The International Journal of Advanced Manufacturing Technology
https://doi.org/10.1007/s00170-018-2007-9

ORIGINAL ARTICLE

An innovative method for producing balls from scrap rail heads

Zbigniew Pater[1] · Janusz Tomczak[1] · Tomasz Bulzak[1] · Zdzisław Cyganek[2] · Stéphane Andrietti[3] · Mickael Barbelet[3]

Received: 8 December 2017 / Accepted: 10 March 2018

Abstract
The paper describes an innovative technological solution for producing balls from scrap rail heads. The proposed method consists in performing the following operations: the side pressing of a rail head to increase shape compactness, a process for forming a cylindrical rod by cross-wedge rolling (CWR), a CWR process for producing balls that have a diameter which is by 35% larger than that of the billet, quenching of the produced balls. Tools for the above manufacturing operations are designed, and numerical simulations are performed to verify whether the assumptions of the proposed technique are correct. A flat-wedge reversing mill is designed and constructed that enables performing the two abovementioned rolling operations without idle running, which makes the design innovative on a global scale. The implementation of the proposed method would enable producing balls for grinding media used in ball mills.

Keywords Ball forming · Multi-wedge cross rolling · Flat-wedge reverse rolling mill · FEM · Experiment

1 Introduction

Balls are used on a mass scale as grinding media in ball mills. They are used for grinding dry and wet materials in cement plants, lime factories, or metallurgical plants. Currently, balls are produced by open die and die forging processes, helical rolling, and cross-wedge rolling process as well as casting [1–4]. Widely used to produce balls with a diameter range 60 - 80 mm, the die forging process uses scrap railway rail heads as billet [5]. As a result, it is possible to significantly decrease production costs and reduce environment-polluting emissions that are produced when remelting scrap in steelworks. Apart from die forging, balls can also be produced by the cross-wedge rolling technique. The manufacture of balls by cross-wedge rolling leads to increased efficiency, reduced material consumption, reduced noise and vibration, and decreased use of lubricants. The rolling process for producing balls is based on the use of multi-wedge tools enabling that balls can be formed by several pairs of wedges simultaneously. This solution results in considerably reduced tool length, which, in turn, leads to an increase in the forming forces. In addition, the design of tool segments is more complicated, as the shape of the side wedges must allow for workpiece elongation caused by the impact of the central wedges [6–8].

This paper describes an innovative method for producing balls from scrap railway rail heads. The proposed method is based on the cross-wedge rolling process. To implement this method, it was necessary to solve a number of problems, the most important being the following: the formation of a long cylindrical shaft from billet with a cross section other than circular, the manufacture of a ball described by a diameter which is by 35% bigger than that of the billet, the design of a specialist machine enabling the execution of the two aforementioned rolling processes. The above problems were solved using computer software for numerical modeling of forming processes.

✉ Tomasz Bulzak
t.bulzak@pollub.pl

1 Department of Computer Modelling and Metal Forming Technologies, Mechanical Engineering Faculty, Lublin University of Technology, 36 Nadbystrzycka Str., 20-618 Lublin, Poland

2 KC 96 Sp. z o.o., Mechurova 658, 339 01 Klatovy, Czech Republic

3 Transvalor S.A. Parc de Haute Technologie, 694 Avenue Doct Maurice Donat, 06255 Mougins Cedex, France

2 Design of the new method for producing balls from scrap rail heads

The proposed process for producing 70 mm diameter balls from scrap rail heads is schematically illustrated in Fig. 1. The billet (scrap rail head) is heated to a hot forming

