

A novel two-disc cross rolling process for manufacturing large-diameter grinding balls: A numerical comparison with conventional rolling methods

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ABSTRACT

The production of large-diameter steel grinding balls remains a significant technological challenge due to high forming loads and the need for large, specialized rolling mills. This study introduced a novel two-disc cross-rolling (TDCR) process and evaluated its technological potential through a numerical comparison with conventional cross-wedge rolling (CWR) and skew rolling (SR). Finite element simulations using Forge software were performed to analyze the forming of C60 steel balls with a diameter of 125 mm. The comparison included temperature and strain distributions, dimensional accuracy, forming loads, energy consumption, drive power requirements, and production efficiency. The results showed that all analyzed methods enabled the production of balls meeting industrial requirements. The highest dimensional accuracy was obtained in the TDCR process due to final calibration in the disc tools. Moreover, TDCR generated the lowest radial load (366 kN), compared with 677 kN for SR and 1419 kN for CWR, and required the lowest drive power (2×54.6 kW). Although its specific energy consumption was higher than that of CWR, the higher final ball temperature suggests the potential to reduce billet heating energy. The results confirm that TDCR is a promising alternative to conventional large-diameter ball rolling technologies.

Keywords: two-disc cross rolling, cross-wedge rolling, skew rolling, large-diameter grinding balls, finite element analysis, energy consumption.

INTRODUCTION

Steel grinding balls are among the basic working elements used in the comminution processes of ores and other mineral raw materials, and their service life depends on both material properties and manufacturing technology. In industrial practice, such balls are mainly produced by casting, forging, and rolling processes. Among metal forming technologies, particular attention has been paid to cross-wedge rolling (CWR) and skew rolling (SR) [1–4]. CWR is mainly applied to the production of elongated axisymmetric parts, but it can also be used for forming balls, whereas SR is especially suitable for the manufacturing of short rotational components, including steel balls [2,4,5]. These processes belong to

the group of near-net-shape technologies and, compared with forging and casting methods, can provide significantly higher productivity, reduced material consumption, and extended tool life [6,7]. The scale of implementation also confirms their industrial importance. According to Hu et al. [7], more than 60 rolling lines for producing balls with diameters ranging from 20 to 125 mm have been implemented in industry.

In recent years, the development of ball rolling technologies has focused both on increasing material efficiency and extending the range of ball diameters that can be manufactured. One important direction has been the development of a two-stage CWR process for producing balls from discarded railway rail heads, in which the irregular billet is first transformed into a rod with a nearly

circular cross-section, then formed into balls, and separated within the same technological setup [8–10]. This solution enables the utilization of low-cost waste material, reduces material losses, and allows several balls to be formed simultaneously in a single cycle [8–10]. Another development trend concerns the methods for producing small-diameter balls, exemplified by single roller-cross-wedge rolling (SR-CWR), a variation of the CWR process that employs a stationary curved tool and a rotating ring-shaped tool. It has been demonstrated that this method enables the cold forming of very small balls with high dimensional accuracy, and it also has potential for producing micro-balls from various materials [11].

Along with the development of new rolling variants, numerical modeling has become increasingly important in the analysis of ball rolling processes. This results from the complex nature of the phenomena accompanying the forming operation, including nonlinear metal flow, intensive tool–material contact, and strong coupling between mechanical and thermal effects [4,12–15]. Previous studies have shown that finite element models are effective tools for analyzing strain, stress, and temperature distributions, rolling forces and torques, as well as for identifying potential process defects, such as central voids, internal cracks, incomplete die filling, and premature separation of balls [12–16]. Numerical modeling is also used to predict microstructural changes, including carbide spheroidization, grain refinement, dislocation density evolution, and hardness distribution, thereby enabling the correlation of process parameters with the functional properties of the final product [17–20]. Of particular importance is the fact that numerical simulations serve as a powerful design tool enabling the selection of tool geometry and process parameters before manufacturing expensive tooling and conducting technological trials [15,19,21–23]. This approach is also economically justified, as it reduces the number of trial-and-error experiments, decreases material and energy consumption during process development, and lowers the cost of implementing new technological solutions [19,21–23]. Furthermore, available studies indicate that reducing the process temperature and appropriately selecting tool geometry and kinematic parameters may lead to lower rolling forces and torques, thereby encouraging the development of new, less energy-intensive ball forming methods [18,19,21,23].

In view of the considerations above, there is a need to develop new ball manufacturing processes that reduce energy consumption, decrease loads on the rolling mill's working system, and expand the industrial applicability of rolling technologies. One possible direction is the application of a novel two-disc cross rolling (TDCR) method, which combines the advantages of the processes employing rotating tools with the possibility of using conventional two-roll mills. Therefore, the aim of the present study was to propose a novel TDCR process and evaluate its technological potential through a comprehensive numerical comparison with two conventional ball-rolling technologies, namely CWR and SR. Due to economic considerations, the investigation was limited to numerical analysis, assuming that this approach enables a reliable evaluation of the process course, force and energy parameters, and the quality of the formed balls before manufacturing expensive tools and carrying out technological trials.

Scope of the study and assumptions of numerical analysis

The study focused on steel grinding balls with a diameter of 125 mm. This size was deliberately selected because it currently represents the upper diameter limit of balls manufactured by rolling technologies. Balls of larger diameters are practically produced only by forging or casting. Therefore, the selected case represents one of the most demanding applications of the analyzed processes and allows a reliable assessment of their technological capabilities and limitations.

In the case of conventional cross-wedge rolling with flat tools, the production of balls with such a large diameter requires the use of the largest available rolling mills of this type. The length of the wedge tools exceeds 2700 mm, resulting in rolling mills of considerable dimensions and high mass. Similar limitations occur in skew rolling, where the production of such balls requires the largest available skew rolling mills with a roll center distance of approximately 700 mm. In contrast, the proposed TDCR process can be performed using conventional two-roll mills designed for cross-wedge rolling with a roll center distance of approximately 900 mm.

