Rare Metal Materials and Engineering
Volume 46, Issue 10, October 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2017, 46(10): 2770-2774.

ARTICLE

Deformation Feature of TC4 Rod Based on Multi-line Triangle Pass System

Shuai Meirong[1,2], Liu Hao[2], Li Haibin[1,2], Huang Zhiquan[2], Huang Qingxue[1,2]

[1] Taiyuan University of Science and Technology, Taiyuan 030024, China; [2] Shanxi Provincial Key Laboratory on Metallurgical Device Design and Theory, Taiyuan 030024, China

Abstract: The rapid increase of the demand for titanium and titanium alloy rods with high strength and fine ductility results in the necessity to develop a multi-roller mill and a hot continuous rolling process. In this study, the authors proposed to produce TC4 alloy rod on Y-type mill with a multi-line triangle-round pass system. The deformation feature, rolling stability, and temperature distribution of TC4 alloy rod during the hot continuous rolling process were simulated with ANSYS software. The experiments were also conducted on Y-type mill. The results show that the multi-line triangle pass with concavity has a good centrality. Thus, the system can prevent TC4 rod from twisting or deviating from the rolling direction, and the stability of the rolled rod can be improved. Compared with the conventional flat triangle-round pass system, the proposed pass system obviously decreases the temperature gradient along the cross section of TC4 rod, thereby reducing the possibility of surface cracking, and improving the surface quality of the final product.

Key words: TC4 rod; multi-line triangle pass; rolling stability; temperature distribution

Various applications of titanium and titanium alloy rod for large structures and lightweight aerospace components require mechanical strength because of their large plastic deformations[1,2]. At present, small-diameter titanium alloy rods are mainly obtained through an open-train rolling process or a two-roll continuous rolling process[3,4]. Many materials are lost during the subsequent process because of poor surface quality and small dimensional accuracy. Therefore, a three-roller system is used to produce titanium alloy rods in order to decrease cost and save energy. In the present study, firstly, this system has been investigated to better control the deformation and microstructures compared with the conventional two-roller system [5,6]. Secondly, the continuous deformation of a workpiece could be fulfilled through a series of three-roller stands, which guarantees a suitable rolling temperature and avoids intermediate reheating and heat treatment processes. Thirdly, a three-roller system has various advantages, such as easy flow control, small space requirement, and comparatively uniform deformation. Therefore, a three-roller system is suitable for producing titanium alloy rods with narrow rolling temperature and high deformation resistance[7].

So far, many studies have focused mainly on predicting the deformed shape of the rolled workpiece at the exit of three-roller mill. However, few studies have been conducted to improve rod stability in the three-roller system. In general, rolling stability has a critical influence on continuous rolling. However, the rolled workpiece has poor stability in the conventional pass of a flat triangle and round pass system[8]. Therefore, a new type of pass system called multi-line triangle is introduced in the present study, and its validity is verified through the simulation results of FEM and experiment analyses. The temperature gradient of TC4 rod from the multi-line triangle pass system decreases along the cross-section of the rod. This phenomenon is beneficial for the surface quality and microstructure of TC4 rod.

Received date: October 14, 2016
Foundation item: Province Natural Science Research Program of Shanxi (2014011026-1); Doctor Startup Project of School (20122037)
Corresponding author: Shuai Meirong, Ph. D., Associate Professor, School of Material Science and Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, P. R. China, Tel: 0086-351-6963331, E-mail: ruoxin2001@163.com

1 "Multi-line Triangle" Pass System

The multi-line triangle pass belongs to three-roller pass system. It is also derived from the flat triangle pass. The surface of a roller is composed of an arc segment I and a linear segment II. The multi-line triangle pass and round pass, which constitute a multi-line triangle-round pass system, are arranged alternately, as shown in Fig. 1.