Published online: 14 April 2018

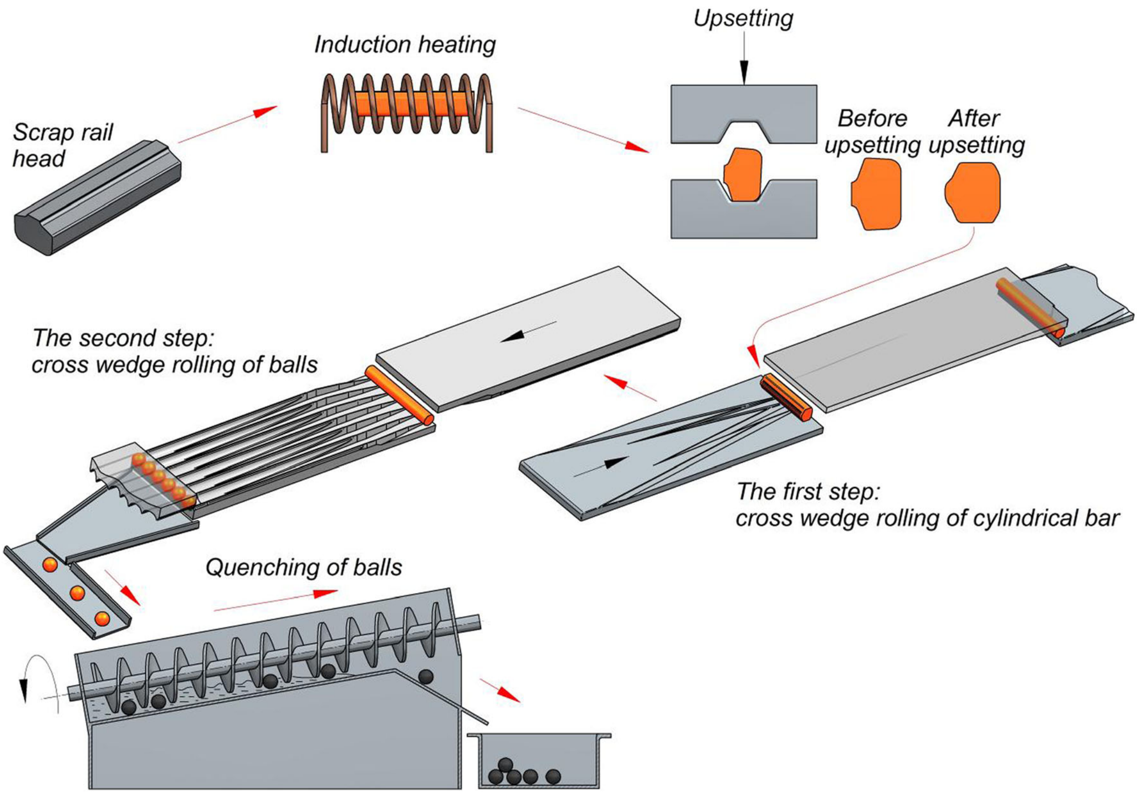


Fig. 1 Schematic design of an innovative process for producing balls from scrap rail heads

temperature. It should be mentioned that the volume of the billet is basically equal to the volume of the formed balls—the billet volume is higher by approx. 5% to include machining allowance. Next, it is subjected to side pressing in the shaped dies to increase the compactness of its shape. The billet is then put between the wedge tools that form a cylindrical shaft with a diameter inscribed in the cross-sectional area of the billet. Next, the shaft is passed on to the other tool set where it is cut into several pieces from which balls with the required diameter are formed. The final stage of the production process involves the quenching of balls in water.

The proposed technique for producing balls from scrap rail heads was designed at the Lublin University of Technology and is patent-protected [9, 10].

3 Numerical modeling of the proposed process for forming balls

First of all, we decided to verify the proposed method for producing balls by means of numerical modeling that would additionally enable solving any identified problems. The modeling was performed using the Forge computer program which allowed us to continue the computations after dividing the workpiece into several separate parts. The software was previously used by other researchers to investigate cross-wedge rolling processes, and the numerical results showed good agreement with the experimental findings [11–15].

The billet was assigned the properties of steel 70Mn3, its chemical compositions resembling that of steel for railway rails. The model of steel was obtained from the material library database of the applied software. Material behavior of the tested material is described by the equation:

$$\sigma = 1602.6e^{-0.002817T} \times \varepsilon^{-0.11358} \times e^{-\frac{0.05174}{\varepsilon}} \times \dot{\varepsilon}^{0.15046}$$

where σ is the yield stress, MPa; σ is the effective strain; $\dot{\varepsilon}$ is the strain rate, s^{-1}; and T is the temperature, °C.

First, we modeled the side-pressing process of a rail head. The process was performed by two dies which together formed a hexagonal impression inscribed into a 71 mm diameter circle. A schematic design of the forging process is shown in Fig. 2. Prior to forging, the entire material was heated to the temperature of 1180 °C and that the temperature of the tools was maintained constant at 250 °C during the forming process. The velocity of upper die during the forming process was maintained constant at 50 mm/s and the working surfaces of the dies were lubricated with graphite described by the friction factor of 0.3. Since the numerical modeling took account of thermal effects, the metal-tool heat transfer coefficient was set to 10 kW/m^2 K.

The aim of the side-pressing operation was to increase the cross-sectional compactness of the billet. This could be done

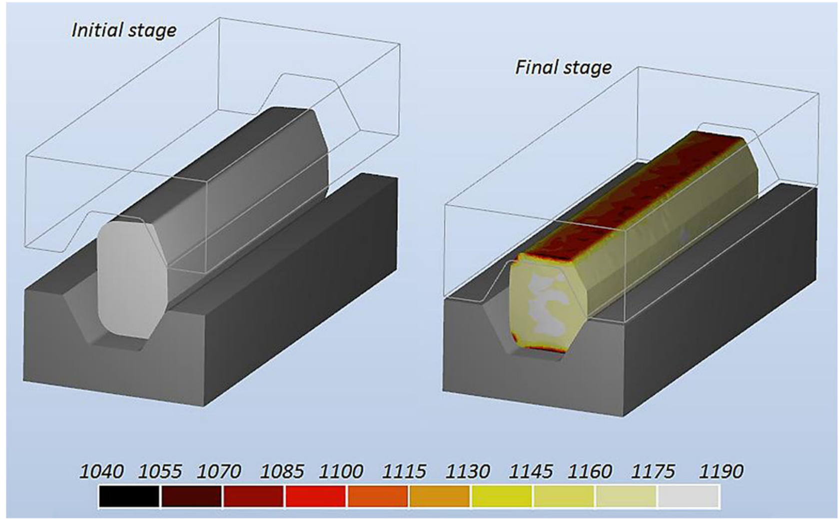


Fig. 2 Side-pressing process for a rail head and the distribution of temperature (in °C)

by squeezing the material toward the longer side of the head, which caused the metal to flow toward the shorter side of the billet. As a result of such a pattern of metal flow, four (out of six) corners of the impression were filled, which was sufficient to ensure correct positioning of the billet in a successive rolling operation.

