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The influence of forming conditions on the hardness of balls formed in the skew rolling process

Wpływ warunków kształtowania na twardość kul otrzymanych w trakcie walcowania skośnego

Abstract
The article presents the research results of analyzing the hardness of the balls formed during the skew rolling process, and then subjected to cooling in different media. The influence of the applied cooling medium (water, quenching oil and air) on the hardness of the obtained balls was analyzed. The effects of the applied methods of rolling (conventional and modified) were compared with respect to the changed hardness of the balls, and the obtained results were referred to the stock materials (bearing steel 100Cr6 and the steel from rail heads).

Keywords: balls for mills, skew rolling, hardness HV, quenching medium

Streszczenie
W artykule przedstawiono wyniki badań twardości kul otrzymanych w trakcie walcowania skośnego, a następnie poddanych chłodzeniu w różnych ośrodkach. Analizie poddano wpływ zastosowanego medium chłodzącego (woda, olej hartowniczy i powietrze) na twardości uzyskanych kul. Porównano również wpływ zastosowanej metody walcowania (konwencjonalna i zmodyfikowana) na zmianę twardości kul, a także odniesiono uzyskane wyniki do wyników otrzymanych w badaniach materiałów wejściowych (stal 100Cr6 i stal uzyskana z główki szyny kolejowej).

Słowa kluczowe: kule do młynów, walcowanie skośne, twardość HV, ośrodek chłodzący

1. Introduction

Balls, especially those of large diameters (30–120 mm), are mainly used in ball mills for grinding ore, coal and similar materials characterized by high hardness. Therefore, they are required to have high values of operating parameters which ensure a sufficiently long service life.

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In the production cycle, the balls are subjected to a special heat treatment, which ensures excellent mechanical properties, including high hardness, wear resistance and fracture resistance [1]. For the balls which are to be the grinding media, specific requirements for hardness are presented. According to the standard PN-H-94057:1998 [2], balls are divided into three classes, depending on their hardness: Class I: min. 500 HB, Class II: 400–500 HB, Class III: min. 280 HB. Hardness tests are mainly used in the industry to evaluate the hardness of metals. Hardness measurements are often used due to the existence of a correlation between the hardness (Vickers, Brinell) and yield strength or tensile strength of metals, but also between hardness and phase composition of a Young's modulus [3].

The article compares two types of stock materials: bearing steel 100Cr6 and the steel from rail heads. Rails are made of steel with high tensile strength, high wear resistance and fracture toughness. Due to these properties, scrapped rails are readily used as a stock material in the production of balls for grinding media (rail heads), flat bars (rail webs) and plowshares (rail feet) [4]. For comparison, a similar analysis was performed for bearing steel 100Cr6, with a view to the application of the types of steel with approx. 1.5% chromium content for mill balls.

2. Stock material

14 samples were subjected to hardness tests: 2 types of stock materials (bearing steel 100Cr6 and steel from rail heads), and 12 samples were obtained by the conventional and modified rolling processes. The latter samples, when rolled, were subjected to the quenching process. During the rolling process, stock material was used in the form of cylindrical bars with a diameter of 33 mm and a length of about 500 mm. The semi-finished products were heated in an electric chamber furnace to a forming temperature of about 1150°C. After leaving the roll gap, the temperature of the rolled balls was measured using a thermal imaging camera, and it amounted to about 1000°C (Fig. 1).

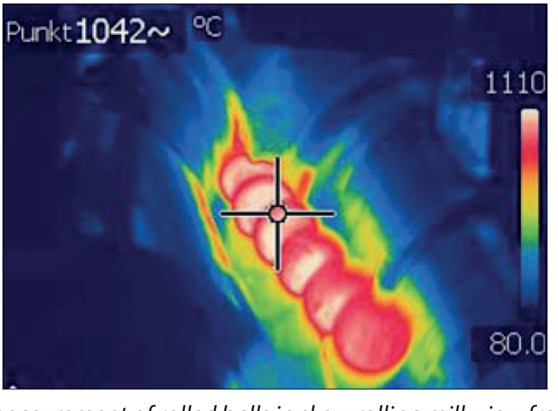

Fig. 1. Temperature measurement of rolled balls in skew rolling mill, view from the output

