METABK 59(2) 175-178 (2020)
UDC – UDK 669.14/621-41:621.771/536.58:539.374:531.79=111

FINITE ELEMENT SIMULATION OF DEFORMATION BEHAVIOR OF PREFABRICATED HOLES IN ULTRA-HEAVY PLATES BY GRADIENT TEMPERATURE ROLLING

Received – Primljeno: 2019-08-28
Accepted – Prihvaćeno: 2019-11-05
Original Scientific Paper – Izvorni znanstveni rad

Based on the Deform-3D finite element simulation software, the numerical analysis of prefabricated holes in the core of ultra-heavy plates is carried out in different rolling schemes. In this paper, the deformation of the hole in core under uniform temperature rolling (UTR) is compared by different gradient temperature rolling (GTR) processes. The results show that the GTR can improve the core deformation compared with the UTR. The increase of the number of water cooling can accelerate the welding of the core holes and the healing of the final gap, and multi-pass water-cooled GTR should be used for ultra-heavy plate rolling.

Keywords: gradient temperature rolling; prefabricated holes; deformation; finite element simulation

INTRODUCTION

Ultra-heavy plates have a wide range of applications in marine offshore steel, bridges, large pressure vessels and other structural components, and as their demand increases, their performance requirements are also increasing [1,2]. Due to the solidification shrinkage during casting, void defects such as voids, shrinkage and pores cannot be avoided [3]. There are two stages, void closure and surface bonding, which included in eliminating void defects in forging or rolling process [4]. Most void defects can be eliminated by strong plastic deformation. During the forging or rolling process, high temperatures and stresses are applied to the voids, which makes the elimination of void defects relatively easy to achieve [5]. It has been shown that the influence of pressure, temperature and holding time on the quality of diffusion welding is very important [6]. Therefore, in the rolling process of ultra-heavy plates, the hole defects in the core are welded by deformation. The research shows that the differential temperature rolling is to perform the water cooling of the slab with a certain intensity and time between the rolling passes, so that the blank produces a certain temperature gradient along the thickness direction, thereby increasing the core deformation during the rolling process and improving quality of the core [7-10]. In recent years, with the development of computer technology, numerical simulation has been widely used due to its low cost and high efficiency [11,12]. Therefore, the numerical simulation technology is more conducive to the study of the deformation law of the core of the ultra-heavy plate rolling [13].

Based on Deform-3D finite element numerical simulation software, the deformation of core prefabricated holes under uniform temperature rolling and differential cooling under different water-cooling conditions was studied in this paper, and the deformation welding laws of holes in core under different rolling conditions are revealed, which provide a theoretical basis for actual production.

Experimental process

In the rolling experimental model, to simplify the calculation of the overall rolling set to 1 / 4 model, the complete size of the rolled piece is 320 mm × 260 mm × 300 mm, the roll diameter is 750 mm, the rolling is divided into 12 passes, and the thickness of the rolled piece is changed to 300 → 270 → 235 → 200 → 170 → 145 → 125 → 110 → 104 → 100 → 96 → 92 → 90 mm. Improving the core defect is one of the key problems in ultra-thick plate rolling. To simplify the study of the deformation law of the shrinkage hole in the core of ultra-heavy plates during the rolling process, a 5 mm × 5 mm × 5 mm cube model is established in the core of the block, and pull out a circular shrinkage hole with a diameter of 3 mm, as shown in Figure 1.

The simulation experiment procedure is as shown in Table 1, and multiple sets of GTR experimental schemes are established, which are compared with the UTR.

The material of the simulated rolled thick plate is EH40 steel, assuming conditions [14,15]: the elastic deformation of the material is negligible; ignore the ef-

B. Xu (e-mail: boxuchina @163.com), H. Fu, College of Metallurgy and Energy, North China University of Science and Technology, Tangshan, Hebei, China
S. Li (e-mail: lishengli@ustl.edu.cn), Q.Xiao, Key Laboratory of metallurgical engineering, University of Science and Technology Liaoning, Anshan, Liaoning, China
T. Kang, 725 Research Institute of China Shipbuilding Heavy Industry

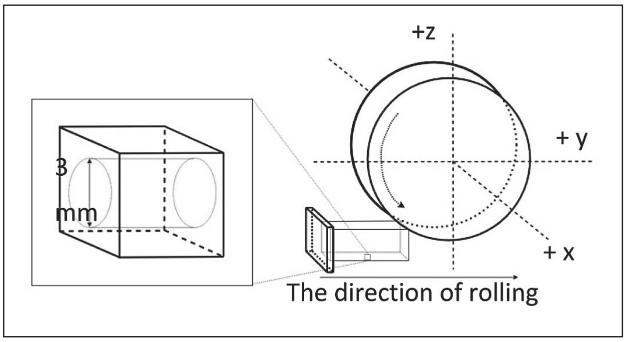


Figure 1 The schematic of prefabricated holes in core

Table 1 **Experimental process**

	After 1st pass	After 3rd pass	After 5th pass
UTR	No	No	No
GTR - 01	Water cooling	No	No
GTR - 02	Water cooling	Water cooling	No
GTR - 03	Water cooling	Water cooling	Water cooling

fects of volumetric forces (gravity and inertial forces, etc.); the material is homogeneous, incompressible, and initially isotropic; material deformation conforms to Levy-Mises yield criterion.