Due to insignificant changes in the shape of the workpiece, the side pressing of a rail head (described by a length of 240 mm) required the application of a small force (approx. 900 kN), which means that the process can be performed using a wide variety of forging presses characterized by small load (Fig. 3). During the side-pressing process, the temperature of the workpiece decreased on contact surface by approx. 50 °C (Fig. 2). However, due to a short time of the side-pressing operation, the cooling occurred only in the surface layers and did not have any effect on subsequent operations.

Figure 4 shows a geometrical model of the rolling process wherein the billet obtained from the side pressing of the scrap rail head is formed into a cylindrical rod with a diameter of 52 mm. The main problem to be solved at this stage of the forming process was to obtain a shaft with a considerable length (approx. 375 mm) using tools, the maximum length of which could not exceed 1250 mm (their maximum length was due to the machine design). For that reason, we decided to employ multi-wedge rolling that is also used for producing elongated parts such as stepped axes and shafts [16–19]. To this end, we designed tools with three wedges described by the same forming angles set to 25°. The side wedges were inclined relative to the central wedge at the angle of 2.5° in order to allow for elongation of the workpiece caused by the central wedge.

The proposed forming method was verified by means of numerical modeling. The following parameters were applied in the modeling: the temperature of the tools was set to 150 °C, the velocity of the lower wedge during the rolling process was set to 400 mm/s, the friction factor on contact surface was made equal to 0.95. Other parameters were identical to those applied in the side-pressing operation.

Figure 5 illustrates the changes in the workpiece shape during the CWR process. In the initial stage of the process, the workpiece is deformed in three separate regions by separate pairs of the wedge tools. Further on, when the forming zones of the wedges become combined, only the shaft's ends are formed. In the final stage of this rolling operation, the shaft undergoes sizing to acquire the desired diameter of 52 mm.

Given that the shape of the cross section of the billet is not circular, the rolling process is characterized by distinctive variations in the forming force, as shown in Fig. 6. These variations result from the varying deformation ratio during workpiece rotation—the higher the deformation ratio becomes, the higher the load is. The radial load (affecting forming accuracy) is approx. three times higher than the tangential load that affects displacement of the wedge. Such a relationship between the forming force components is typical of CWR processes [20].

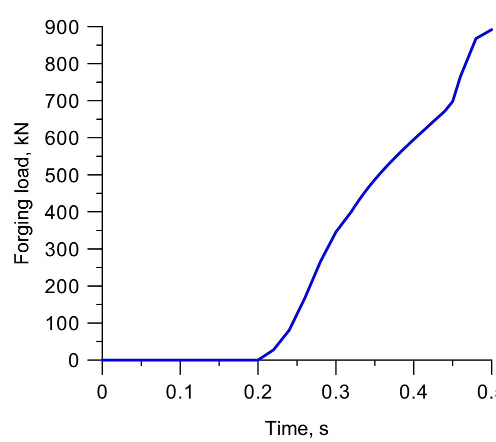


Fig. 3 Forging load during the side pressing of a rail head in a hexagonal pass

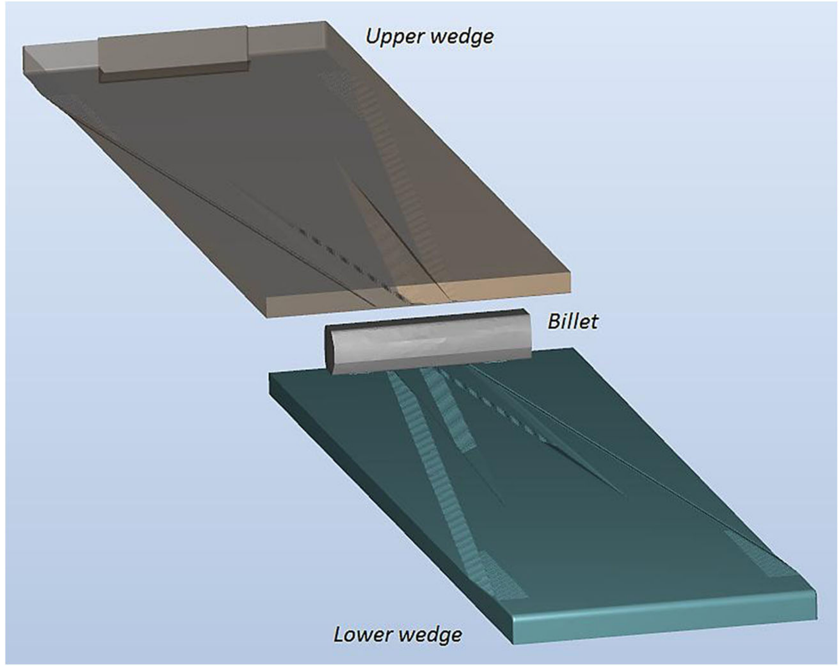


Fig. 4 Geometrical model of a cross-wedge rolling process for forming a cylindrical rod from a scrap rail head (billet)

Despite the relatively long forming time (approx. 6.5 s), the workpiece does not undergo excessive cooling. The temperature of the surface layers that are in cyclical contact with the tools decreases to 1020 ÷ 1100 °C (Fig. 5). In contrast, the temperature of the central region of the semi-finished product is similar to the temperature of the billet. This means that the forming process can be continued without metal reheating. The temperature of the bar after rolling (1020 ÷ 1100 °C) is high enough to proceed with a successive second rolling operation. If the temperature dropped below 1000 °C, it would be difficult to perform upsetting of the material. What is more, the temperature of balls after the rolling process could have been too low to subject them to quench hardening.