Deformations occur deeply inside the rod because of the special pass with a concave groove bottom. This outcome is in favor of product quality. A concavity in the middle of the rod exists because of the multi-line triangle pass. Thus, it may not be overfilled in next round pass. This type of pass system can produce round rods of various diameters, which satisfies the demand for small-quantities and multi-variety of titanium alloy rod.

2 Influence of Pass System on Rolling Stability

One disadvantage of the Y-type mill is the poor stability of the rod in continuous passes. The symmetric axis of a rod frequently deviates from that of a pass, resulting in interruptions and low equipment efficiency. Therefore, the stability of the rod in the continuous rolling process must be improved and solved.

The spread of rod is presumably ignored, i.e., the cross section of rod at the exit of the pass is in accord with the pass shape. The uneven reduction coefficient of any cross section along the groove width direction is assumed as k_y, which represents the stability of rod in the pass [8].

$$k_y = \frac{\Delta z(y_{max}) - \Delta z(y)}{y_{max} - y} \tag{1}$$

$$\Delta z(y) = \Delta z_2(y) - \Delta z_1(y) \tag{2}$$

where, y is the distance between any point of the cross-section outline to intersection point of rod, y_{max} is the distance between the culmination point of the cross-section outline to intersection point of rod, $z_1(y)$ is the curve equation of cross-section outline of the rod, $z_2(y)$ is the curve equation of pass, $\Delta z(y_{max})$ is the max reduction of rod, and $\Delta z(y)$ is the reduction of any point y of the cross-section outline of the rod.

The meaning of each parameter is shown in Fig.2.

If the symmetric axis of rod is found to deviate from that of multi-roller pass, it is certain to turn from unstable position to more stable or balanced position. At the two ends of roller, corresponding to straight-line segment of roller surface, k_y maintains a constant value. So it is impossible for the workpiece to deviate away. However, corresponding to arc segment of roller surface, the absolute value of k_y is decreasing gradually, and it will reach the minimum value at the middle of roller. Therefore, there are two chances that the workpiece will not deviate away in the whole rolling process, or it will turn toward the middle of roller. It is obvious that the multi-line triangle pass is good to improve the stability of rod in rolling process.

3 Finite Element Simulations

3.1 Finite element model

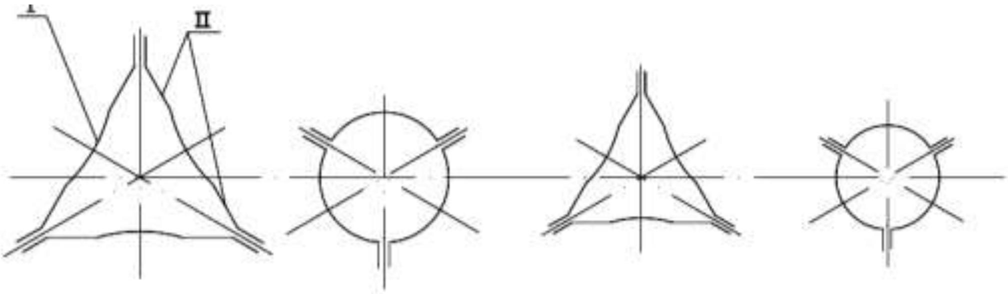

Fig. 1 Multi-line triangle-round pass system

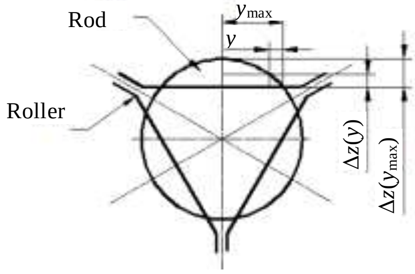

Fig. 2 Parameters display for rolling stability

The continuous rolling process of titanium alloy rod is simulated with ANSYS finite element software. Eight stands with a multi-line triangle-round pass system are used. The three-dimensional graph of the eight mills is shown in Fig.3.