Simulation results and analysis

During the deformation process, the deformation of the prefabricated holes is shown in Figure 2. To study the prefabricated holes deformation, the *K* value to quantify the deformation of the shrinkage cavity was defined.

$$K = \frac{h}{a}, 0 \le K \le 1$$

Where *h* is the height of the hole, *a* is the length of the hole.

In each of the four cases, the prefabricated holes of each pass are shown in Table 2. It can be clearly seen that in the case of multi-pass water cooling, the final thickness is smaller, and the gap of the core is shorter, and the gap is completely healed in GTR - 03, so the increase in the number of water cooling can increase the deformation of the core, thereby making the prefabricated holes of the core heals.

It can be seen from Figure 3 (a) that the prefabricated holes are closed at the 9th pass of the UTR, and the 3 sets of the GTR are at the 8th, 7th, and 6th passes respectively closed, and the K value of the pass after adding water cooling drops faster, that is, the prefabricated holes closes faster. During the deformation process of the prefabricated holes, it will become elliptical from a circle, and after the prefabricated holes is closed, the

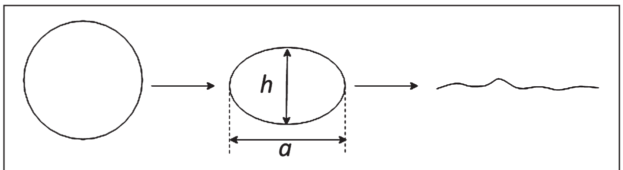


Figure 2 The change of shrinkage deformation

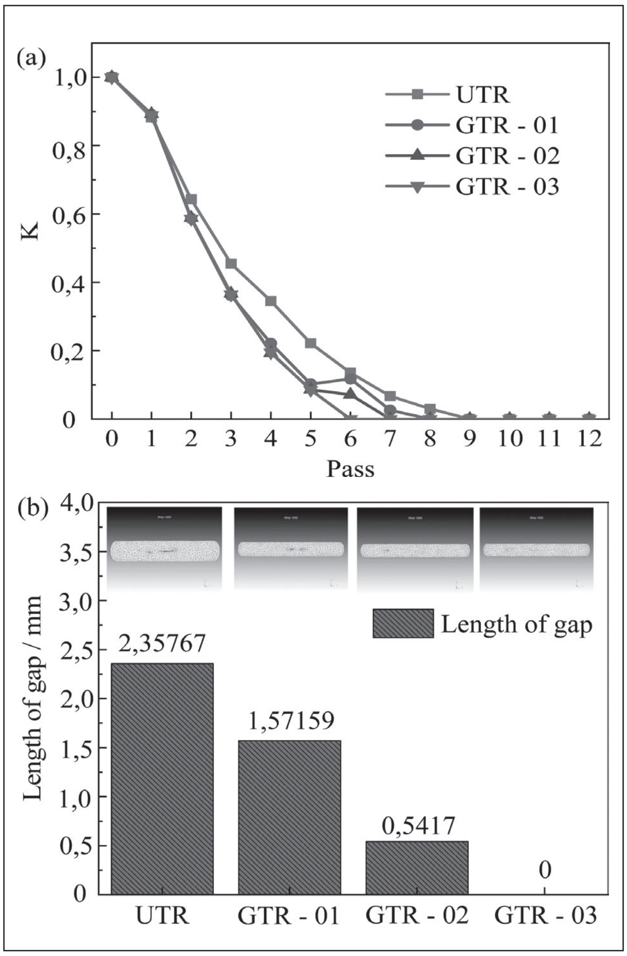