Three ball rolling methods, schematically illustrated in Figure 1, were compared in this study. The first one was cross-wedge rolling using flat tools (CWR), in which the balls are formed

between two flat wedge tools performing a translational motion relative to each other. The second analyzed method was skew rolling (SR), performed using two working rolls inclined at a small angle relative to the axis of the billet, the rotation of which causes simultaneous rotation and axial movement of the material. The third method was the newly proposed TDCR process, in which two discs rotating in the same direction form the balls in a cyclic manner, with one ball being produced during one complete revolution of the tools.

The geometric models of the tools used in the analyzed ball rolling processes are presented in Figure 2. In the case of CWR, two flat wedge tools containing six consecutive impressions were applied, enabling the simultaneous forming of six balls. The ball forming process begins with the gradual increase in the height of the flange ridges, which causes the reduction of the billet cross-section and the formation of successive balls. In the final section of the tools, the height of the flanges increases almost to the axis of the rolled billet, resulting in a significant reduction in the cross-section of the material bridges connecting adjacent balls and their subsequent fracture. In

order to remove the flash formed at the separation plane, the final part of the impressions is inclined with respect to the direction of tool movement. As a result, the separated balls rotate around their own axes, which leads to the smoothing of the surface in the separation area.

In the SR process, two working rolls with their axes inclined at an angle of 2° were applied, and their surfaces contained helical impressions. During the rotation of the rolls, these impressions induce simultaneous rotation and axial movement of the billet, while the gradually increasing height of the flange ridges leads to the progressive formation of necks between consecutive balls and their final separation. Due to the nature of the material motion, the process requires the use of linear guides, which stabilize the billet position within the working space of the rolling mill.

The newly proposed TDCR method employs two discs rotating in the same direction. In contrast to the other two methods, the process is cyclic, and one ball is formed during each complete revolution of the discs. The circumference of the discs contains flanges with a gradually increasing height, which form a neck between the

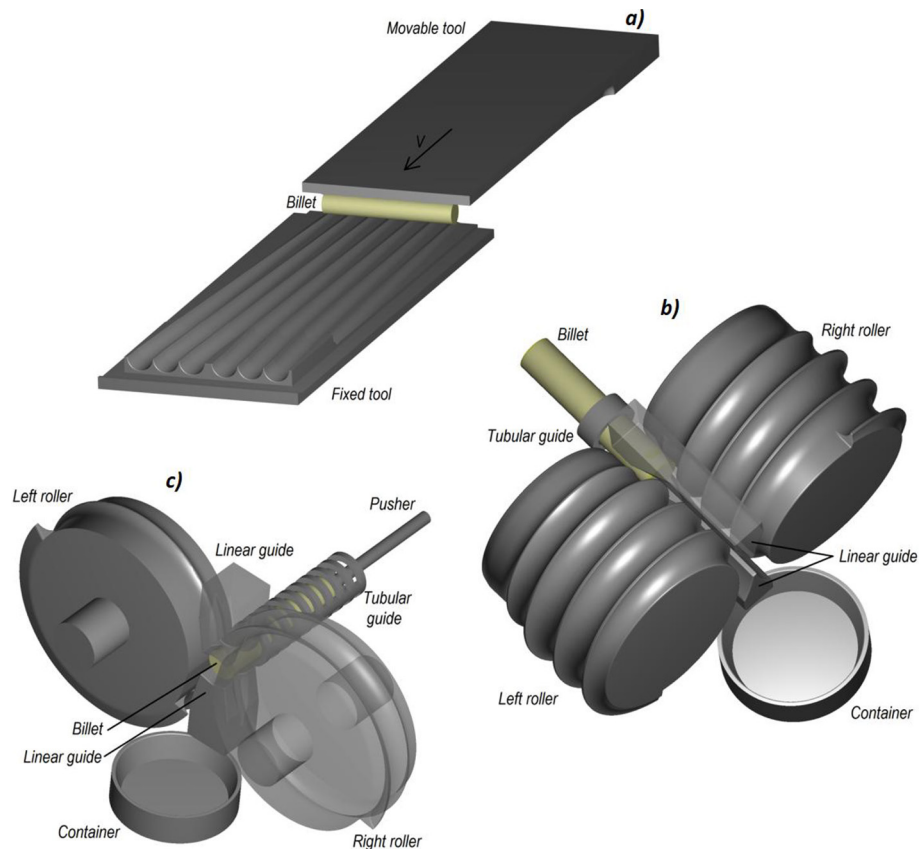


Figure 1. Three-dimensional models of the analyzed ball rolling processes: (a) cross-wedge rolling with flat wedge tools (CWR), (b) skew rolling (SR), (c) two-disc cross rolling (TDCR)

currently formed ball and the remaining part of the billet. In the final stage of rotation, the flanges reach a height close to the billet radius, resulting in fracture of the material bridge and separation of the ball. A calibrating flange is also located along part of the disc circumference, against which the formed ball is pressed. Further rotation of the discs results in ball calibration, ensuring the required dimensional accuracy and spherical shape. After one complete revolution, the discs are stopped, and the feeding system advances the billet by a distance corresponding to the volume of one ball. At the same time, the newly introduced portion of the billet pushes the previously formed ball out of the calibration zone. Due to the necessity of forming a hemispherical billet end before the beginning of the actual forming operation, as well as the occurrence of an end scrap, the production of six balls requires seven complete revolutions of the discs.

Due to significant differences in the tool design and kinematics of the analyzed processes, their direct comparison requires the application of advanced computational methods enabling a detailed analysis of the forming process. During ball rolling, complex phenomena occur, including large plastic deformations, intensive tool–material contact, varying friction conditions, and strong coupling between mechanical and thermal effects. The application of the finite element

method (FEM) enables the determination of strain, stress, and temperature distributions within the material, as well as the evaluation of forming loads and energy parameters, which constitute the basis for the assessment and comparison of the analyzed technologies.

The numerical analysis was carried out using the Forge software, which is one of the most widely applied tools for modeling metal forming processes. Its applicability to the analysis of rolling processes has been repeatedly confirmed in the literature. The software has been successfully employed, among others, for simulations of skew rolling processes, including rotary piercing and bar rolling [24–26, 29], as well as for the analysis of cross-wedge rolling and ring rolling processes [27, 28]. Previous studies have demonstrated that Forge allows reliable reproduction of the actual course of rolling processes, provided that an appropriate constitutive material model and contact parameters defining friction and heat transfer conditions between the material and tools are properly selected [24, 26–28].