3. Methods of rolling: conventional and modified

The conventional method of tool calibration is based on the selection of such a contour of the groove and a pitch of the helical line, so as to maintain a constant volume of the metal captured by flanges throughout the entire process. The edges of the grooves – the flanges, projecting from the working surface of the rollers, are characterized by concave lateral surfaces, with the constant radius over the entire length of the helical impression and equal to the radius of the rolled ball. The extending flanges gradually narrow the connections between the individual rolled balls, calibrating their diameter and separating them from each other. Such a method for tool calibration is difficult to implement and makes it necessary to continuously change the value of the pitch of the helical impression, which is calculated by dividing the stock material into the fixed volumes, equal to the volume of the rolled ball and the connecting bridge. A frequent result is the failure to fill or overfilling the helical impression, which adversely affects the accuracy of the rolled balls. Therefore, as part of the research work carried out at the Department of Computer Modelling and Metal Forming Technologies of the Lublin University of Technology, a new method of tool calibration for the skew rolling of balls was developed. A significant change, compared to the traditional method of calibration, is the introduction of a helical wedge surface in the grooving area, which then develops into the concave forming flanges. As in the case of traditional helical impressions, the basis for calculating the pitch and the shape of the groove outline is to keep a constant volume of the material between the flanges of the tools, as well as an equal volume of the rolled ball and the connector.

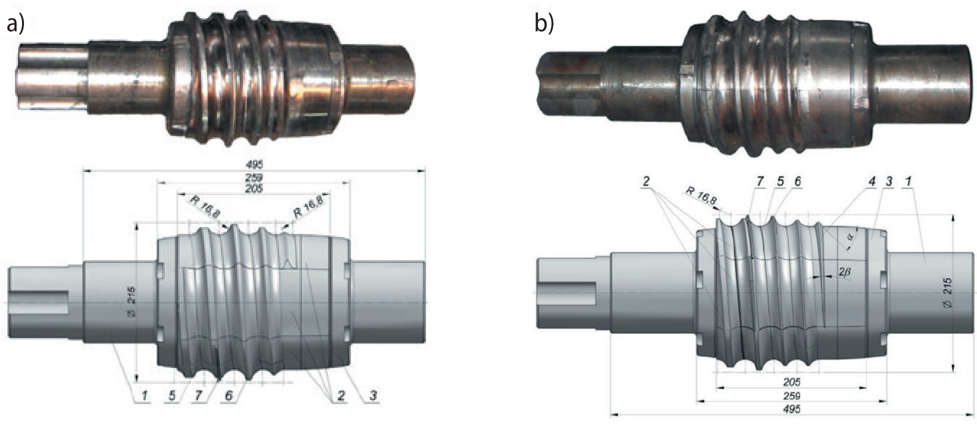

Fig. 2. Sets of screw segments tools for rolling the balls: a) conventional method; b) modified method; description in the text

Figure 2 demonstrates the working rolls used in the two rolling methods. The working impressions of each roller are formed by six tool segments (2), made of hot-work tool steel. The segments are attached to the shaft (1) of the rolling mill using two spindle nuts (3). On the surface of the segments, there are shaping grooves (5) separated by the flanges (6) having concave lateral surfaces. In the grooving area, there is a wedge--shaped helical ledge (4) with a wedge angle of 2β and the inclination angle of the lateral walls of α. A cutter (7) – denotations in Figure 2 [3, 5–9].

4. Own research

The temperature of the stock material and of the final product is essential to the rolling process, due to the relatively long contact time between the hot material and the cold rolls (several seconds). An excessive temperature drop may cause increasing resistance to the plastic flow of metal, which is associated with heavy load of the tools and difficulty in filling the impression by the metal. It is frequently the case that, directly after the process of rolling, the balls are subjected to quenching treatment. Therefore, maintaining a high temperature of the rolled balls is crucial. During the rolling process, the temperature distribution on the surface of the balls was recorded with a thermal imaging camera (Fig. 1). Despite the long shaping process of about 20 seconds, the material during the rolling did not cool down significantly. Immediately after rolling, the balls were cooled to room temperature using three media: water, oil and air.

