Technical Sciences, 2021, 24, 171–182

Yearbook peer-reviewed scientific journal
ISSN 1505-4675
e-ISSN 2083-4527
TECHNICAL SCIENCES
Homepage: https://czasopisma.uwm.edu.pl/index.php/ts/

DOI: https://doi.org/10.31648/ts.6814

STUDY OF THE PROCESS OF ROLLING STEEL BALLS IN SKEW ROLLING MILL – METALLOGRAPHIC ANALYSIS

Piotr Chyła

ORCID: 0000-0001-5159-6746
Faculty of Mechanical Engineering and Robotics
University of Science and Technology in Kraków

Received 15 June, accepted 13 October 2021, available online 28 October 2021.

Keywords: skew rolling of balls, microstructure, 100Cr6, rail steel.

Abstract

This paper presents the results of metallographic research studies carried out for stock materials as well as the samples collected from the balls formed in the rolling process in a skew rolling mill. The stock material was bearing steel 100Cr6 and the steel from rail scrap. The rolling process was carried out in parallel for the two assumptions: the conventional method (hereinafter referred to as convntional rolling) and the modified method (hereinafter referred to as modified rolling). After the rolling process, three cooling media were used: air, water and oil. The pictures below, which depict microstructures, were taken using the bright-field and the dark-field microscopy technique, the samples were etched with a 4% solution of picral.

Introduction

Mass-scale production of steel balls, which are used as grinding media in various types of ball mills, forces producers to search for new technologies with greater efficiency and lower production costs. Currently, depending on the diameter, the balls for grinding media are manufactured worldwide in casting, closed-die forging and rolling processes (TOMCZAK et al. 2005).

Correspondence: Piotr Chyła, Katedra Systemów Wytwarzania,Wydział Inżynierii Mechanicznej i Robotyki, Akademia Górniczo-Hutnicza, al. Mickiewicza 30, 30-059 Kraków, e-mail: pchyla@agh.edu.pl.

Nowadays, they are manufactured mainly in the process of closed-die forging of semi-finished casting products or pre-cast cast steel. Unfortunately, such methods do not ensure the desired functional characteristics of the balls and the production costs are relatively high – mainly related to the price of the material and a relatively low level of its exploitation. For example, the concern KGHM Polska Miedź S.A. itself utilizes approximately 15 thousand tons of balls annually. Therefore, improving their performance is still a current issue.

In order to reduce the production costs, the stock material which is frequently used for their production are scrap rails (PATER et al. 2015). It is obvious that the life cycle of the balls depends on their performance characteristics, such as material strength, cracking and abrasion resistance. But an equally important factor is their correct shape, which depends on the production technique used to manufacture the balls (GRONOWSKIJ 1980, BŁAŻEWSKI et al. 1981, DOBRZAŃSKI 1993, ASHBT et al. 1996, BLICHARKI 2001, PRZYBYŁOWICZ 2007, XIAOZHONG et al. 2012, CHYŁA 2014).

The previous studies conducted to determine the properties of steel balls were rather focused on the possibility to shape these balls using rolling methods to obtain a product with the right shape (sphericity) (TOMCZAK et al. 2012a, 2012b, CHYŁA et al. 2016). However, there was no verification of the structure of the rolled balls or their mechanical properties (e.g. hardness), which resulted in carrying out the research studies presented in this article.

Stock material

The skew rolling process of steel balls was carried out for the two different stock materials: bearing steel (100Cr6) and the steel obtained from rail heads and two different methods of tool calibration. Bearing steel 100Cr6 is characterized by exceptionally high quality due to particularly strict production conditions. This material is required to have a narrow and strictly maintained tolerance of alloying elements and impurities. Its chemical composition is as follows for 100Cr6: carbon 0.95-1.1%, manganese 0.25-0.45%, silicon 0.15-0.35%, chromium 1.3-1.65%, phosphorus 0.025%, and sulfur – up to 0.025%. Chemical composition for steel from rail scrap: carbon 0.62-0.8%, manganese 0.7-1.2%, silicon 0.15-0.58%, phosphorus max. 0.025%, and sulfur 0.008-0.025%.

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 (CHYŁA 2019).

Figure 1 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 1.