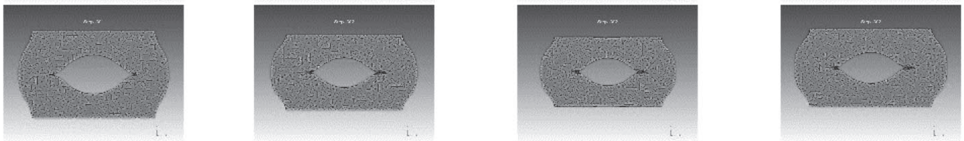
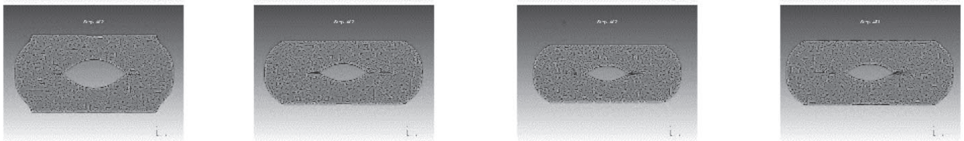
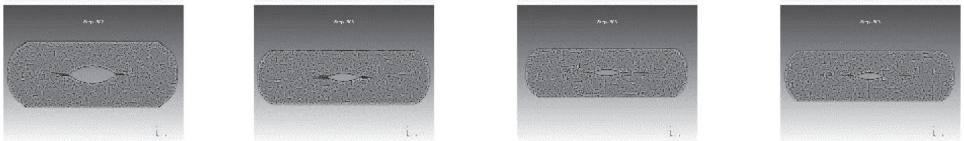
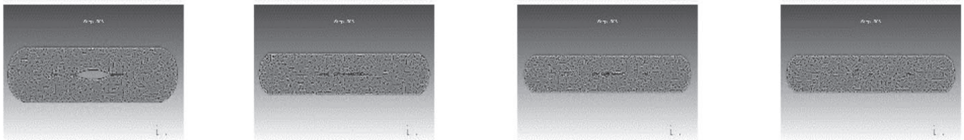
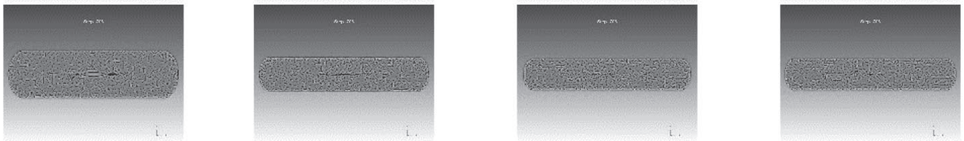
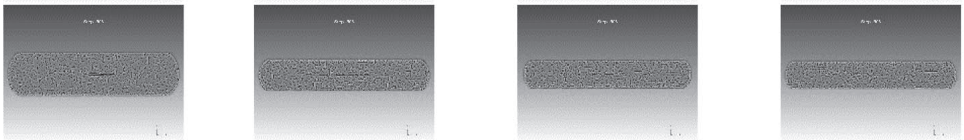
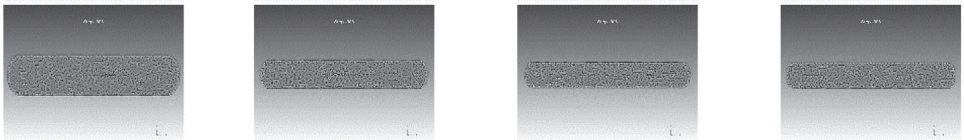
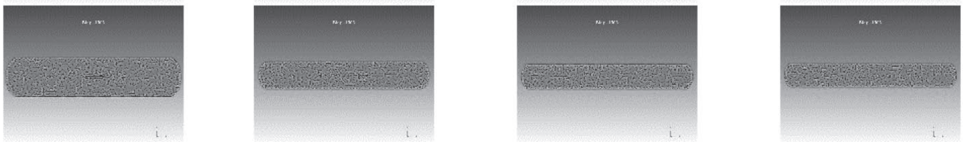
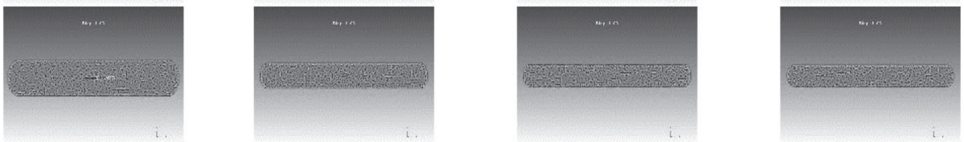
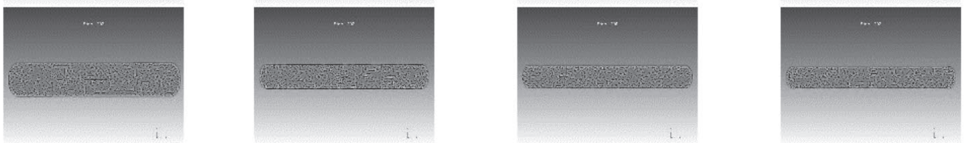
Figure 3 The simulation of hole's deformation
(a) the change of K-value; (b) the final length of gap

defect is not completely repaired, but a gap is gradually formed, and the gap is gradually healed by further rolling, finally, the defect will be gradually fixed. Figure 3 (b) is the comparison of the length of the gap remaining in the final shrinkage after the last pass. It can be seen that under different experimental schemes, the gap length of the UTR is the longest, and as the number of water-cooling increases, the length of gap will gradually decrease. By comparing the data, it can be found that the final gap length of the three GTR is reduced by 33,34 %, 77 02 %, and 100 %, respectively, compared to the UTR. Particularly, at GTR - 03, the gap has all healed, which indicates that the differential temperature rolling has a significant improvement on the defect of the core, and multiple pass water cooling is more conducive to the repair of the defect of the core.