The rolling of balls (Fig. 7) is done by two identical multi-wedge tools enabling the formation of four balls simultaneously, each ball having a diameter of 70 mm. Since the diameter of the ball is bigger by 35% than the diameter of the shaft, the tools must upset the metal to obtain the required diameter. This is done when the contrary moving wedges act on the workpiece simultaneously. As reported by Tofil et al. [21], in cross-wedge rolling, the diameter of the billet can be increased even by 50% depending on the applied tool angle [21].

To verify whether the designed tools enable producing balls with the desired diameter, the rolling process was modeled numerically using nearly the same parameters as

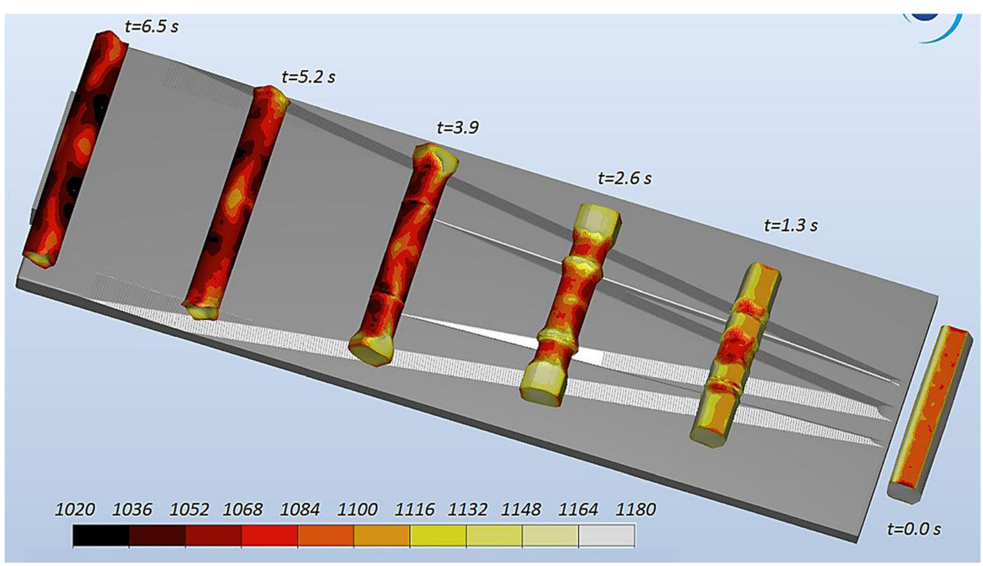


Fig. 5 CWR process for producing a cylindrical shaft and the distribution of temperature (in °C)

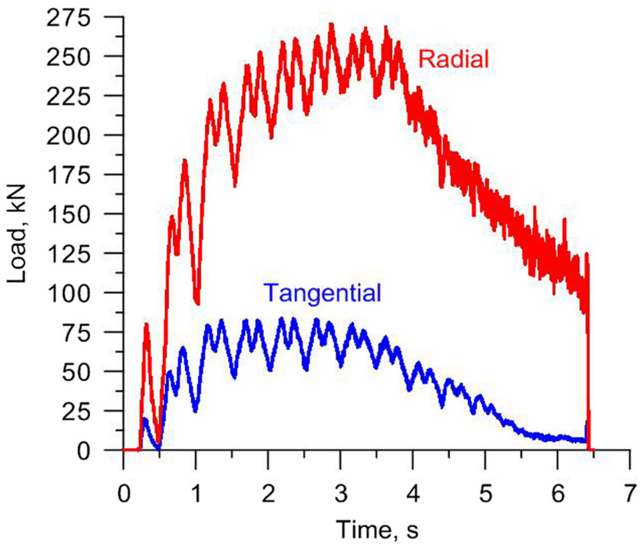


Fig. 6 Variations in the rolling force components during the forming of a 51.5 mm diameter cylindrical rod

those applied in the rolling process for producing the shaft. The only change was the tool velocity that was set to 300 mm/s. The numerical modeling led to determining the changes in shape of the workpiece during the rolling process that are shown in Fig. 8. In the initial stage of the rolling process, the wedges sink into the workpiece and begin to form ring-shaped grooves. It should be stressed that the amount of metal constrained between the adjacent balls should be equal to the amount of metal required to produce a single ball. After that, the material is divided into four parts, each part being formed into a separate ball. To divide the material, the standard Cockroft–Latham ductile fracture criterion was used. The limit value of the Cockroft–Latham integral was set to $C = 2.75$. At this juncture, the ends of the billet are made uniform, which leads to producing some waste material. In a further stage of the process, due to the impact of the side walls of the wedges, the material is subjected to upsetting, which leads to the formation of balls.