The application of Forge in the present study enabled a uniform comparative analysis of three different ball rolling methods, including the evaluation of the forming process course, temperature, and strain distributions, as well as force and energy parameters. Such an approach allows a reliable assessment of the technological potential of

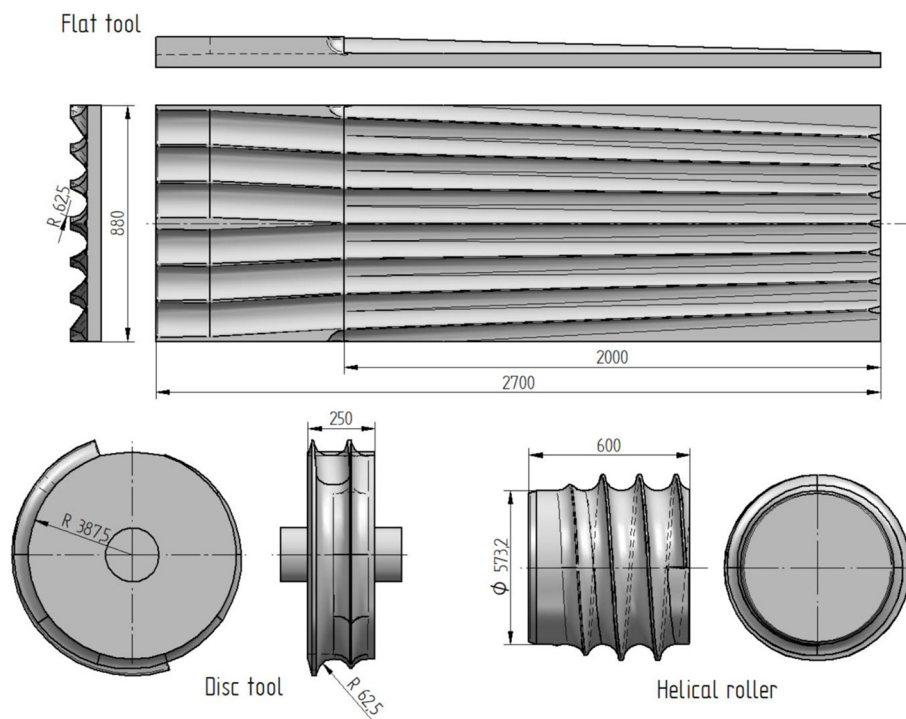


Figure 2. Geometrical models of the tools used for the analysis of 125 mm diameter ball forming processes

the newly proposed two-disc cross rolling method before the manufacture of expensive tools and the performance of technological trials.

The numerical models of the analyzed ball rolling processes, the schemes of which are presented in Figure 1, were developed using the Forge software based on the finite element method. In all cases, identical initial and boundary conditions were adopted, which enabled an objective comparison of the considered forming methods.

It was assumed that the balls were formed from C60 steel, the plastic behavior of which was described by the following equation [30]:

$$\sigma_F = 1706.99e^{-0.0028T} \dot{\varepsilon}^{-0.19371} e^{-0.07421/\varepsilon} \dot{\varepsilon}^{0.1467} \quad (1)$$

where: σ_F – flow stress, ε – effective strain, $\dot{\varepsilon}$ – strain rate, and T – temperature.

The billets used for rolling were cylindrical bars with a diameter of 120 mm and a length of 590 mm, heated before the beginning of the process to a temperature of 1180 °C. All working tools were assumed to be rigid bodies with a constant temperature of 250 °C. In the case of CWR, the upper wedge tool moved with a velocity of 300 mm/s, whereas in SR the rotational speed of the rolls was 15 rpm.

For the newly proposed TDCR method, the rotational speed of the discs was set to 12 rpm. Due to the cyclic nature of the process, after each complete revolution, the discs were stopped for 2 s to allow the billet to be advanced by means of a pusher. Consequently, one forming cycle lasted 7 s, and seven cycles were required to produce six balls, which corresponded to a total process time of 49 s. The numerical models also included all auxiliary tools necessary for the implementation of the processes, including the linear guides used in skew rolling and the pusher, as well as ball receiving containers applied in the two-disc cross rolling process.

The friction conditions at the material–tool interface were described using the constant friction model according to the following equation:

$$\tau = m k \quad (2)$$

where: τ – shear stress at the material–tool interface, m – friction factor ($m = 0.99$ was assumed for the working surfaces of the forming tools, i.e., wedge tools, rolls, and discs, whereas $m = 0.6$ was adopted for the remaining auxiliary tools), and k – shear yield stress ($k = \sigma_F/\sqrt{3}$).

The adopted friction factors were based on previous numerical studies of hot ball rolling conducted under comparable thermomechanical conditions [30].

The calculations also included heat transfer between the workpiece, tools, and the environment. The heat transfer coefficient for the material–tool interface was assumed to be equal to 10.000 W/m²K, whereas a value of 200 W/m²K was adopted for the free surfaces of the workpiece exchanging heat with the surroundings. The adopted heat transfer coefficients were consistent with those successfully used in the previous numerical analyses of hot steel ball rolling [30].

The simulation of ball separation from the remaining part of the billet was carried out using the normalized Cockcroft–Latham damage criterion described by the following equation:

$$f = \int \frac{\sigma_1}{\sigma_i} d\varepsilon \quad (3)$$

where: σ_1 – maximum principal stress, σ_i – equivalent stress, and ε – effective strain. It was assumed that the material bridge fractures and the ball is separated when the damage function reaches the critical value of $C = 3.0$, adopted based on the literature data reported in [15].

RESULTS OF NUMERICAL ANALYSIS AND DISCUSSION

Evolution of the ball rolling processes

The evolution of the analyzed ball rolling processes is presented in Figures 3–5. In each case, six balls with a diameter of 125 mm were produced from a cylindrical billet with a diameter of 120 mm and a length of 590 mm. Despite the application of different tool systems and kinematic conditions, all analyzed methods enabled the production of balls the shape of which fulfilled industrial requirements. A detailed evaluation of their dimensional accuracy will be presented in the following sections.