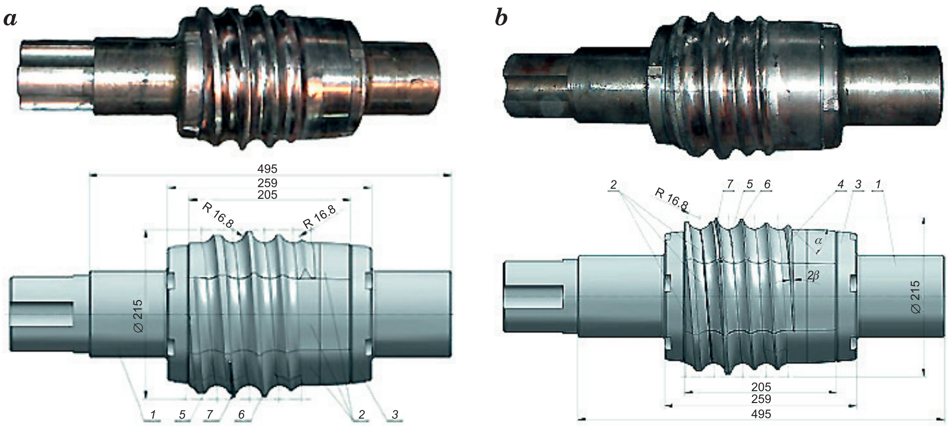

Fig. 1. Sets of screw segments tools for rolling the balls: *a* – conventional method, *b* – modified method; description in the text
Source: based on CHYŁA (2019).

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). The Vickers hardness test method was performed using a Zwick durometer according to the standard PN-EN ISO 6507-1:2007, 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 2*a*. 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 2*b* illustrates the scheme of the measurement points (CHYŁA 2019).

a ***b***

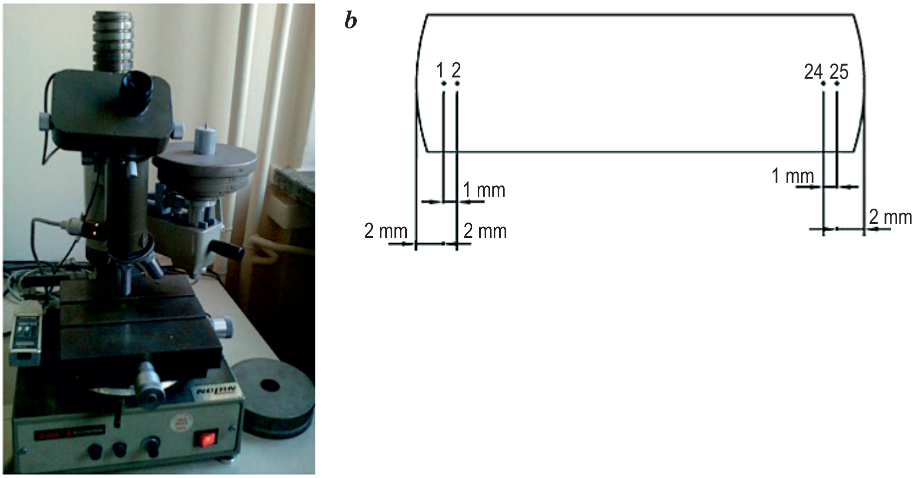

Fig. 2. Hardness measurements: *a* – hardness tester;
b – scheme of points positioning on the length of the sample
Source: based on CHYŁA (2019).

From the images of microstructures of the bearing steel 100Cr6 (Fig. 3), it is visible in the stock material that it has been subjected to spheroidizing annealing. This is a typical condition of this type of stock material (high content of carbon and chromium) for further plastic working. There is abundant fine carbide precipitation (most probably M_3C) of a spheroidal character, uniformly distributed throughout the volume of the material. Carbides are in the ferritic matrix, which is characteristic for long annealing used for this type of steel. In some places, the remains of pearlitic cementite platelets are noticeable, which did not coagulate completely. There are also areas where carbides are arranged

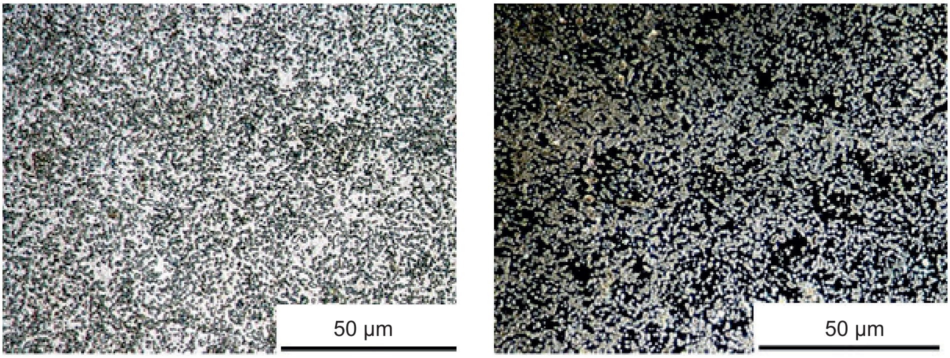

Fig. 3. Microstructure of the samples of the bearing steel 100Cr6 – stock material

linearly, resulting in the spheroidization of cementite present in pearlite (eutectoid cementite). However, these are small areas and they should not affect adversely material properties in the later stages.