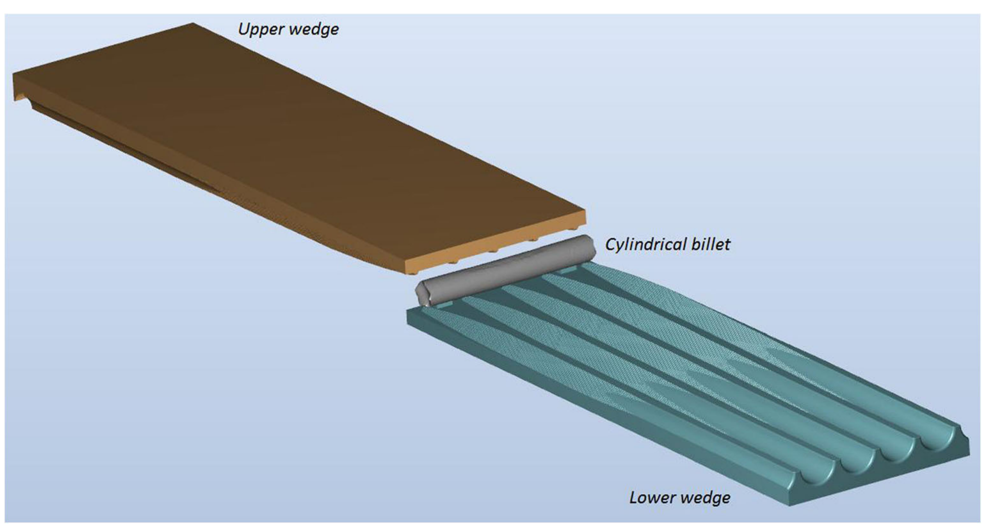
Figure 8 also illustrates the variations in the temperature of the metal during the rolling process for balls. It can be observed that due to the fact that heat is carried away to the colder tools, the temperature of the metal at the ball surface decreases to 870 ÷ 970 °C. In contrast, the temperature inside the workpiece is higher by approx. 100 °C. Due to the fact that the quenching temperature for balls is 860 °C, the balls must be maintained in free air in order to decrease their temperature and level out any temperature difference. This effect is produced when the balls are being transported to the quenching tank.

Figure 9 illustrates the distribution of effective strains in produced balls. It can be observed that the billet undergoes the greatest deformation in the places where it is separated into individual parts. One can notice that there occurs a rapid metal flow in the tangential direction caused by the impact of the tools. The smallest strains occur in the central region of the balls where the material is subjected to upsetting.

Figure 9 provides information about the accuracy of the produced balls. It can be observed that the shape of the two balls in the center is correct. In turn, the balls on the edges show a slight underfill in their central region. The underfill results from the fact that a small amount of the metal gets squeezed out of the tools (end waste). Given that the balls will be used as grinding media, the engineering tolerance of their diameter is quite considerable and amounts to 70 ± 3 mm. Hence, the observed underfill does not disqualify these balls. The defect can be prevented by increasing the amount of material that is constrained between the adjacent balls, which can be done by increasing the diameter of the shaft formed in the first rolling operation.

Figure 10 illustrates the variations in the tangential and radial load during the rolling of 70 mm diameter balls. It has been found that the tangential component of the rolling force

Fig. 7 Geometrical model of a cross-wedge rolling process for producing four 70 mm diameter balls from a 51.5 mm diameter cylindrical rod



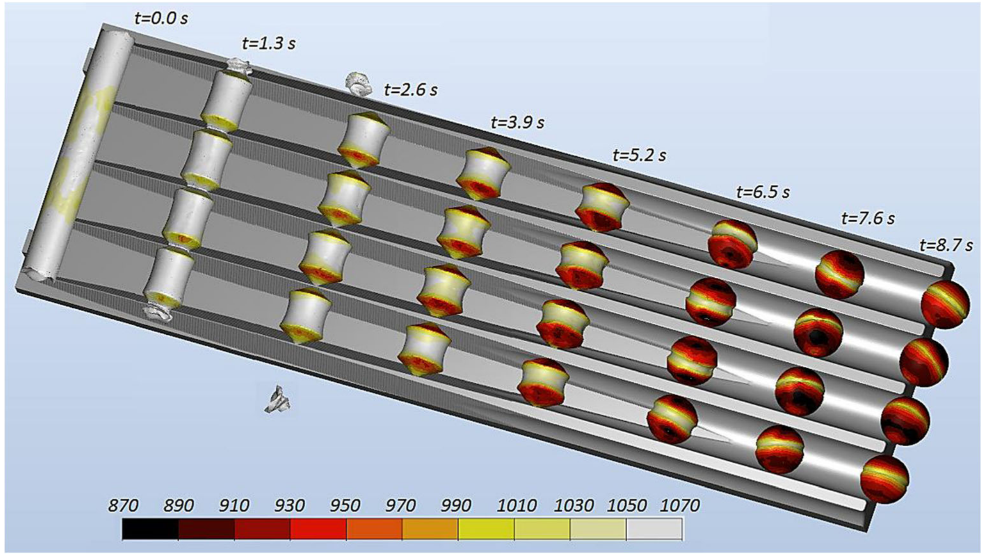


Fig. 8 Changes in workpiece shape in the cross-wedge rolling process for producing 70 mm diameter balls from a 51.5 mm diameter cylindrical rod

is the highest when the material is separated to form balls and the wedges cut into the workpiece to the highest depth. The radial load is the highest in the final stage of the process, i.e., during the upsetting of the central region of a ball. Examining the variations in the tangential force, it can be claimed that the developed numerical model agrees with real process conditions.

