

Zhenghuan HU, Baoyu WANG, Zhenhua ZHENG

Research and industrialization of near-net rolling technology used in shaft parts

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Abstract Shaft part rolling is an efficient and green near-net shaping technology offering many advantages, including high production efficiency, high material utilization rate, high product quality, and excellent production environment. In this paper, the features of shaft part rolling are introduced along with the working principles of two main shaft part rolling technologies, namely, cross wedge rolling (CWR) and skew rolling (SR). In relation to this technology, some R&D achievements gained by the University of Science and Technology Beijing are summarized. Finally, the latest developments in shaft part rolling are presented, including SR steel balls, precise forming of camshaft blank by CWR, SR phosphorous copper balls at room temperature, and CWR hollow axle sleeve. Although the shaft part rolling technology has been widely used in China, it only accounts for about 15% of applicable parts at present. Nevertheless, this technology has broad application prospects.

Keywords cross wedge rolling, skew rolling, near-net rolling, shaft part

1 Introduction

Shaft part rolling is a type of technology that forms shaft parts by means of rolling [1]. As shaft parts are shaped during rotation, this technology is also classified as a rotary forming process [2]. In China, researchers began to study shaft part rolling in the mid-20th century. After 60 years of development, China has fully mastered this technology, and the process has been widely applied in the industrial manufacture of shaft parts, balls, preforms of forging, and so on.

Received May 16, 2017; accepted July 10, 2017

Zhenghuan HU (✉), Baoyu WANG, Zhenhua ZHENG
School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China
E-mail: huzhengah@ustb.edu.cn

This paper briefly introduces the features of shaft part rolling and the working principles of the two main types of shaft part rolling: Cross wedge rolling (CWR) and skew rolling (SR). Some R&D achievements gained by the University of Science and Technology Beijing (USTB) regarding this technology are summarized. Finally, the latest developments in shaft part rolling are presented.

2 Features and working principles of shaft part rolling

2.1 Shaft part rolling as a highly efficient and green near-net forming technology

Compared with cutting and forging, shaft part rolling has many advantages. For example, the production efficiency of shaft part rolling can be increased by 3–10 times, the material consumption can be reduced by 10%–30%, the comprehensive performance of the parts can be improved, the die service life is about 10 times better than its counterparts, there is no impact during production, and automation can be easily realized using this technology [3]. Thus, shaft part rolling has been recognized as an important part of advanced forming technologies and as a highly efficient and green near-net forming technology. However, the dies are of larger sizes and more complex compared with forging dies; hence, shaft part rolling is only suitable for the mass production of shaft parts.

2.2 Shaft part rolling as a cross development of metallurgical rolling and mechanical forming

Traditional metallurgical rolling technology manufactures products with excellent performance at a high production efficiency. Such a technology is mainly used to create products, such as sheets, bars, and pipes, with the same cross section in terms of length. Shaft part rolling takes bars or pipes as raw material, and achieves further rolling to produce shafts. It is an extension of traditional

metallurgical rolling and a deep processing of metallurgical rolling products.

The traditional mechanical forming methods of shafts are mainly two kinds, namely, cutting and forging. Compared with cutting, shaft part rolling is a plastic forming process [4], which enables it to yield higher production efficiency and material utilization. Compared with forging, shaft part rolling also has higher production efficiency, higher material utilization, a longer die service life, and lower noise without much impact. Hence, it is a development of the mechanical forming technology. In summary, shaft part rolling is the intersection, extension, and development of metallurgical rolling and mechanical forming technologies.

2.3 Working principles and characteristics of shaft part rolling

Many different types of shaft part rolling are currently being used in the industries, and the two most widely used are CWR and SR.

2.3.1 Working principle of cross wedge rolling

As shown in Fig. 1, during the working process, two rollers with wedge-shaped molds are rotated in the same direction to drive the work piece to rotate in the opposite direction. Under the action of the wedge-shaped molds, the bar is compressed in the radial direction and stretched in the axial direction, thus forming the required shaft parts [1,5].

CWR is usually applied in the metal forming industry for the manufacture of elongated products, such as stepped shafts [6–9], balls [10], and preforms of forging [11–17].

Typical wedge dies mainly consist of knifing, stretching, and sizing zones. Forming angle, stretching angle, area reduction, and temperature are the main parameters of the CWR process, and these can directly affect the product

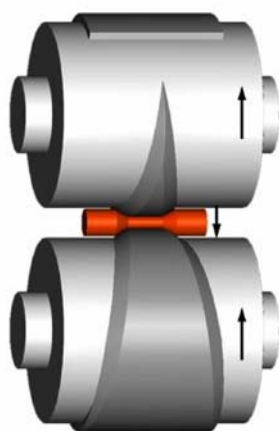


Fig. 1 Working principle of CWR

quality and die wear. Hence, many studies have investigated these parameters. For instance, Zhang et al. [18] studied the cause of spiral groove in CWR. Zheng et al. [19] examined the effect of forming angle on the central quality of 21-4N valves by CWR. Huang et al. [20–23] studied the surface spiral and internal quality of 4Cr9Si2 forming by CWR through the analysis of the influence of the main CWR parameters. Zhou et al. [24] investigated the influence of tool parameters on tool wear in a two-roll CWR by simulation and as manifested by the statistical data from factories. Meanwhile, Huo et al. [25–27] used a set of constitutive equations to predict the microstructure and ductile damage of a high-speed railway axle steel during CWR. Novella et al. [28] modelled the ductile damage for CWR of AA6082-T6 bars. Huang et al. [29] compared the warm and hot CWR by numerical simulation and experimental trial.