Apparently, the microstructure of the steel from rail heads (Fig. 4) was delivered after spheroidizing (softening) annealing. If that was the case, the microstructure would look like in the first case (Fig. 3), ferrite + spheroidal Fe_3C. This is probably the microstructure after normalizing annealing, or immediately after rolling. In the picture there is a characteristic pearlitic microstructure with various thickness of platelets (mostly fine pearlite). Colonies of pearlite are visible, strongly deformed in some places. The average size of these colonies ranges from several to several tens of micrometers. This condition is typical for pearlitic steels without alloying elements and sufficient for further plastic working.

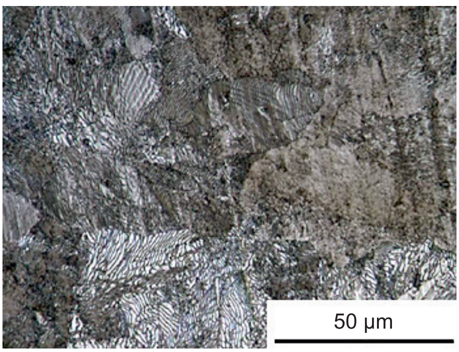

Fig. 4. Microstructure of the samples of the rail steel – stock material

Microstructure of the rolled balls after cooling in different media

After the rolling process, the balls were directly subjected to cooling in three different cooling media: air, water and oil.

In the case of the air-cooled material, pearlitic microstructure was obtained (Fig. 5÷8). The microstructure of the bearing steel (approx. 1% C), in addition to pearlite, contains a characteristic cementite mesh at the grain boundaries (typical for the steel with such carbon content). In the picture depicting the sample of the bearing steel 100Cr6, obtained in the modified rolling process and cooled in air (Fig. 6), the mesh is not as visible as in the picture illustrating the sample from the same type of steel, obtained in the conventional rolling process, also cooled in air (Fig. 5). The microstructure of pearlite and cementite at the grain boundaries adversely affects both the mechanical and plastic properties. Cementite is a hard and brittle phase, and therefore, as a result of the applied stress (mesh), it is a place prone to cracks and their propagation at the grain boundaries.

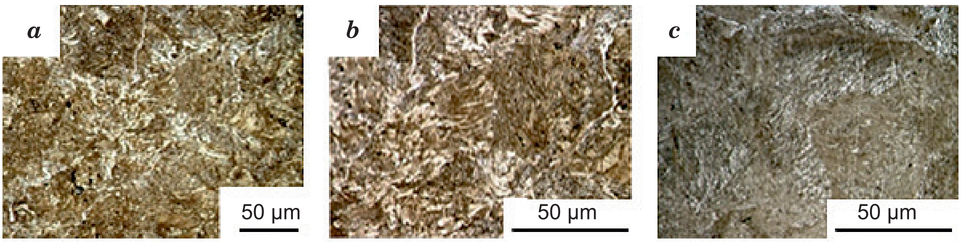

Fig. 5. Microstructure of the samples of the bearing steel 100Cr6 obtained in the conventional rolling process, cooled in air: *a* – left edge of the sample, *b* – the middle part of the sample, *c* – right edge of the sample

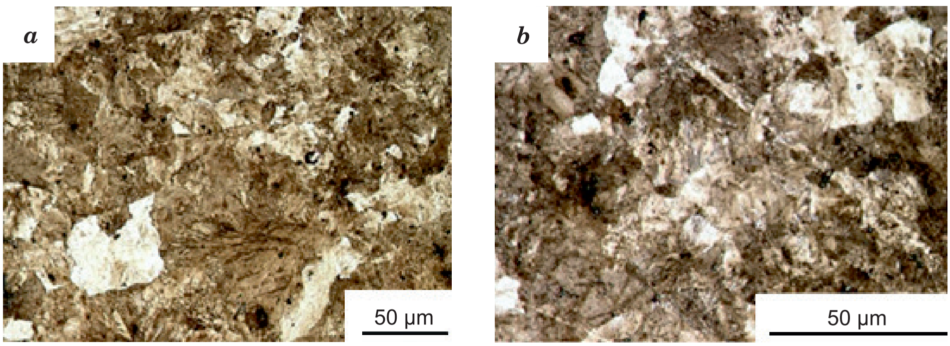

Fig. 6. Microstructure of the samples of the bearing steel 100Cr6 obtained in the modified rolling process, cooled in air: *a* – left edge of the sample, *b* – right edge of the sample