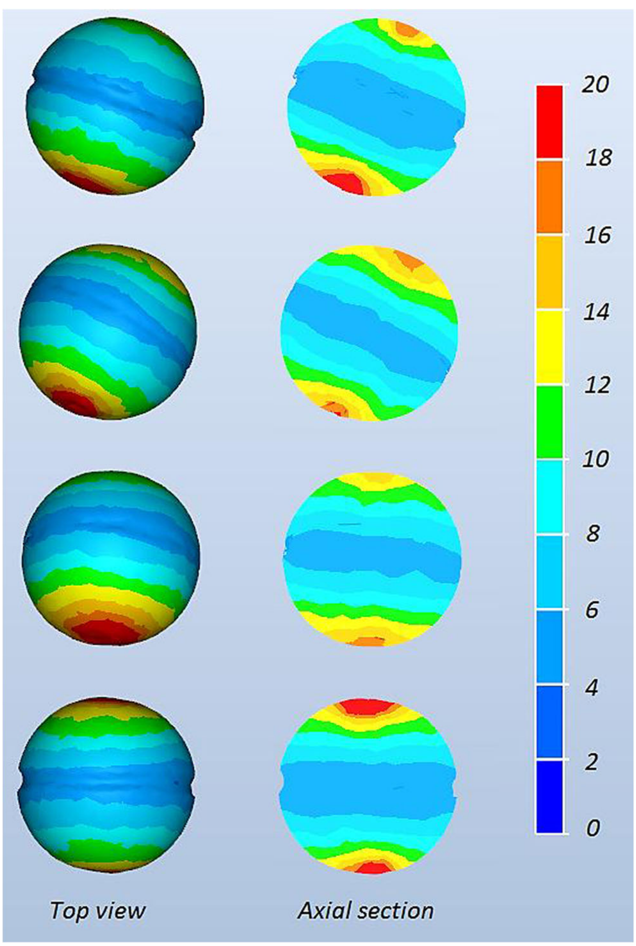


Fig. 9 Effective strain distributions in 70 mm diameter balls produced from scrap rail heads

4 Flat-wedge reverse mill

Flat-wedge reverse mills currently available on the market involve idle running of the tools. Given the overall dimensions of the tools (1250 mm in length), the industrial implementation of the proposed ball forming method would require the use of two standard rolling mills. One mill would be used for producing a cylindrical rod, the other for producing balls. An alternative solution is to design a rolling mill that enables performing both rolling processes.

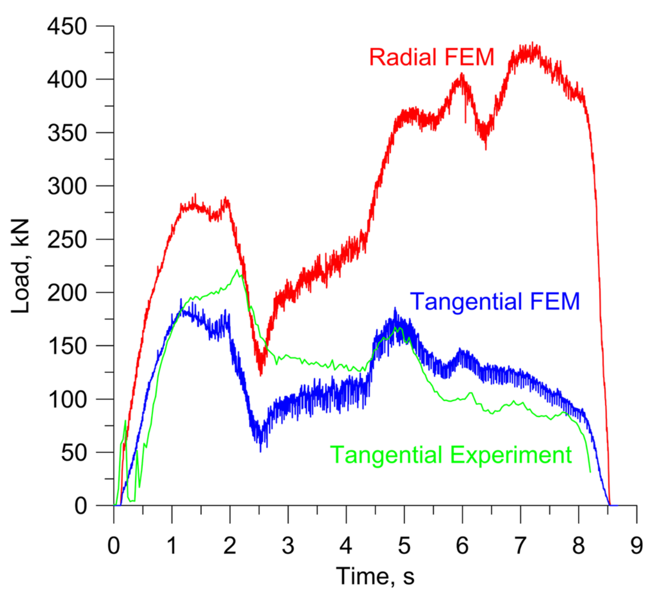


Fig. 10 Variations in the rolling force components during the forming of 70-mm diameter balls from 51.5 mm diameter rod