Recently, some researchers have focused on forming super alloys by CWR. For example, Wang et al. [30] studied the effect of stretching angle on internal defects in 21-4N forming by CWR. Zhang et al. [31,32] conducted thermo-mechanical coupled numerical simulation and analyzed the microstructure changes of GH4169 alloy forming by CWR. Çakırcalı et al. [33] experimentally and numerically investigated CWR deformation and fracture of Ti6Al4V alloy. Mirahmadi et al. [34] analyzed the effects of CWR tool parameters on formability of Nimonic 80A and Nimonic 115 superalloys. Finally, Li et al. [35] carried out experiments and finite element (FE) simulations to research effects of the CWR parameters on the formability of Ti-6Al-4V alloy.

2.3.2 Working principle of skew rolling

As depicted in Fig. 2, the axes of two rollers with helical grooves incline in opposite directions with a small angle; these are then rotated in the same direction to drive the bar to rotate in the opposite direction along its own axis. Under the action of the helical grooves, the bar moves forward into the forming zone, the diameter of the bar is compressed, and the length is extended to shape the required parts. The parts are cut off in sizing zone by the ribs on the rolls [36]. SR is also called “helical rolling” and is mainly adopted in the production of short rotational parts, such as steel balls [37].

3 Development and promotion of shaft part rolling by USTB

3.1 Promoting nearly 300 part rolling production lines in China and around the world

The USTB research team has promoted over 290 part rolling production lines distributed in 27 provinces

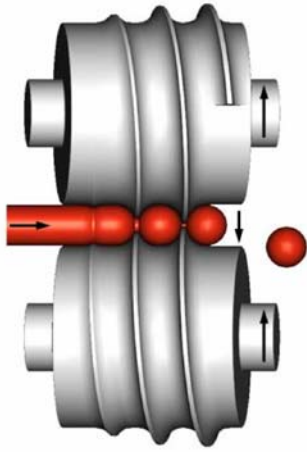


Fig. 2 Working principle of SR

throughout China. Of these, about 16 production lines have been sold to such countries as the United States, Japan, Russia, and Turkey, among others. The annual production of various parts reaches about 2 billion, with a combined weight of about 400000 tons. Total output has surpassed 5 million tons. Figures 3 and 4 show the CWR and the SR production lines, respectively.

3.2 Helping build nearly 20 professional part rolling plants

Due to its characteristics, such as high production efficiency, special complex mold features, and distinct process, part rolling technology is suitable for the construction of professional plants that can provide customers with shaft blanks. The professional plants help make the part rolling larger, stronger, and better. At present, the USTB team has helped enterprises build nearly 20 professional part rolling plants, each yielding an annual output of more than 10000 tons. The USTB team has helped build professional rolling plants for engine

camshaft blanks in Sichuan, Shandong, Anhui, and other places in China; it has also helped build professional rolling plants for heavy truck transmission shaft blanks in Shandong, Hebei, Hubei, and other provinces in China. Moreover, the team has made contributions to building professional rolling plants for car and light vehicle transmission shaft blanks in Anhui, and also helped build professional rolling plants for grinding balls and bearing balls in Hebei, Jiangsu, and Liaoning. Meanwhile, in Guangdong and Jiangsu, the USTB team promoted the establishment of professional rolling plants for the production of phosphorous copper balls used in electroplating. All these plants are equipped with many rolling mills of different sizes, specialize in part rolling, and skilled in one application field. Their high-quality products lead to strong market competitiveness and significant economic benefits. Figures 5 and 6 show the professional plants of CWR and SR, respectively.

3.3 Successfully developed processes for the production of over 500 kinds of shaft parts

The USTB team has successfully developed processes for the production of over 500 types of shaft parts, including shafts and balls used in cars, tractors, motorcycles, engines, ball millings, bearings, hardware tools, power fittings, and so on. The diameters of the developed products range from 8 to 165 mm, and the lengths from 20 to 1200 mm. Some of the products formed by CWR and SR are shown in Figs. 7 and 8, respectively.

4 Innovative developments

In recent years, the USTB team has cooperated with enterprises in accordance with national demands and has achieved several innovative developments in the field of part rolling.



