Progress in Research of Dragon Rolled Plates

Wu Lei\textsuperscript{a}, Qin Ming\textsuperscript{b}, He Bing\textsuperscript{c}, Gu Bin\textsuperscript{d}

School of Materials Science and Engineering, Baise University, Guangxi, China, 533000
\textsuperscript{a}e-mail: wulei@bsuc.cn
\textsuperscript{b}e-mail: qinming@bsuc.cn
\textsuperscript{c}e-mail: hebing@bsuc.cn
\textsuperscript{d}e-mail: gubin@bsuc.cn

Abstract. Progress in research of dragon rolled thick plates are summarized in this paper. Basic characteristics, reduction and gap supplement, plate bending, rolling force and energy parameters, shear deformation at the center of the thick plates and the materials and methods in current research were introduced. Although the potential of the application of dragon rolling in thick plate production is obvious, there are still many unsolved problems, especially that the experimental data is still less, therefore there is still a lot of work to do from the practical application.

1. Introduction

Dragon rolling is a kind of asymmetric rolling method which, based on the traditional different speed rolling. By misaligns two rolls to a certain degree, and upon the dual effect of the different speeds and the roll misalignment, dragon rolling forms a "rolling zone" inside the deformed plate, together with a large shear deformation, to exaggerate the deformation at the core of the plate. This not only improves the situation where the cores of conventional rolled medium to thick plates are not deformed sufficiently, but also refines the grain structure and enhances mechanical properties. At the same time, with the misalignment, this method can effectively reduce or alleviate the plate bending defects caused due to different roll speeds in the asynchronous rolling.

Although the dragon rolling model has been proposed for many years, there are few practical applications, and its studies remain at the stage of theoretical analysis, computer simulation, and laboratory experiment, mainly around aluminum plates. The researches on dragon rolling of steel plates are limited. This paper sorted out the progress of some researches in dragon rolling field, for the reference of scholars and technicians.

2. Basic Characteristics of Dragon Rolling

The traditional rolling, namely the symmetrical rolling, cannot achieve the sufficient deformation at the center of the plate along its thickness, and is prone to cause such problems as deformation of the surface and center of the rolled plate, uneven structure and performance, and excessive residual stress, which seriously degrades the plate performance\textsuperscript{1}. Dragon rolling, also known as snake rolling, is a type of asymmetric rolling. Generally asymmetric factors fall into two categories: 1) geometric factors, such as different diameters and horizontal misalignment of the upper and lower rolls, and the angle of incidence during the plate rolling; and 2) other factors, e.g., inconsistent linear surface velocities,
smoothness, and thermal diffusions of the upper and lower rolls. By introducing different asymmetric factors, the asymmetric rolling derives different rolling methods, including such typical representatives as asynchronous rolling, horizontal dislocation constant velocity rolling, and dragon rolling [2].

The dragon rolling was proposed by a Dutch scholar. It refers to a process that, based on the asynchronous rolling, shifts two rolls with different speeds back and forward horizontally, to increase a bending moment that can offset the potential plate bending, and achieve the bending-free rolling by adjusting and matching the different speed ratio, misalignment, rolling reduction, and some other parameters.

The dragon rolling deformation zone is as shown in Figure 1. In the figure, I is the backward slip zone, II is the rolling zone, III is the forward slip zone, and IV is the reverse bending zone. The above four zones are all plastic deformation zones. In Zones I, II, and III, the metal plate becomes thinner; while in Zone IV, the metal plate contacts with the upper roll only, thus its thickness remains unchanged, but the plate goes through the reverse bending and straightening [3].

3. Main Research Issues

3.1. Rolling Reduction and Gap Compensation
In the dragon rolling, because the upper and lower rolls are misaligned to a certain degree, the resulting gap is not the position difference between the lowest point and the highest point of the upper and lower rolls in the traditional rolling. Compared with the conventional rolling, under the same roll gap, in the dragon rolling, the rolling reduction is less due to the added reverse bending zone (where the thickness remains unchanged), therefore, in order to ensure the same reduction between the dragon rolling and the conventional rolling, it is necessary to compensate the roll gap [3].

Lei Junyi et al. [3] calculated the gap compensations and reduction ratios of two dragon rolling scenarios: 1) same diameter but different speeds and 2) same speed but different diameters. In the same-diameter different-speed dragon rolling, the gap compensation ∆S is as shown in Equation (1):

$$\Delta S = R - \sqrt{R^2 + L^2}$$  \hspace{1cm} (1)

where, ∆S is the gap compensation, R is the radius of the roll, and L is the misalignment. On this basis, it is calculated that in the same-diameter different-speed dragon rolling, the reduction of the slower roll is greater than that of the faster one, and the difference between the reductions of the two rolls relates to the misalignment L.