The balls for mechanical tests were cut from these samples (in this case, hardness tests were considered to be the most representative ones). Denotation of the samples are presented in Table 1.

Table 1. Samples for hardness testing

Symbol	**Rolling method**	**Material**	**Quenching medium**
A1	conventional	100Cr6	H_2O
B2	conventional	100Cr6	quenching oil
C3	conventional	100Cr6	Air
A4	conventional	steel from a railway rail	H_2O
B5	conventional	steel from a railway rail	quenching oil
C6	conventional	steel from a railway rail	Air
D7	modified	100Cr6	H_2O
E8	modified	100Cr6	quenching oil
F9	modified	100Cr6	Air
D10	modified	steel from a railway rail	H_2O

Table 1. cont.

E11	modified	steel from a railway rail	quenching oil
F12	modified	steel from a railway rail	Air
A13	–	100Cr6	–
B14	–	steel from a railway rail	–

The Vickers hardness test method was performed using a Zwick durometer according to the standard PN-EN ISO 6507-1:2007 [10–17], owned by the Department of Metal Forming, Faculty of Metals Engineering and Industrial Computer Science of AGH University of Science and Technology in Krakow – as demonstrated in Figure 3a. The samples of the rolled balls were subjected to the measurements of hardness at 25 points. The first and last measurement points were located 2 mm from the edge of the sample, the remaining points at a distance of every 1 mm over the entire length. Figure 3b illustrates the scheme of the measurement points.

a) 

b) 

Fig. 3. Hardness measurements: a) hardness tester; b) scheme of points positioning on the length of the sample

5. Results and their analysis

Figures 4–7 demonstrate the hardness distributions of the balls formed from the bearing steel 100Cr6 and the steel made of rails in the conventional and modified rolling processes for the three cooling media: water, oil and air.

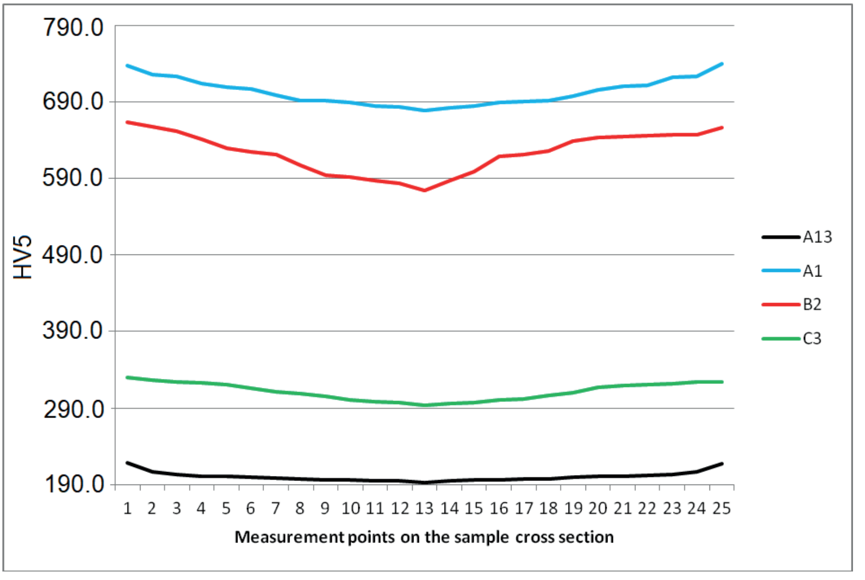

Fig. 4. Graphs of ball hardness obtained from 100Cr6 steel rolled in the conventional method, cooled in three quenching media