The evolution of the cross-wedge rolling process is shown in Figure 3. In the initial stage of the process, the moving wedge tool penetrates into the billet, causing its rotation and the gradual formation of necks between the future balls. With further displacement of the tool, the height of the flanges increases, leading to the formation

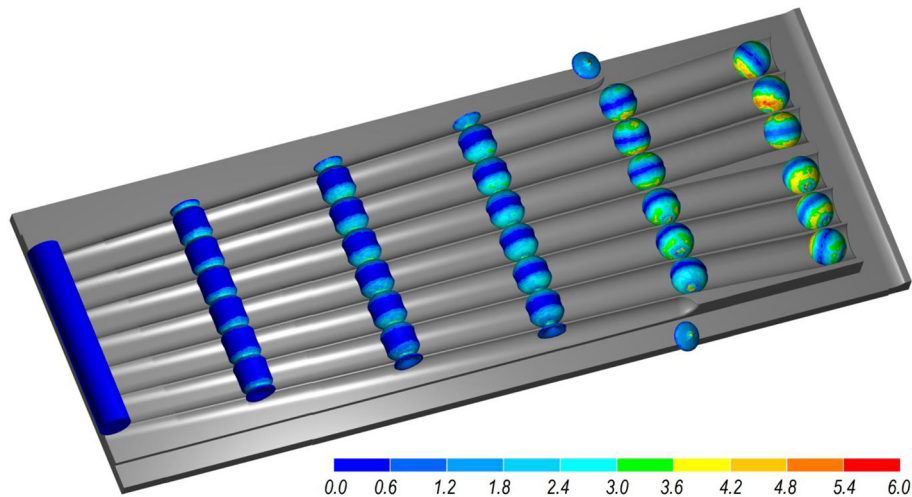


Figure 3. Evolution of the cross-wedge rolling process of balls with flat wedge tools, shown on the stationary lower tool together with the effective strain distribution

of successive balls and a reduction in the cross-section of the material bridges connecting adjacent products. In the final stage of the process, the material bridges fracture, and the balls are separated. Owing to the inclined arrangement of the final part of the impressions, the separated balls are additionally set into rotational motion about their own axes, which results in the smoothing of the separation regions.

The evolution of the skew rolling process is presented in Figure 4. In this case, the forming process is carried out continuously as a result of the interaction of two working rolls the axes of

which are crossed at an angle of 2° . The rotation of the rolls causes simultaneous rotation and axial movement of the billet, which successively passes through the working zones of the helical groove. The gradual increase in the height of the flanges leads to the formation of necks between successive balls and their subsequent separation. Unlike cross-wedge rolling with flat-wedge tools, this process is performed without any translational movement of the tools, which enables a continuous forming operation. The evolution of the newly proposed TDCR process is presented in Figure 5. Unlike the two previously discussed

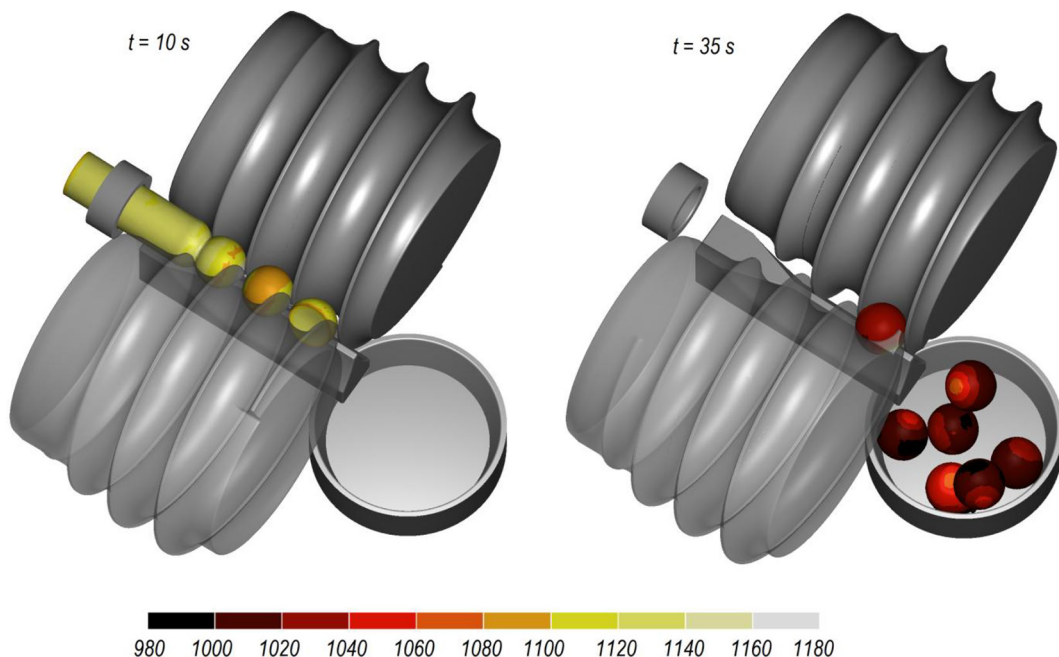


Figure 4. Evolution of the skew rolling process of six balls together with the temperature distribution (in $^\circ\text{C}$)

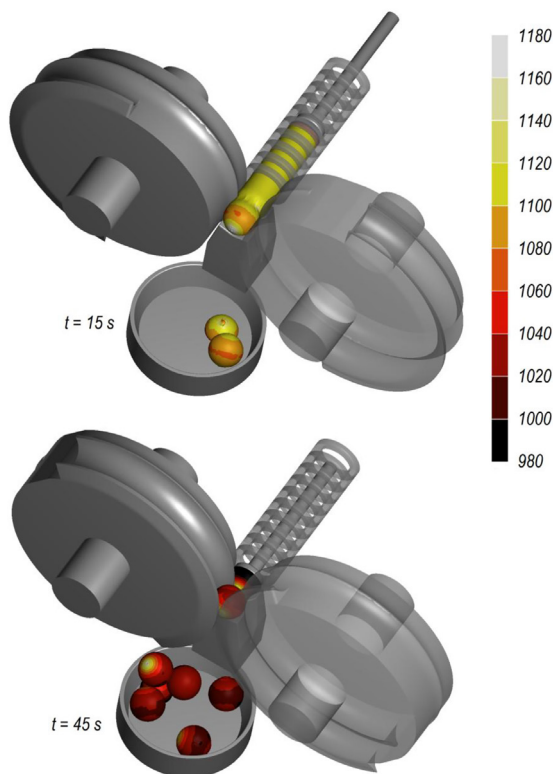


Figure 5. Evolution of the two-disc cross rolling process of six balls together with the temperature distribution (in °C)