Fig. 3 CWR production line



Fig. 4 SR production line



Fig. 5 Professional CWR plant for transmission shafts

4.1 Automatic short process SR ball production line

The demand for grinding steel balls in China and other countries is huge. The USTB team has conducted in-depth research on the curved surface of the SR roller [38], groove design method of the SR roller [39], numerical control (NC) machining of the SR roller and error analysis [40], metal flow law of ball forming [41], and other aspects. The team has successfully developed a short process for steel ball production, including long bar heating, skew rolling, and heat treatment. The process is fully automatic, with many advantages including a short process, no need for raw material cutting, use of residual heat for heat treatment and so on. Moreover, compared with casting and forging,

the process is highly efficient, energy saving, and environment friendly. Thus far, there have been more than 60 production lines established in China and other countries, of which 11 lines are built in other countries. Figure 9 shows the grinding steel balls with a diameter of 20–125 mm formed by SR.

4.2 Precision CWR of steel engine camshaft

Camshaft is an important part of the engine, and is a shaft with dense narrow steps. The traditional production methods are cutting and forging, which are characterized by low production efficiency, that is, the material utilization for both methods is only about 40%. The



Fig. 6 Professional SR plant for grinding balls



Fig. 7 Some parts produced by CWR

USTB team has carried out much research on the right-angle step shaping curves, dense steps shaping curves, and narrow step shaping curves [42–47] and has successfully developed precision CWR of steel engine camshaft. The material utilization rate has increased to about 60%, realizing no more machining on the rolled steps and the cam sides, which can save 70% of the machining. At present, China's main diesel engine plants, Yuchai, Weichai, and Shanghai Diesel Engine Co. Ltd. among others, have used camshaft blanks formed by CWR. More than 80% of China's steel multi-cylinder camshaft blanks are manufactured by CWR. With its annual output total of over 4 million, it has helped save more than 12000 tons of materials per year. The benefits are indeed significant. Figure 10 shows the precision CWR camshaft blanks and finished products.

4.3 Skew rolling phosphorous copper balls at room temperature

With the rapid development of electronic technology, demands for circuit boards have increased significantly; however, the manufacturing of circuit boards requires tens of thousands of tons of $\Phi 25\text{--}28$ mm anode phosphorous copper balls. The traditional production process of anode phosphorous copper balls is cold heading. Balls produced by cold heading have a ring on their equator, which affects the electroplating quality. At the same time, the use of lubricating fluid causes pollution, and a degreasing process is required. The USTB team has conducted studies on the forming process [48], temperature field [49], and rolling force [50] of the SR phosphorous copper balls at room temperature. The new technology uses high-speed defor-



Fig. 8 Some parts formed by SR

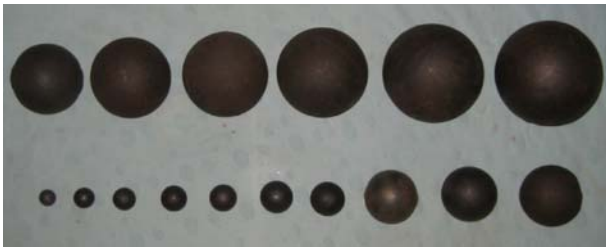


Fig. 9 Grinding steel balls with a diameter of 20–125 mm formed by SR



Fig. 10 The precision CWR camshaft blanks and finished products

mation to increase the temperature of copper rods so as to form the copper balls in its good plastic zone. The team first created the SR phosphorous copper ball process at room temperature with excellent ball shapes, low energy consumption, ball surfaces without oxidation, and no grease pollution. The results have been applied in the construction of over 40 production lines in China, two of which have been sold to the United States. The annual output of $\Phi 26$ mm copper balls is more than 100000 tons. Figure 11 depicts the phosphorous copper balls formed by the SR technology at room temperature.

4.4 CWR hollow axle sleeve of heavy-duty truck

Traditionally, the axle sleeves of a heavy-duty truck are formed by multi-pass hot extrusions. However, this has several disadvantages, such as huge equipment tonnage, complex processes, and low material utilization. The USTB team has researched stable rolling conditions, flattening deformation [51], microstructure evolution [52], and ellipse generation [53–55] of hollow pieces formed by CWR with mandrel. The team has successfully originated the method of CWR hollow axle sleeve of a heavy-duty truck with mandrel [56]. Compared with the extrusion, the new method can save 37% of raw material; it also features such advantages as high production efficiency, high dimensional accuracy, one-heating forming, and tempering with residual heat. The technology has been introduced to establish production lines in Shandong, China, which have been put into operation. Figure 12 shows the hollow axle sleeve formed by CWR.



Fig. 11 The phosphorous copper balls formed by SR at room temperature



Fig. 12 The hollow axle sleeve formed by CWR

5 Conclusions

Shaft part rolling is an advanced technology of shaft part forming and manufacturing. It features high efficiency, material saving, low consumption, and high product quality. The process is environment friendly, which is in line with China's national policy to build a resource-efficient and environment-friendly society. China's shaft part rolling technology has reached an advanced level internationally, and even occupies the leading position in some aspects. At present, only about 15% of shaft parts suitable for part rolling are produced by this rolling process. Hence, part rolling has broad application prospects.

Acknowledgements The authors would like to acknowledge the support given by the Fundamental Research Funds for the Central Universities (Grant No. FRF-BD-16-002A) and by the Yang Fan Innovative and Entrepreneurial Research Team Project (Grant No. 201312G02).

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