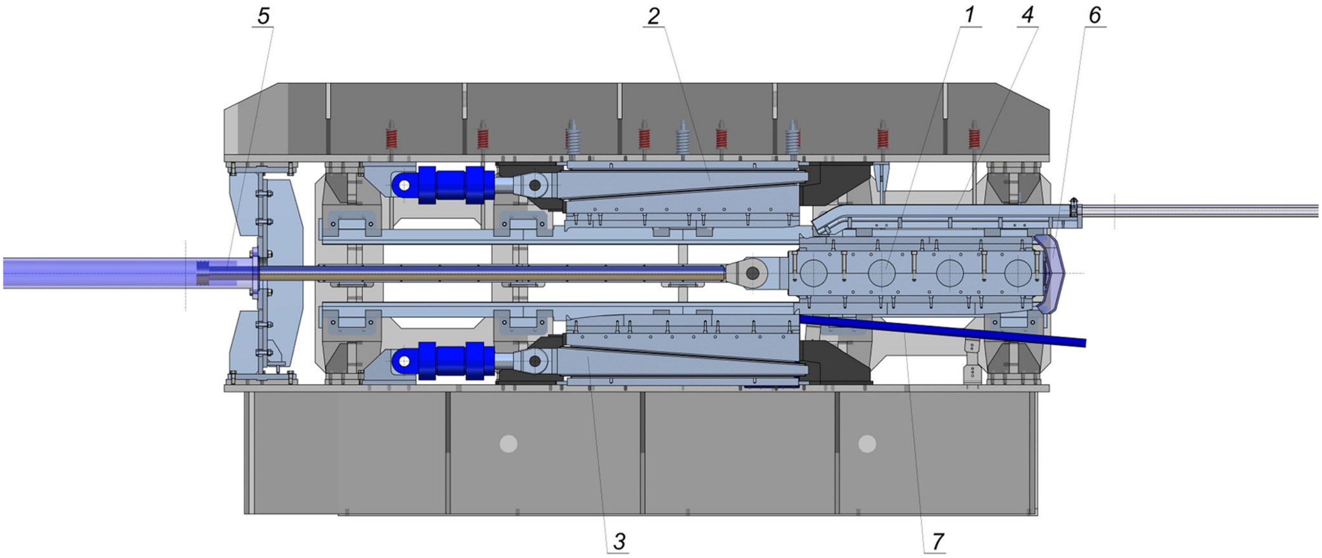


Fig. 11 Schematic design of the flat-wedge reversing mill designed at the Lublin University of Technology (description in the text)

As part of research conducted at the Lublin University of Technology, we designed a flat-wedge reverse rolling mill that operates without idle running; its schematic design is shown in Fig. 11. The machine is provided with a hydraulically driven slide 1 to which mounted are two wedges (upper wedge for rolling a shaft and the bottom one for rolling balls). Two tool sets 2 and 3 are mounted in the center of the machine. To these tool sets other immovable wedges are mounted (a wedge for forming a shaft in the tool set 2 and a wedge for forming balls in the tool set 3). These tool sets can be adjusted vertically by means of hydraulic cylinders. The billet (a side-pressed rail head) is loaded into the work space of the mill by means of a hydraulic cylinder 4 when the slide is in the extreme left position. A cylinder 5 moves the slide to the extreme position on the right. During this movement of the slide, the cylindrical shaft is formed; once the slide motion is stopped, the shaft drops under its own weight onto the lower tool set. In this way, the displacement of the shaft is controlled by a guide 6. After that, balls are formed when the slide is moving to the extreme left position. Formed balls roll down along a guide 7. After that, the work cycle is repeated.

Fig. 12 Flat-wedge reversing mill for producing 70 mm diameter balls

Figure 12 shows the flat-wedge reverse mill constructed according to the design and founded in a Polish manufacturing plant. Selected technical specifications of the mill are given in Table 1. Given that the mean velocity if the slide is 0.35 m/s (in reality its velocity during the forming of a shaft is 0.4 m/s, while during the forming of balls, it is 0.3 m/s), and the overall length of the slide path is 5 m, the time required for the slide to move is 14.3 s. Adding the time of billet loading and shaft reloading, the total time of one work cycle is 20 s. In one cycle, it is possible to produce four balls that are 70 mm in diameter. Therefore, the theoretical yield rate of the designed reverse mill is 720 balls per hour (1008 kg/h).

Table 1 Technical specification of the flat-wedge reversing mill for forming balls from scrap rail heads

Parameter	Unit	Value
Power of motor	kW	132
Maximal working pressure	MPa	25
Slide velocity in bar forming	m/s	0.4
Slide velocity in ball forming	m/s	0.3
Maximal force on piston displacement	kN	290
Maximal force on return motion	kN	190
Maximal tool length	mm	1300
Maximal tool width	mm	410
Minimal diameter of produced balls	mm	70
Overall dimensions L × W × H	m	9 × 2.4 × 2.4
Weight	kg	32,000