methods, this process has a cyclic nature. During one complete revolution of the discs, one ball is formed, whereas after the tools are stopped, the billet is advanced by a pusher by a distance corresponding to the volume of one ball. The first revolution of the discs is used to form the hemispherical end of the billet, resulting in the generation of initial scrap. In the subsequent cycles, consecutive balls are formed and calibrated, and after the billet advancement, they are pushed out of the working zone. During the last cycle, the sixth ball is formed, while the remaining part of the material constitutes the end scrap. Consequently, the production of six balls requires seven complete revolutions of the discs.

The conducted analysis demonstrated that despite significant differences in the tool kinematics and material forming mechanisms, all analyzed methods enable the production of balls meeting industrial requirements. The main differences between the analyzed processes concern the dimensional accuracy of the produced balls, as well as the force and energy parameters, which are presented and discussed in the following sections.

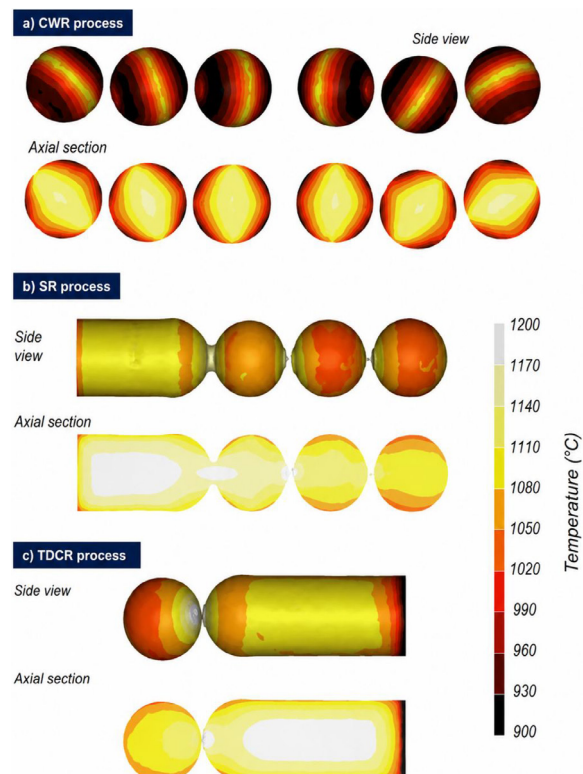


Figure 6. Temperature distributions in the workpieces during the analyzed ball rolling processes: (a) CWR at $t = 17$ s, (b) SR at $t = 20$ s, (c) TDCR at $t = 27$ s

Analysis of temperature and strain distributions

The temperature and effective strain distributions in the balls produced using the analyzed rolling methods are presented in Figures 6 and 7, respectively. These parameters are of key importance from the perspective of product quality, as they affect not only the subsequent heat treatment process but also the material microstructure and the mechanical properties of the balls.

In all analyzed processes, the temperature of the formed balls after rolling remains high, significantly exceeding the temperature range recommended for quenching C60 steel, which is 800–845 °C. This means that, regardless of the applied technology, the balls must be temporarily held in the air to equalize the temperature distribution throughout their volume and to reduce their temperature to a level suitable for subsequent heat treatment.

However, the comparison of the temperature distributions presented in Figure 6 reveals significant differences between the analyzed processes. The greatest temperature decrease of the balls occurs during CWR, which results from the intensive contact between the material and the long flat

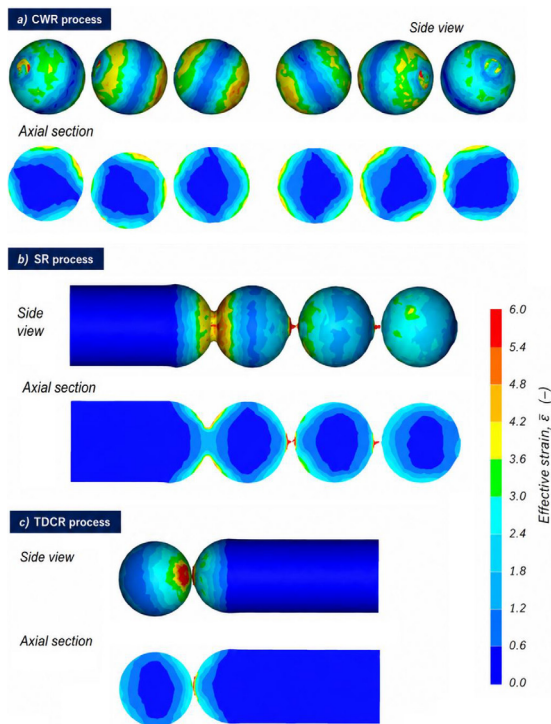


Figure 7. Effective strain distributions in the workpieces during the analyzed ball rolling processes: (a) CWR at $t = 17$ s, (b) SR at $t = 20$ s, (c) TDCR at $t = 27$ s

wedge tools, as well as the large heat transfer area between the billet and the tools. In the case of SR and TDCR, the final temperature of the balls is considerably higher, indicating lower heat losses during these processes.

The obtained results suggest that a lower billet heating temperature may be applied in the SR and TDCR processes while maintaining a final ball temperature suitable for subsequent quenching. In practice, this would lead to a reduction in the energy required for billet heating and a shorter waiting time after rolling to reach the temperature required for heat treatment. This constitutes an important advantage of these methods from the perspective of the overall energy efficiency of the entire production process.

The analysis of effective strain distributions demonstrated that an appropriate degree of plastic deformation was achieved throughout the entire volume of the balls in all considered processes. Despite different kinematic conditions as well as mechanisms of ball forming and separation, no significant differences in the character of the strain distributions were observed. This indicates that the resulting microstructural changes, particularly grain refinement

associated with plastic deformation, should also be comparable for the balls produced by each of the analyzed methods.