3.2. Rolled Plate Bending
Fu Yao et al. [4] established an analytical model to predict the curvature of the dragon rolled plate. With the increase of the misalignment, the difference in the shear strain between two sides of the rolled plate
caused by the different speeds of the rolls would increase the plate curvature, but the difference in the curved strain would decrease the plate curvature. Under the joint impact of both factors, the total plate curvature decreased firstly and then increased. The calculations proved that the roll misalignment could effectively alleviate the rolled plate bending. The experiments verified the accuracy of the analytical model, obtained the calculated curvature error equivalent to 12% of the experimental value, and concluded that the optimal misalignment between 25 ~ 35 mm could effectively alleviate the rolled plate bending. However, it should be noted that the optimal misalignment referred herein was based on the materials, thickness and different speed ratio used in the study, but not a general conclusion.

Zheng Xizhao [5] established the coupled thermal-mechanical model of the dragon rolling with the elastic-plastic finite element method, studied the impact of the process parameters including the entrance thickness, rolling reduction, different speed ratio, and misalignment on the rolled plate bending, defined the optimal misalignment to control the rolled plate bending, studied the impact of the entrance thickness, rolling reduction, and different speed ratio on the optimal misalignment, and generated the mathematical model of the optimal alignment for bending control of the rolled plate using the 1stOpt nonlinear regression, as shown in Equation (2) which obtained the correlation coefficient up to 98.31%. The 1stOpt (First Optimization) is a mathematical optimization analysis software.

\[ S_b = 1.46 \times 10^7 h^{-2.51} \cdot \Delta h^{0.4727} \cdot (i - 1)^{0.166} \]  

Where, \( S_b \) is the optimal misalignment, \( h \) is the entrance thickness of the rolled plate, \( \Delta h \) is the rolling reduction, and \( i \) is the different speed ratio.

3.3. Rolling Mechanical Parameters
Zhen Tao [6] established an analytical model of rolling force and rolling moment of the same-diameter different-speed snaking rolling/differential temperature rolling with deformation resistance gradients. The calculation results had an error of less than 10% compared with the simulation results. According to the calculations, as the different speed ratio increased, the rolling force reduced. If the deformation zone was composed of a backward slip zone, a forward slip zone, a rolling zone, and a reverse bending zone, when the misalignment increased, the rolling forces increased slightly, the rolling moment of the slower roll decreased gradually, and that of the faster one increased gradually. When the rolled parts’ surface resistance to deformation increased, the rolling force increased. If the deformation zone had only a rolling zone and a reverse bending zone, the rolling moments of both slower and faster rolls increased.

Meng Qingcheng [7] established mathematical models for two snaking rolling methods: 1) same diameter but different speeds and 2) same speed but different diameters. In the same-diameter different-speed rolling, with the increase of the different speed ratio, the neutral point of the slower roll moved to the entrance side of the deformation zone, and that of the faster roll moved to the exit side of the deformation zone. As the distance between the neutral points of the two rolls increased (it meant the rolling zone increased), the shearing effect strengthened, which was beneficial to the plastic deformation of the metal and decreased the rolling force; while the increase in the misalignment led to decrease of the rolling force, and if the deformation zone consisted of a backward slip zone, a rolling zone, and a reverse bending zone, the increase in the misalignment had the same impact as concluded by Zhen Tao; however, if the deformation had only a rolling zone and a reverse bending zone, the rolling moments of the faster and lower rolls were in opposite directions, and as the alignment increased, the rolling moment of the slower roll increased but that of the faster one decreased.

3.4. Shear Deformation at the Core of the Rolled Plate
In the dragon rolling, without increasing the rolling reduction, the resulting additional shear deformation makes the deformation deep into the center, thus improving the uniformity of the deformation and structure of the rolled plate. Figure 2 shows the comparison of the central structures of the synchronous rolled and dragon rolled aluminum plates. It can be seen from the figure that the dragon rolling can significantly refine the core structure of the aluminum alloy plate [8].
In his study on the deformation penetration of steel plate in snaking rolling, Meng Qingcheng \cite{7} used a finite element software to build a steel plate snake rolling model. Through simulation and comparison with the synchronous rolling, the difference in metal flow velocity between the upper and lower surfaces of the steel plate in the snake rolling led to a strong shear deformation along the thickness of the steel plate, which helped the deformation penetrate to the core of the steel plate. The increases in both the speed ratio and the rolling reduction enlarged the equivalent strain in the core of the steel plate; but the increase in the misalignment along the thickness of the steel plate had little impact on the equivalent strain.

4. Research Methods and Materials

In terms of materials, current researches focus on aluminum plates and sheets, mainly 7 series \cite{9, 10} aluminum alloy, as well as Al-Cu-Mg \cite{11}, Al-Mg-Si \cite{12} alloy, etc. There are few researches on the application of steel plate dragon rolling, and these few researches mainly concentrate upon the analytical calculation \cite{6} and numerical simulation \cite{7}.

The standard dragon rolling can enable different roll speeds (or different roll diameters) and roll offset at the same time, which is largely different from the conventional rolling requirements including synchronous roll rotation and roll center alignment. This requires a major modification on the conventional rolling mills. At present, researches mainly explore the following methods:

1. Experiments with modified dragon rolling equipment \cite{11, 13}. Such equipment is generally modified from a conventional rolling mill, using two motors to drive two rolls to achieve different speeds, or replacing one roll of the original rolling mill with a roll of different radius to achieve different diameters. The roll offset is mainly realized by modifying the original rolling mill frame, but it will cause a certain damage to the rolling mill frame and adversely affect the rolling stability and the rigidity of the rolling mill.