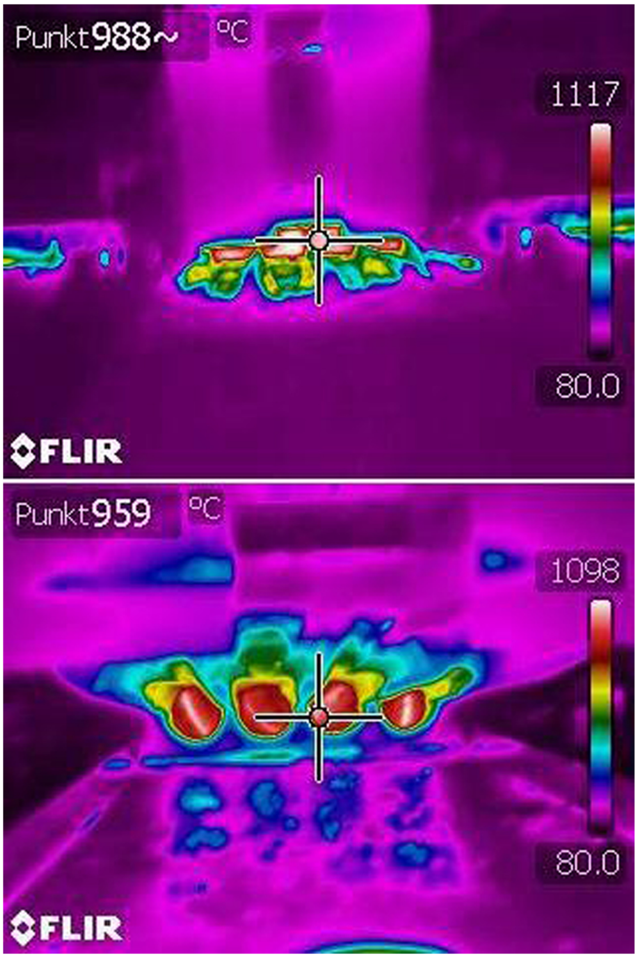


Fig. 13 Temperature measurement in the analyzed CWR process. Cylindrical shaft (top) and produced balls (down)

Fig. 14 Starting from top: billet (side-pressed rail head), 52 mm diameter rod, balls with nominal diameter of 70 mm

5 Ball rolling tests

Rolling tests were performed to produce 70 mm diameter balls from scrap rail heads using the developed flat-wedge reverse mill. The billet was heated to the temperature of 1180 °C in an electric chamber furnace. Next, it was subjected to side pressing in a hexagonal pass and to rolling in two passes, as described in Section 3 of this paper. During the rolling process, a thermal imaging camera was used to measure the temperature of the shaft produced in the first rolling operation and the temperature of the balls produced in the second rolling operation. The results given in Fig. 13 demonstrate that the material maintained the hot forming temperature during the entire forming process. In addition, comparing the data given in Figs. 5, 8, and 13, one can observe a good agreement between the numerical and experimental results of the temperature of the shaft and balls.

Figure 14 compares the semi-finished products produced in individual operations of the proposed method for producing balls, i.e., side-pressed rail head, 52 mm diameter shaft, and balls described by a nominal diameter of 70 mm. The analysis of ball shape reveals that the balls are slightly flattened on the side exposed to impact of the tools and show slight underfill in their center. Such shape defects are acceptable in the case of balls used as grinding media in ball mills. The results demonstrate that the diameter of the produced balls amounts to 69.52 ± 1.66 mm, which is within the expected engineering tolerance ± 3 mm.

Following the quenching operation, some of the produced balls were cut to examine them for internal cracks that often occur in parts produced by cross-wedge rolling processes. The examination reveal that the balls produced by the new method are crack-free (Fig. 15). The results demonstrate that the hardness of the produced balls is adequate for balls that are used as grinding media in ball mills.

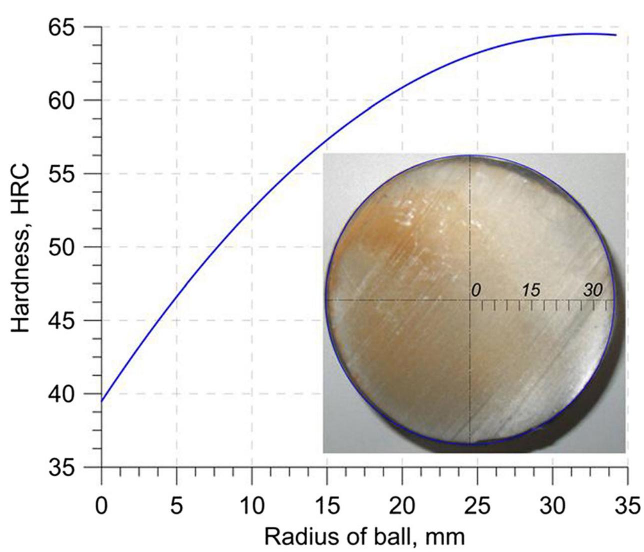


Fig. 15 Distribution of hardness in a ball produced by the proposed method

6 Conclusions

The results of the conducted research and development work have led to the following conclusions:

- The production of balls from scrap rail heads by cross-wedge rolling requires that the process be run in two operations, where the first operation involves the rolling of a semi-finished product with a regular shape (bar), while in the second operation the bar is formed into balls.
- The first stage of the proposed method, i.e., the formation of a scrap rail head into a bar, does not prolong the production cycle because it is realized on the return motion of the slide.
- Cross-wedge rolling with upsetting can be used to produce balls described by a diameter that is by 35% bigger than that of the billet (cylindrical rod).
- Despite the considerable complexity of the production process, the temperature of the produced balls is sufficient to subject them to water quenching.
- The proposed rolling method can be effectively used in the production of other parts, where high cross-sectional reduction requires the application of either a two-stage rolling process or very long tools.

Acknowledgements This research was part of the agreement no. INNOTECH-K3/IN3/12/226286/NCBR/14 on conducting and financing projects under the "INNOTECH" program, IN-TECH program path.

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