A detailed analysis of the geometry of the produced balls revealed certain differences between the individual technologies. In the case of cross-wedge rolling, slight underfilling was observed in the central part of the balls, resulting from axial material flow during forming. This phenomenon is associated with the necessity of local upsetting of the billet with a diameter of 120 mm into a ball with a diameter of 125 mm. In the case of skew rolling, small local imperfections occur in the ball separation regions. The most favorable ball geometry was obtained in the TDCR process, in which the final calibration of the balls in the tool flange allows products with an almost ideal spherical shape to be obtained. However, it should be emphasized that the shape deviations observed for all analyzed methods do not exceed the allowable manufacturing tolerance of ± 3 mm, which means that all produced balls satisfy industrial requirements.

Analysis of force parameters

The radial force histories acting on the tools during ball rolling by CWR, SR, and TDCR methods are presented in Figures 8–10, respectively. These forces are of key importance for rolling mill design, as they determine the required structural stiffness, the strength of the working components, and the parameters of the machine drive system.

In the case of CWR, the radial force history is characterized by a gradual increase as the process progresses, reaching a maximum value of 1419 kN. This is related to the progressive increase in the height of the wedge tool flanges and the simultaneous forming of the entire series of balls, which leads to a continuous increase in the contact area between the material and the tools. Such high loads require rolling mills with high structural stiffness and a massive machine frame.

In the case of SR, the maximum radial force is significantly lower and reaches 677 kN; however, its history exhibits an oscillatory character. This results from the specific design of the working rolls, where the forming flanges are arranged along a helical path and their height gradually increases along the helix. During roll rotation, successive sections of the flanges cyclically penetrate into the material, causing

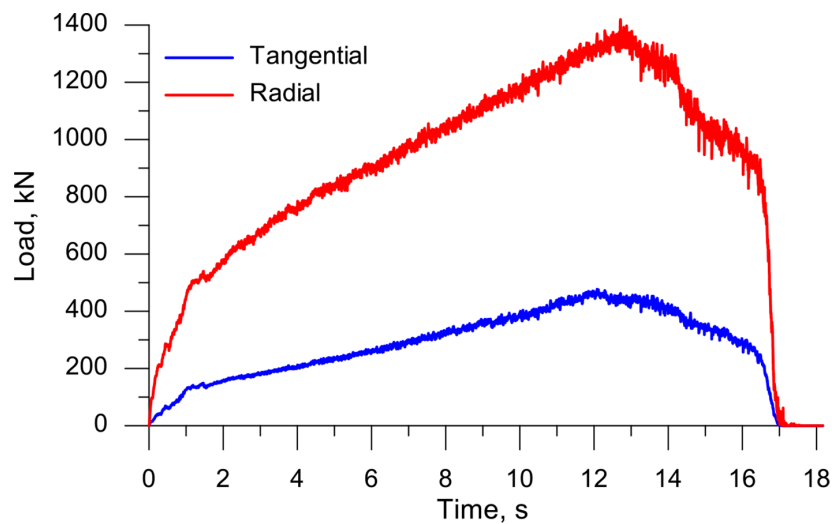


Figure 8. Radial and tangential force histories acting on the moving (upper) wedge tool during cross-wedge rolling of six Ø125 mm balls

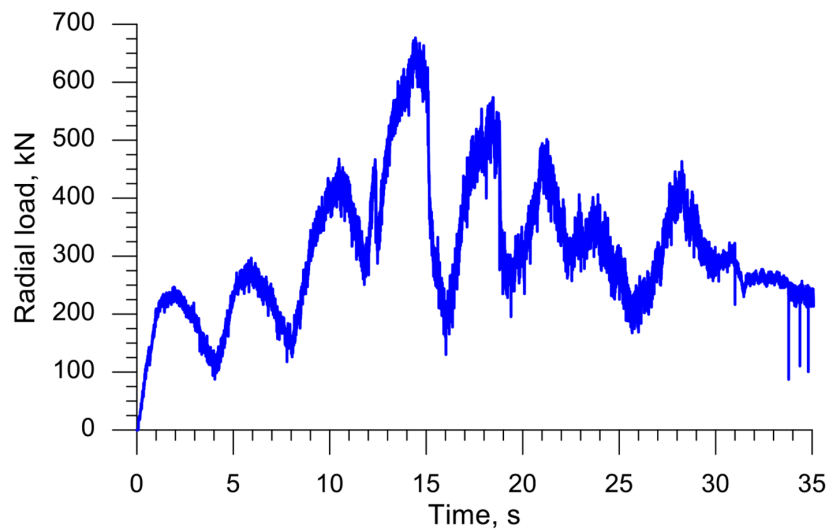


Figure 9. Radial force history acting on the rolls during skew rolling of Ø125 mm balls

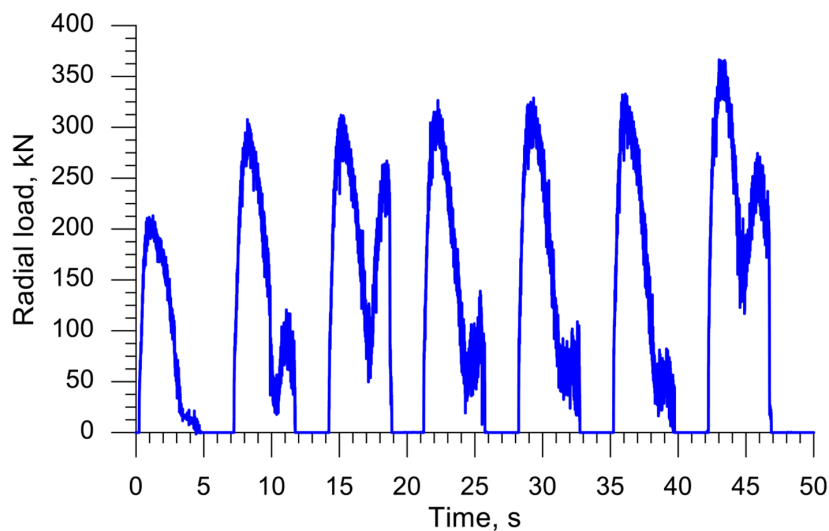


Figure 10. Radial force history acting on the discs during two-disc cross rolling of Ø125 mm balls

periodic increases and decreases in the radial force. Despite these fluctuations, the maximum force is less than half that obtained in cross-wedge rolling, which allows the use of rolling mills with smaller dimensions and lower structural stiffness requirements.