Prior to the modeling, the following assumptions about the process are established. The roller is presumably rigid, and no roller abrasion exists [9,10]. The TC4 rod is deemed toan elastic plastic material with isotropy. The initial rod temperature is even, and no temperature gradient exist s along the longitudinal direction.

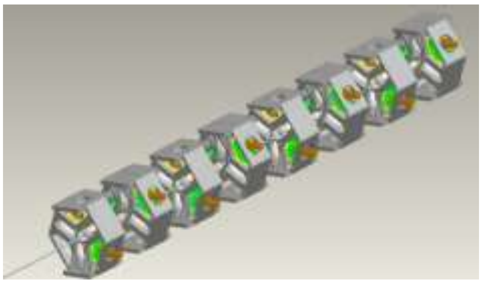

Fig.3 Three-dimensional graph of the mills

During the numerical simulation, the stress-strain curves of TC4 at various temperatures are obtained using a Gleeble 3500 testing machine. The Von Mises yield criterion is used to judge whether plastic deformations are developed.

$$f(\sigma'_{ij}) = \sqrt{3J'_2} - \bar{\sigma}(\bar{\varepsilon}_{\mathrm{p}}) = 0 \qquad (3)$$

where, J'_2 is the second invariant of the stress deviator, $\bar{\sigma}$ is the equivalent stress of subsequent yield, and $\bar{\varepsilon}_{\mathrm{p}}$ is the plastic strain.

3.2 Analysis of simulation results

3.2.1 Analysis of deformation regularity

The shape of the TC4 rod through each rolling pass in a stable stage is shown in Fig.4, where Fig.4a, 4c, 4e, and 4g represent the mesh distortion of the round rod in the multi-line triangle pass, while Fig.4b, 4d, 4f, and 4h represent the mesh distortion of the triangle rod in the round pass.

Fig.4a illustrates that the contact areas deform firstly when the workpiece enters the first multi-line triangle pass, and the metal is forced to flow rapidly toward the gap areas.

This phenomenon results in the constant increase of metals in the gap areas.

As the rolling process continues, the large deformation could occur deeply inside the rod, thereby positively influencing product quality [11, 12]. On the contrary, the compressed metals in the front pass are located on the gap areas of the next pass. Fig.4b illustrates that the shape of TC4 rod is apparently out-of-round at the exit of the pass. The reason for this shape is that the extending deformation in this round pass occupies a dominant position, and a little spread does not compensate for the concave formed from the front pass. In the sequence pass system, mesh distortion is similar to the first two passes. At the exit of the seventh pass, the small concave shape appears, as shown in Fig.4g. It is compensated well by a little spread, as shown in Fig. 4h.

3.2.2 Analysis of temperature distribution

The temperature distribution of the TC4 rod depends on the contact area, press distribution, surface temperature, relative speed, and coefficient of thermal conductivity. In the rolling process, the reduction value of the workpiece is uneven along the wide direction of the pass. Thus, the deformation degree and heating exchange with external environment are also different, resulting in the uneven temperature distribution for TC4 rod.

The four points at different positions are chosen as representatives to reflect directly the temperature gradient. One of the measured points is the center of rod, one marked (A), another (B) at the mid-height, the third (C) and the fourth (D) near the surface of rod apart of 60°. Location of four points is shown in Fig.5.