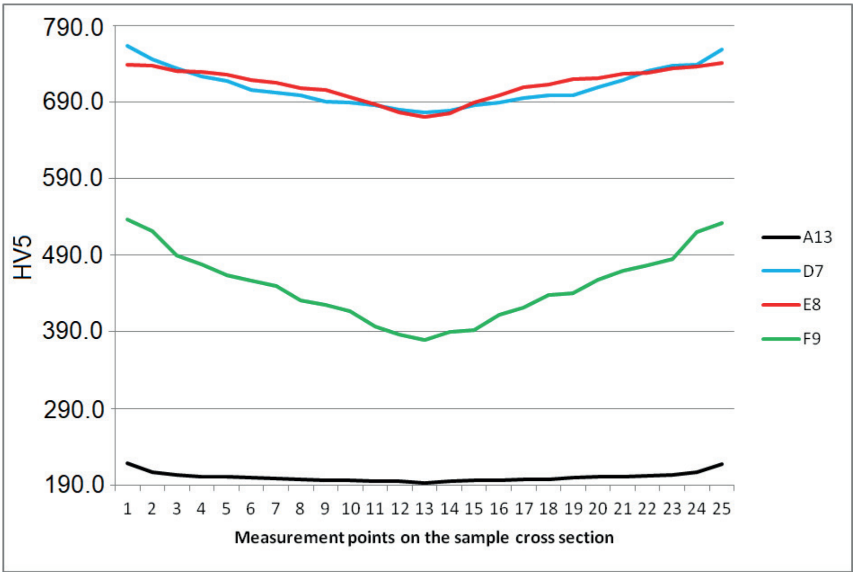

Fig. 5. Graphs of ball hardness obtained from 100Cr6 steel rolled in the modified method, cooled in three quenching media

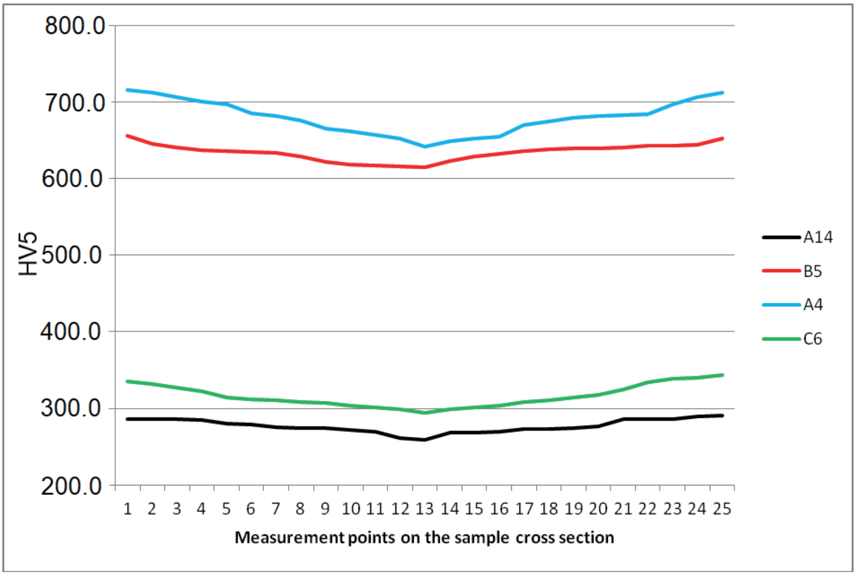

Fig. 6. Graphs of ball hardness obtained from steel cut from railway rail rolled in the conventional method, cooled in three quenching media

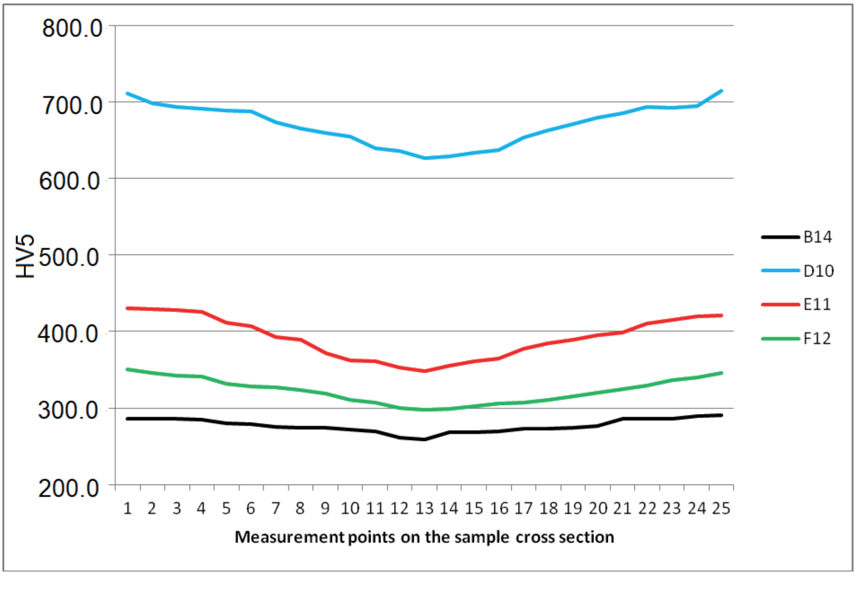

Fig. 7. Graphs of ball hardness obtained from steel cut from railway rail rolled in the modified method, cooled in three quenching media