The most favorable results were obtained for the newly proposed TDCR process. The maximum radial force reaches only 366 kN, which corresponds to approximately 26% of the value obtained for CWR and approximately 54% of the maximum force recorded in the SR process. Such a significant reduction in loading results from the cyclic nature of the process, in which only one ball is formed during a single revolution of the discs. This considerably reduces the volume of material subjected to simultaneous deformation and consequently decreases the forces acting on the tools. The low radial forces enable the use of conventional two-roll mills without the need for specialized large-scale rolling machines.

The conducted analysis demonstrated that the application of the TDCR process provides the most effective reduction of loads acting on the working system of the rolling mill. This is particularly important in the production of large-diameter balls, such as the analyzed Ø125 mm balls, for which the conventional CWR method requires very large rolling mills equipped with long wedge tools. The obtained results confirm that the proposed method constitutes an attractive alternative to existing technologies, combining high quality of the produced balls with the possibility of their manufacturing using widely available two-roll rolling mills.

Analysis of energy consumption and drive power requirements

The histories of the tangential force and torques generated during ball rolling are presented in Figure 8 and Figures 11–12, respectively. Based on these parameters, the mechanical energy required to form a single ball and the minimum power required to drive the rolling mill were determined. In the case of CWR, the process energy was determined based on the history of the tangential force acting on the wedge tools and their displacement. The obtained specific energy consumption was 167 kJ per ball, representing the most favorable result among the analyzed technologies. This is related to the continuous nature of the process, in which six balls are formed simultaneously during a single pass of the tools, resulting in the most efficient utilization of mechanical energy. At the same time, the maximum required drive power reaches approximately 143 kW.

In the case of SR, the process energy was determined based on the torques acting on the two working rolls. Despite relatively low radial forces, this method has the highest energy demand of 520 kJ per ball. This is associated with the high torques required to maintain continuous forming and axial transportation of the material between the rolls. In this case, the minimum required drive power is 2×82.6 kW.

Intermediate results were obtained for the TDCR process. The specific energy consumption is 279 kJ per ball, which is approximately 67% higher than that obtained in the CWR process, but approximately 46% lower than in skew rolling.

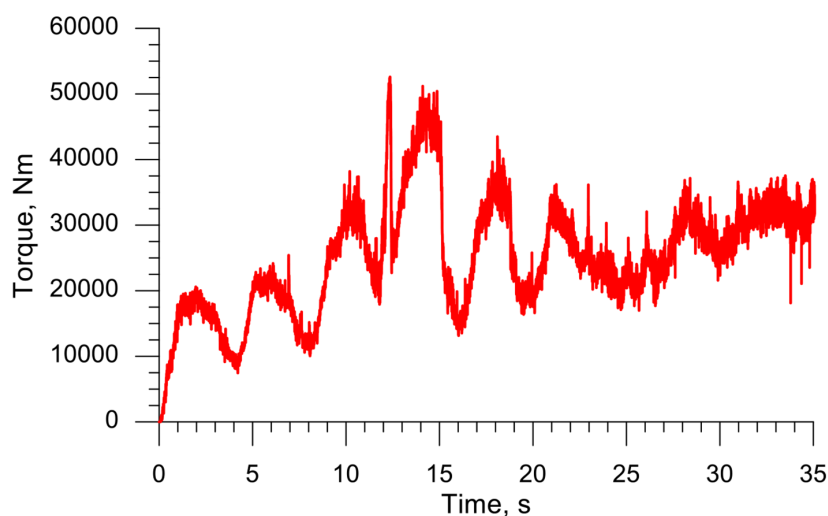


Figure 11. Torque history acting on the roll during skew rolling of Ø125 mm balls

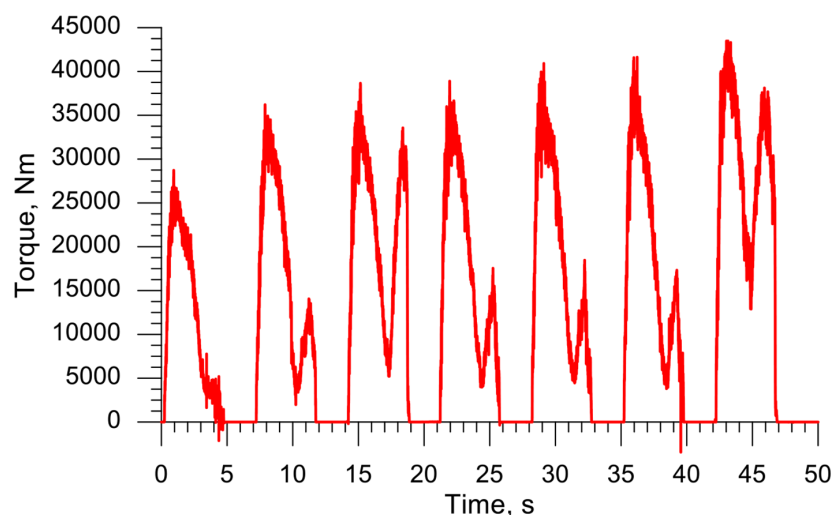


Figure 12. Torque history acting on the disc during two-disc cross rolling of six Ø125 mm balls

Despite higher energy consumption than CWR, this process requires the lowest drive power, amounting to only 2×54.6 kW. This results from the cyclic nature of the process, in which only one ball is formed at a given moment, which limits the torques acting on the working discs. The obtained results indicate that, from the viewpoint of specific energy consumption during the rolling operation itself, CWR is the most advantageous method, whereas SR is the least energy-efficient solution. The newly proposed TDCR method occupies an intermediate position. However, it should be emphasized that the presented analysis considers only the energy consumed by the rolling mill drive system. Under real industrial conditions, a significant contribution to the total energy balance of the process also comes from the energy required for billet heating. As demonstrated in Section 3.2, the higher temperature of the balls after rolling in the TDCR process indicates that a lower billet heating temperature may be applied compared with CWR, which may lead

to a reduction in energy consumption in the heating furnace. Consequently, the differences in the total energy demand of both technologies may be smaller than those resulting from the comparison of the mechanical energy of the rolling process alone. Furthermore, the TDCR method is characterized by the lowest required drive power and radial forces, enabling simpler rolling mill designs subjected to significantly lower mechanical loads.