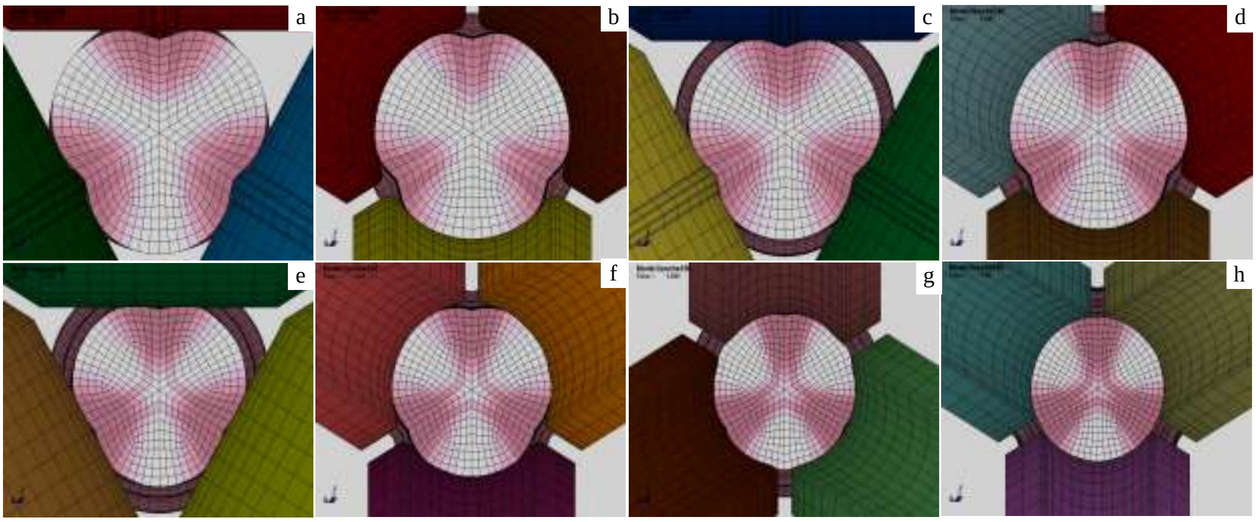

Fig.4 Cross-sectional shapes of the workpiece: (a, c, e, g) the mesh distortion of the round rod in the multi-line triangle pass; (b, d, f, h) the mesh distortion of the triangle rod in the round pass

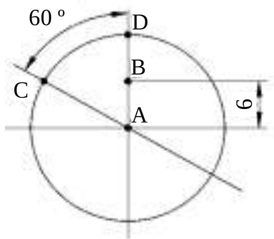

Fig.5 Locations of different points

During the whole rolling process, the temperature distribution of TC4 rod is uneven as predicted. Here, the deformation heat and frictional heat with the different pass systems have been considered. The temperature data of the measured points are imported from LS-DYNA SOLVER into the Origin software. The temperature distribution obtained from the multi-line triangle-round pass system is compared with that from the flat triangle-round pass system, as shown in Fig.6.

Fig.6 illustrates that the temperature values of A and B points near the center of rod increase constantly because of plastic deformation and frictional heat. Exchanging temperature with each other in a short time is difficult for the internal points because of its poor thermal conductivity.

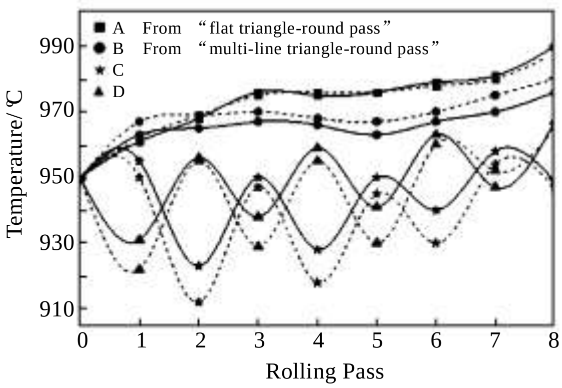

Fig.6 Temperature change curves for measured points from the two types of pass systems

Therefore, the temperatures of A and B points are higher than those of the surface points. At the end of the rolling process, the temperature of B point is slightly lower than that of A point, because the former lies in the upper middle section of rod and its temperature is affected by the surface points. The temperature of C point increases during the first, third, fifth, and seventh rolling passes because it lies in the gap area and no contact with the roller occurs. Its temperature is only influenced by the surrounding air and other points of the rod. However, the temperature of C point decreases sharply during the second, fourth, sixth, and eighth rolling passes because it lies in the contact area with the roller, where the heat transfer occurs between the high-temperature rod and the low-temperature roller. The D point near the surface of rod is 60° apart from C point, and its temperature curve is contrary to that of C point. Given that C and D points come into contact with the roller in turn, their temperatures would rise or decrease at regular intervals. This finding reveals that heat transfer is a key factor influencing the temperature distribution of TC4 rod.