2. Numerical simulation through software \cite{9, 12}. As the finite element simulation software becomes mature in elastoplastic simulation, thermal-mechanical coupling analysis, algorithm optimization, etc., MARC, ANSYS, ABAQUUS, and other large commercial finite element analysis software for modeling analysis can not only save costs, adjust parameters flexibly, and shorten the experiment cycle, but also analyze and explore the related material properties, rolling theories, plastic deformation mechanism, and some other aspects in the modeling process.

3. Calculation with analytic methods. So far, many scholars have used the principal stress method, slip line method, and other methods for in-depth researches on stresses, bending conditions, and rolling moments of rolled plates in conventional rolling and asynchronous rolling. The analytical model established by Fu Yao et al. \cite{4} for predicting the curvature of the snake rolled plate has a high accuracy, with the comparison error not more than 12% of the experimental value.

5. Conclusions

This paper sorted out the progress of some researches in the dragon rolled plates, mostly aluminum plates with a few of steel plates. In terms of rolling mechanism, through the theoretical analysis,
analytical calculation, and finite element simulation, the paper clearly described the formation of the "rolling zone" and its effect on the shear strain at the core of the plate, studied the rolled plate bending, rolling force, rolling moment, and equivalent strain inside the plate around two critical characteristic process parameters: different speed ratio and misalignment, and made some conclusions that have not been widely recognized. However, due to the lack of experimental support, the rule of the impact of the dragon rolling parameters on the shape, mechanical properties, metallographic structure, and construction of the plate has not been intuitively established, and there was a large shortage of relevant measured data.

In short, the dragon rolling has an obvious potential for plate production, but there are still many theoretical "blind spots" and experimental blanks, indicating a long way to actual production applications. In the future, we should improve the rolling mechanism gradually, transition from theories to laboratory tests, accumulate more measured data, and finally step toward practical applications.

References

[1] Fu Yao. Research on snake rolling of thick Plate of high strength and toughness aluminun alloy[D]. Beijing: General Research Institute for Nonferrous Metals, 2011.

[2] Liu Jie. Curvature, microstructure and mechanical properties of aluminum sheets processed by snake rolling[D]. Changsha: Central South University, 2014.

[3] LEI Jun-yi, JIANG Lian-yun, MENG Qing-cheng. Analysis and research on hot rolled thick metal plate snake rolling reduction and threading condition[J]. Heavy Machinery, 2018(3), 21-25.

[4] Fu Yao, Xie Shuisheng, Xiong Baiqing, Huang Guojie, Cheng Lei, Xiao Xiangpeng. Analytical Study of Plate Curvature in Snake Rolling of Aluminum Alloy[J]. 2011, 35(6), 805-811.

[5] Force analyze and calculate of dragon rolling mill and bending analyze and control of rolling plate[S]. Changsha: Central South University, 2014.

[6] Zhen Tao, Huang Jin-bo, Wei Yao-yu, Jiang Lian-yun. Analysis of rolling force on the heavy steel plate snake/gradient temperature rolling with the same roll diameters[J]. Heavy Machinery, 2020(1), 23-32.

[7] Meng Qing-cheng. Research on Mechanical parameters and Deformation permeability of Heavy steel plate Snake rolling[M]. Taiyuan: Taiyuan Science University, 2018.

[8] Haszler, A. Technical challenges and solutions of aluminum in the transportation market[A]. In: Hirsch J., eds. Proceedings of the 11th International Conference on Aluminum Alloys[C]. Aachen, Germany: 2008: 24-34.

[9] Qin Guo-hua, Yang Yang, Li qiang, Lin Feng. Analysis and prediction of multi-pass snake hot rolling for 7075 aluminum alloy thick plate[J]. Optics and Precision Engineering, 2017, 25(4), 437-446.

[10] Li Qing. Analysis and Simulation of Multi-pass Snake Hot Rolling of 7075 Aluminium Alloy Thick Plate[M]. Nanchang: Nanchang Hangkong University, 2016.

[11] Xu Fu-shun, Zhang Jin , Deng Yun-lai , Zhang Xin-ming. Effect of snake rolling on strength, toughness and microstructure of Al-Cu-Mg alloy plate[J]. The Chinese Journal of Nonferrous Metals, 2017, 27(10), 2005-2011.

[12] Ling Liyue, Tang Jianguo , Liu Wenhui. Numerical simulation evolution of shear strain and crystallographic textures during snake rolling of Al-Mg-Si alloy plate[J]. Journal of Central South University (Science and Technology), 2017, (48)9, 2279-2286.

[13] Hu Cai, Lin Huaqiang , Deng Yunlai, Tang jianguo. Effects of Snake Rolling on Microstructure and Texture of 2024-T39 Aluminium Alloy Sheet[J]. Hot Working Technology, 2017, 46(21), 1-4.