Analysis of process efficiency and industrial aspects

The final aspect considered in the evaluation of the analyzed ball-rolling technologies is their production efficiency and the requirements related to billet preparation. Table 1 summarizes the main technological parameters of the analyzed processes, including cycle time, production capacity, force and energy parameters, and rolling mill drive requirements.

Table 1. Comparison of the main parameters of the analyzed rolling methods for Ø125 mm balls

Parameter	CWR	SR	TDCR
Number of balls produced from one billet [-]	6	6	6
Forming time of six balls [s]	18	36	49
Idle and loading time [s]	33	15	15
Total cycle time [s]	51	51	64
Production rate [balls/h]	424	424	338
Mass of one ball [kg]	8.0	8.0	8.0
Mass production rate [kg/h]	3392	3392	2704
Maximum radial force [kN]	1419	677	366
Specific process energy [kJ/ball]	167	520	279
Minimum required drive power [kW]	143	2×82.6	2×54.6

In the case of CWR, the actual forming time of six balls is approximately 18 s. However, the return stroke of the wedge tools must also be considered, and its duration was assumed to be equal to the forming time. Consequently, the total operating time of the tools is approximately 36 s. After adding the time required for removing the rolled balls and introducing the next billet, assumed to be 15 s, the total cycle time reaches approximately 51 s. This allows a production rate of approximately 420 balls per hour.

In the case of SR, the process has a continuous character, and six balls are formed during a single passage of the billet between the rolls. The rolling time is approximately 36 s, and after taking into account the time required for loading the next billet, a production rate comparable to that of CWR is obtained. It should be noted, however, that the productivity of the SR process can be relatively easily enhanced by increasing the rotational speed of the rolls or by using longer billets. This, however, requires higher drive power and appropriate adaptation of the system responsible for collecting the rolled balls. In the TDCR process, due to the cyclic nature of forming, only one ball is produced during a single complete revolution of the discs. Seven cycles are required to obtain six balls because the first revolution is used to form the hemispherical end of the billet, while after the final cycle, an end scrap remains. The time required to produce six balls is approximately 49 s, and after considering the billet replacement time, the total cycle time reaches approximately 64 s. As a result, the production rate is approximately 340 balls per hour.

It should be emphasized that due to the large diameter of the analyzed balls, their mass is approximately 8 kg. This means that even for the least productive TDCR process, the mass production rate reaches approximately 2700 kg/h, and after accounting for the material used for initial and end scrap, the actual billet heating capacity must be even higher. In the case of CWR and SR processes, this value exceeds 3300 kg/h. This necessitates the application of heating furnaces with very high capacities and significant thermal power.

For this reason, the total energy efficiency of the technologies cannot be assessed solely based on the mechanical energy consumed by the rolling mill. A significant contribution to the overall energy balance of the process also comes from the energy required for billet heating. The billet heating temperature may be reduced in SR and especially TDCR processes compared with CWR,

because the balls reach higher temperatures after rolling. Considering the large mass of the material subjected to heating, even a small reduction in the billet temperature may result in a significant decrease in thermal energy consumption.

The presented results indicate that none of the analyzed technologies is absolutely superior in every aspect. CWR is characterized by the highest productivity and the lowest mechanical energy required for deformation; however, it requires very large rolling mills due to the high radial forces. SR provides high productivity and the possibility of its further increase, but it is characterized by the highest process energy consumption. The newly proposed TDCR method exhibits lower productivity but provides the highest geometric accuracy of the balls, the lowest radial forces, and the lowest drive power requirements. Taking into account the possibility of reducing the billet heating temperature, this method may constitute an attractive alternative to conventional technologies used for manufacturing large-diameter balls.

CONCLUSIONS

The performed numerical analysis demonstrated that all considered rolling methods, i.e., CWR, SR, and the newly proposed TDCR, enable the production of large-diameter steel balls ($\varnothing 125$ mm) satisfying the industrial requirements.

- The highest geometrical accuracy was achieved in the TDCR process due to the application of a final ball calibration operation performed in the calibrating flange of the disc tools. In the CWR process, slight underfilling in the central region of the balls was observed, whereas the SR process resulted in minor imperfections in the ball separation regions. In all cases, the dimensional deviations did not exceed the allowable tolerance of ± 3 mm.
- From the viewpoint of force parameters, the most favorable results were obtained for the TDCR process, in which the maximum radial force reached only 366 kN, while the corresponding values for SR and CWR were 677 kN and 1419 kN, respectively. Such a significant reduction in loading makes it possible to carry out the process using conventional two-roll rolling mills without the necessity of employing large specialized machines.
- The analysis of energy parameters showed that the lowest deformation work was obtained in

the CWR process (167 kJ/ball), whereas the corresponding values for TDCR and SR were 279 and 520 kJ/ball, respectively. However, it should be emphasized that the total energy consumption also includes billet heating. The higher temperature of the balls after the SR and TDCR processes indicates the possibility of reducing the initial billet temperature, which may partially compensate for the higher mechanical energy demand of these methods.

- From the viewpoint of production efficiency, the continuous CWR and SR processes remain the most advantageous methods, whereas the TDCR process is characterized by lower productivity resulting from the cyclic character of forming individual balls. Nevertheless, the obtained productivity of the TDCR process remains sufficiently high for industrial applications.
- The obtained results indicate that the newly proposed TDCR process constitutes an attractive alternative to conventional methods for manufacturing large steel balls. Its main advantages result from the combination of low loads acting on the working system, low drive power requirements, high geometrical accuracy of the produced balls, and the possibility of using widely available two-roll rolling mills. Further research should focus on process parameter optimization and experimental verification.

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