The hardness of the balls formed from the steel 100Cr6 in the conventional rolling process (Fig. 4), are similar to the samples from the modified method (Fig. 5). The smallest increase in the hardness was observed for the sample cooled in air (green curve), about one and a half times compared to the stock material (black curve). On the other hand, their hardness after cooling in water (blue curve) and in oil (red curve) increased by almost three times. From the hardness distribution of the samples made of the bearing steel 100Cr6 in the modified rolling process (Fig. 5), it can be noted that the balls cooled in water (blue curve) and in oil (red curve) reached an almost four-fold increase in their hardness compared to the stock material (black curve). The last cooling medium used during the study was air. In this case, the hardness (green curve) more than doubled.

In the hardness distribution of the samples formed from the rail steel in the conventional rolling process (Fig. 6), an almost two-fold increase in their hardness could be observed in the two media: water (blue curve) and oil (red curve), with respect to the hardness of the stock material (black curve). However, after cooling the samples in air (green curve), there was an average increase in the hardness of approximately 20 HV5 units. The balls made of rail steel in the modified manner were also subjected to cooling in the three media. The largest increase in hardness (Fig. 7) was recorded after cooling in water (blue curve), two-fold compared to the stock material (black curve). The hardness in the other media: oil (red curve) and air (green curve) had a slight increase, in oil it was 100 HV5 units, and in air it was about 50 HV5 units.

Comparing all four graphs illustrating the hardness distribution in the conventional and modified rolling processes, for the samples made of two types of steel: 100Cr6 and the rail steel, it can be observed that the smallest increase in hardness occurs in the air medium. In contrast, a significant increase in hardness can be obtained in the other two cooling media, i.e. water and oil.

For the samples made of the bearing steel 100Cr6, the hardness distribution for the conventional rolling process (blue curve on Figure 4) proceeds in a very similar way as for the modified process (blue curve on Figure 5). More than a three-fold increase in the hardness can be observed, compared to the stock material (black curves on Figures 4 and 5). The hardness distribution for balls made of rail steel is similar to the first type of steel used in the tests (100Cr6). In relation to the stock material (black curves on Figures 6 and 7), a two-and-a-half times increase in hardness in both of the rolling technologies applied can be observed. In the case of the hardness distribution for the samples of the bearing steel 100Cr6 after cooling in oil, the curves for the both rolling methods is almost identical. The difference in hardness between the modified method (red curve on Figure 5) and conventional method (red curve on Figure 4) is approximately 100 HV5 units. In comparison with the hardness of the stock material (black curves on Figures 4 and 5), a more than three-fold increase in the hardness for the conventional and the modified rolling processes can be noted. In the cooling medium of air, it can be seen from the hardness distribution that higher values can be achieved using the modified rolling process (green curve on Figure 5). The increase in the hardness, compared to the stock material (black curves on Figures 4 and 5), almost doubled. In contrast, the hardness of the samples obtained in the conventional rolling process (green curve on Figure 4) is about one-and-a-half times greater.

In the hardness distribution of the samples from rail steel, for the conventional method (red curve on Figure 6) a two-fold increase can be observed, whereas for the modified method (red curve on Figure 7) an increase of about 100 HV5 units compared to the stock material is noticed (black curves on Figures 6 and 7). The hardness distributions obtained for the samples of rail steel, cooled in oil (red curves on Figures 6 and 7) differ from the hardness distributions for the samples of this steel in the other two cooling media (in water – blue curves on Figures 6 and 7, and in air – green curves on Figures 6 and 7). In this case, the course of the curves (red curves on Figures 6 and 7), suggests the influence of the rolling method on the change in hardness, which other presented graphs failed to demonstrate. It is most likely that the disturbance in the hardness distribution was affected by the temperature of the rolling finishing stage, and this temperature influenced the changed course of the curve. In the case of the hardness distribution for rail steel, no clear differences in the hardness values can be observed in either of the rolling methods. The modified rolling (green curve on Figure 7) practically coincides with the green curve in Figure 6 (conventional rolling), demonstrating an increase in the samples from the balls of about 40 HV5 units, compared to the stock material (black curves on Figures 6 and 7).