SUMMARY

Gradient temperature rolling is more favorable for the welding of the prefabricated holes than the uniform temperature rolling, and the increase of the number of water-cooling times significantly improves the deformation of the prefabricated holes. Prominently, adding three times of water cooling can completely weld the prefabricated holes. Therefore, a reasonable differential temperature rolling process can effectively improve de-

Table 2 **The change of hole's deformation in each pass**

Pass No.	UTR	GTR-01	GTR-02	GTR-03
Before rolling				
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				

fects welding of the hole in core of the ultra-heavy plate and improve the microstructure performance.

Acknowledgments

This work was financially supported by Opening Fund for National Key Laboratory of Metallic Materials for Marine Equipment and Application (SKLMEA-K201801), Liaoning Province Natural Science Fund Project (201602385), 2017 Provincial Key Laboratory Opening Project of Liaoning University of Science and Technology (USTLKFSY201709), Liaoning Provincial Department of Education Innovation Team Project (LT2016003)

REFERENCES

[1] B. S. Xie, Q. W. Cai, Y. Yun, et al. Development of high strength ultra-heavy plate processed with gradient temperature rolling, intercritical quenching and tempering [J], Materials Science & Engineering A 680 (2017), 454 - 468.

[2] J. Chen, K. Chandrashekhara, C. Mahimkar. Void closure prediction in cold rolling using finite element analysis and neural network [J], Journal of Materials Processing Technology 211 (2011), 245 - 255.

[3] W. Deng, D. W. Zhao, X. M. Qin. Simulation of defects closing behavior during ultra-heavy plate rolling [J], Iron Steel 49 (2009), 58 - 62.

[4] H. Kakimoto, T. Arikawa, Y. Takahashi, et al. Development of forging process design to close internal voids [J], Journal of Materials Processing Technology 210 (2010), 415 - 422.

[5] Y. S. Lee, S. U. Lee, T Van, et al. Internal void closure during the forging of large cast ingots using a simulation approach [J], Journal of Materials Processing Technology 211 (2011), 1136 - 1145.

[6] Y. W. Dong, Z. H. Jiang, Y. L. Cao, et al. Effect of slag on inclusions during electroslag remelting process of die steel [J], Metallurgical and Materials Transactions B 45 (2014), 1315 - 1324.

[7] B. Wang, J. M. Zhang, C. Xiao, et al. Analysis of the evolution behavior of voids during the hot rolling process of medium plates [J], Journal of Materials Processing Technology 221(2015), 121 - 127.

[8] M. R. Forouzan, .I Salehi, A. H. Adibi-sedeh, et al. A comparative study of slab deformation under heavy width reduction by sizing press and vertical rolling using FE analysis [J], Journal of Materials Processing Technology 209 (2009), 738 - 736.

[9] G. S. Li, W. Yu, Q. W. Cai, et al. Effect of gradient temperature rolling (GTR) and cooling on microstructure and properties of E40-grade heavy plate [J], Archives of civil and mechanical engineering 17 (2017), 121 - 131.

[10] T. Zhou, H. Yu, S. Y. Wang, et al. Effect of microstructural types on toughness and microstructural optimization of ultra-heavy steel plate: EBSD analysis and microscopic fracture mechanism [J], Materials Science & Engineering A 658 (2016), 150 - 158.

[11] J. Hu, L. X. Du, H. Xie, et al. Microstructure and mechanical properties of TMCP heavy plate microalloyed steel [J], Materials Science & Engineering A 607 (2014), 122 - 131.

[12] J. T. Yeom, S. L. Chong, J. H. Kim, et al. Finite-element analysis of microstructure evolution in the cogging of an Alloy 718 ingot [J], Materials Science & Engineering A 449 (2007), 722 - 726.

[13] S. Wang, B. Yang, M. Zhang, et al. Numerical simulation and experimental verification of microstructure evolution in large forged for pipe used for AP1000 nuclear power plants [J], Annals of Nuclear Energy 87 (2016), 176 - 185.

[14] J. Y. Wu, B. Wang, B. X. Wang, et al. Toughness and ductility improvement of heavy EH47 plate with grain refinement through inter-pass cooling [J], Materials Science & Engineering A 733 (2018), 117 - 127.

[15] F. Faini, A. Attanasio, E. Ceretti. Experimental and FE analysis of void closure in hot rolling of stainless steel [J], Journal of Materials Processing Technology 25 (2018), 235 - 242.

Note: Q. H. Xiao is responsible for English language, Liaoning, China