Fig.6 also illustrates that the temperature gradient of the rod from the multi-line triangle-round pass decreases by approximately 10 ℃ compared with that from flat triangle-round passes. This phenomenon contributes to the reduction of temperature stress, structural stress, and residual stress of TC4 rod. In general, surface crack is closely related to inhomogeneous temperature distribution [13-15]. Thus, the decreased temperature gradient could also alleviate surface cracks and improve product quality.

4 Experiment Research

Rolling experiment is conducted on the Y-type mill. Two types of pass systems are used to compare the continuous rolling stability and quality of the final product. The rolled products from the flat triangle-round pass are shown in Fig. 7a and 7b. It can be seen that the rod surface has rolling edges and torsion scratches. Poor torsion and deviation may result in poor roller bite, serious guide wear, dynamic speed drop of the transmission mechanism, and poor rolling stability.

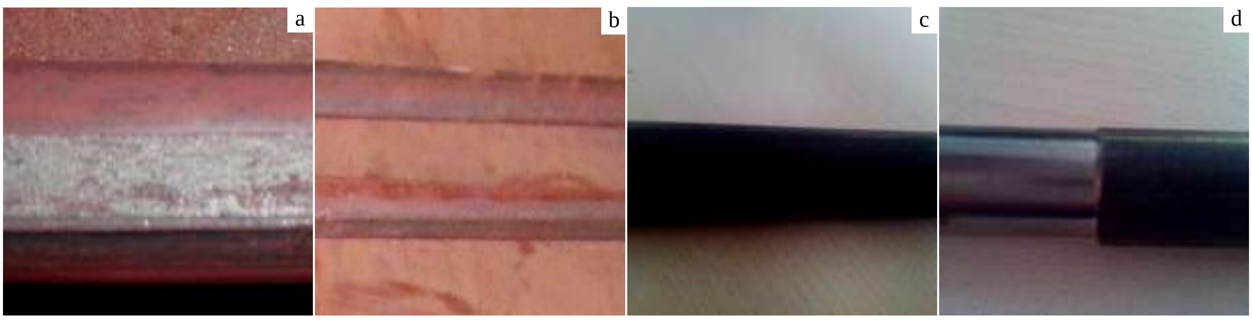

Fig.7 Flat triangle-round pass TC4 rod (a,b), multi-line triangle-round pass TC4 rod (c), and the peeled TC4 rod (d)

The rolled products from the multi-line triangle-round pass are shown in Fig. 7c. The rod surface is smooth and no torsion scratches appear. However, some cracks still appear on the rod surface. Peeling test is conducted on the lathe mill to measure the depth of surface cracks. The peeled TC4 rod is shown in Fig. 7d. The average diameter value of the rolled rod is approximately 8.94 mm, whereas that of the peeled rod is approximately 8.24 mm. The peeling depth is approximately 0.35 mm, so the metal loss rate of TC4 rod is approximately 15%, which is more economical than before.

5 Conclusions

A three-roller system with a multi-line triangle-round pass is used to produce TC4 rod. According to the results of FEM simulation and experiment research, the three-roller mill with multi-line triangle-round pass is suitable to roll metals with narrow temperature range and poor heat conductivity. First, the rolled rod is stable in the multi-line triangle-round pass system during the continuous rolling process. The symmetric axis of the workpiece does not deviate from that of the pass. Second, the temperature gradient of the TC4 rod from the multi-line triangle-round pass is lower than that from the unimproved pass. The proposed pass system can alleviate surface cracks and improve product quality. Last, the metal loss rate of the TC4 rod during the peeling process is approximately 15%, which is more economical than before. Thus, the multi-line triangle-round pass could be effectively used in the rolling process of other metals.