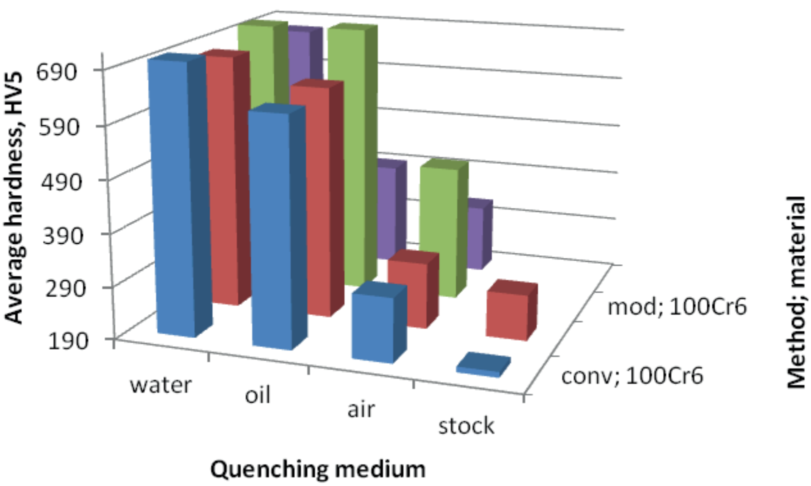

Fig. 8. The mean hardness of the analyzed samples

Figure 8 illustrates the mean values of all the variants of the samples (Tab. 1). While analyzing the mean values of the obtained hardness, it can be noticed that in the case of the rolling of the bearing steel, the modified method is more favorable. However, in the case of forming balls of a second test material, higher values are obtained for the conventional method. As a result of rolling and subsequent quenching, a greater increase in hardness is observed for the bearing steel.

6. Summary and conclusions

Despite a relatively long forming process, the temperature of the material is maintained within the range which is appropriate for the hot working, and it is sufficient to carry out the quenching process immediately after the rolling of the balls. The quenching was performed in three cooling media: in water, oil and in air.

The results of the experimental studies demonstrate that in the skew rolling process both with traditional tools, as well as in the modified shape of the impressions, it is possible to obtain balls which meet the requirements for the grinding media for the ball mills. All rolled balls reached a hardness higher then provided for in the standard PN-H-94057:1998, which means that these balls can be used successfully as grinding media in ball mills.

From the samples obtained under the conventional conditions, a more uniform distribution of the HV is observed (small changes). Under the modified conditions, "softer" middle parts of the samples can be spotted. A significant difference between the center and the edge of the sample is discernable.

The courses of all the curves demonstrate that the balls have the lowest hardness in the middle parts. The measurement points from 10 to 15 correspond to it, which calculated to the size of the sample proves that the smallest values are in the distance of 13 mm to 16 mm from the edge of the sample (geometric center). Below the measurement point 10 and above the measurement point 15 (the periphery of the sample), a significant increase in hardness is observed. Based on these graphs, it can be concluded that the non-uniformity of properties on the cross-section of the balls rolled in skew rollers is due to the heterogeneity of the material flow during the rolling process. Although the balls are worked throughout, the strain in the formed spheres are distributed in layers in the manner characteristic of the cross rolling processes. This means that the outer layers of the material flow differently from the inner layers located in the rolling axis.

In the case of the rolling of the bearing steel, modified rolling is a better method due to the higher hardness values compared to the conventional method.

The hardness of the balls quenched in oil and water by far exceeds the minimum requirements to qualify as Class I balls, in accordance with the standard [2]. In contrast, the balls cooled in air feature the lowest increase in hardness, as compared to the stock materials.

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