论**]研究结果有助于实现优化船体中厚钢板自动化成形的参数获取,对进一步研究船体中厚钢板局部热压成形的回弹问题也具有基础性指导作用。

关键词:中厚板; 热压成形; 回弹; 数值仿真; 有限元法