References

1 Li Chonghe, Zhu Ming, Wang Ning *et al. Journal of Rare Metals*[J], 2009, 33(1): 849 (in Chinese)
2 Froes F H. *JOM*[J], 2005, 57(9): 41
3 Ramesh S, Karunamoorthy L, Palanikumar K. *Materials and Manufacturing Processes*[J], 2008, 23(2): 175
4 Rack H J, Qazi J I. *Materials Science and Engineering*[J], 2006, 26(8): 1269
5 Shuai Meirong, Huang Qingxue, Qin Jianping *et al. Materials Review*[J], 2012, 26(3): 111 (in Chinese)
6 Min J H, Kwon H C, Lee Y *et al. Journal of Materials Processing Technology*[J], 2003, 140(1): 471
7 Zhang Zhu, Xie Yongsheng, Zhao Yunhao. *Titanium Plastic Processing Technology* [M]. Beijing: Metallurgical Industry Press, 2010 (in Chinese)
8 Li Zhiqiang, Liu Yazheng, Ye Wenjun. *Steel Wire Products*[J], 2002, 28(1): 30 (in Chinese)
9 Hwang Y M, Tsai W M, Tsai F H *et al. International Journal of Machine tools and Manufacture*[J], 2006, 46(12): 1555
10 Zhao Lili, Du Fengshan, Xu Zhiqiang *et al. Journal of Wuhan University of Science and Technology*[J], 2010, 33(4): 367 (in Chinese)
11 Oiinther Schnell. *Innovation Production Technology for Titanium and Special Alloy of Wire and Rod*[C]. Beijing: China Non-ferrous Metals Industry Association Titanium Zirconium & Hafnium Branch, 2009
12 Li Hui, Zhao Yongqi, Qu Henglei *et al. Titanium Industry Progress*[J], 2004, 21(6):19 (in Chinese)
13 Kwon H C, Lee H W, Kim H Y *et al. Journal of Materials Processing Technology*[J], 2009, 209(9): 4476
14 Wei Yongsheng, An Shaokong, Fan Zhaobao. *Aviation Precision Manufacturing Technology*[J], 2010, 46(5): 45 (in Chinese)
15 Wu Huan, Zhao Yongqing, Zeng Weidong *et al. Rare Metal Materials and Engineering* [J], 2008, 37(8): 1403 (in Chinese)

基于“多线段三角孔型系统”轧制 TC4 合金棒材变形特征研究

帅美荣[1,2]，刘 昊[2]，李海滨[1,2]，黄志权[2]，黄庆学[1,2]

(1. 太原科技大学，山西 太原 030024)

(2. 山西省冶金设备设计理论与技术重点实验室，山西 太原 030024)

摘 要：随着对高强度，高延展性钛及钛合金棒材的迅速需求，开发有色金属棒材多辊热连轧技术是非常必要的。本研究在Y型三辊轧机上采用“多线段三角-圆”孔型系统生产钛合金棒材。采用ANSYS有限元软件模拟了TC4棒材在热连轧过程中的变形特征，轧制稳定性及温度分布；并在Y型连轧机上进行了试验验证。结果表明：带有凹面状的“多线段三角”孔型具有良好的对中性，能有效阻止轧件扭转或偏离轧制中心线，提高棒材轧制稳定性；此外，相对于“平三角-圆”孔型系统，采用这种孔型轧制棒材，显著降低了TC4合金棒材横截面的温度梯度，从而减少产品表面裂纹，提高表面质量。

关键词：TC4 棒材；多线段三角孔型；轧制稳定性；温度分布

作者简介：帅美荣，女，1978 年生，博士，副教授，太原科技大学材料科学与工程学院，山西 太原 030024， E-mail: ruoxin2001@163.com