In the picture of the microstructure of the stock material, the most visible (distinguishable) alternately arranged platelets of ferrite and cementite are made of the rail steel (Fig. 4). In the case of both stock materials: the rail steel and the bearing steel (Fig. 7, 8), after deformation and cooling in air, individual platelets are not so distinguishable at specific magnification. Pearlite colony size for the individual analyzed cases varies in a wide range of several to tens of micrometers. The thickness of the platelets affects mechanical properties (of a given carbon content), e.g. the hardness of steel. On the other hand, it depends on the supercooling of austenite (above the temperature of bainite formation): the greater the supercooling, the smaller the thickness of the platelets. The lower the hardness of the balls, the more prone to wear they will become. Performance characteristics of the balls will be better with the smaller distance between the platelets.

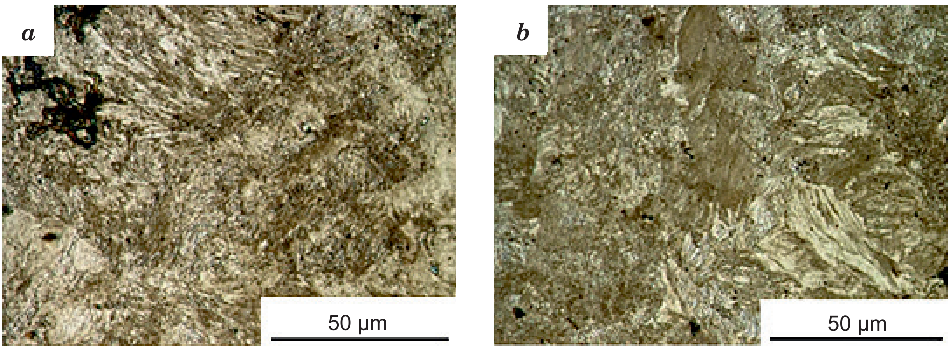

Fig. 7. Microstructure of the samples of the rail steel obtained in the conventional rolling process, cooled in air: *a* – left edge of the sample, *b* – right edge of the sample

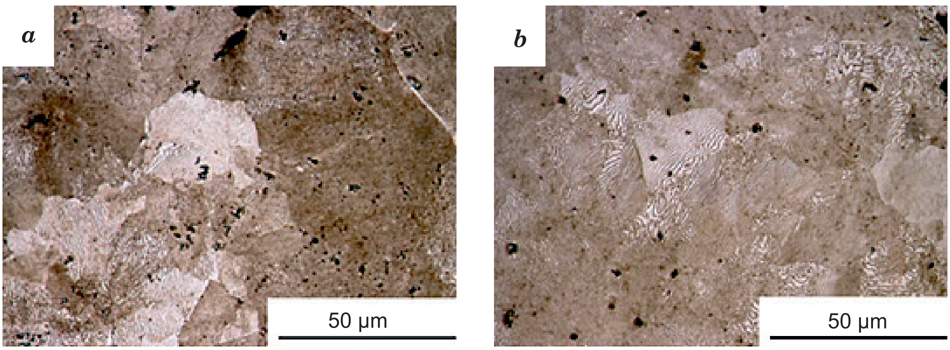

Fig. 8. Microstructure of the samples of the rail steel obtained in the modified rolling process, cooled in air: *a* – left edge of the sample, *b* – right edge of the sample

The microstructure of the steel both from the bearing steel (Fig. 9, 10) and from scrap rails (Fig. 11, 12), after cooling in water (quenching), is composed of martensite and retained austenite. In the case of the samples of the bearing steel 100Cr6 after the conventional rolling process (Fig. 9) and the modified rolling process (Fig. 10), there is a characteristic microstructure of (thick) plate martensite and retained austenite. The high content of retained austenite in the bearing steel 100Cr6 is associated with a high carbon and chromium contents,

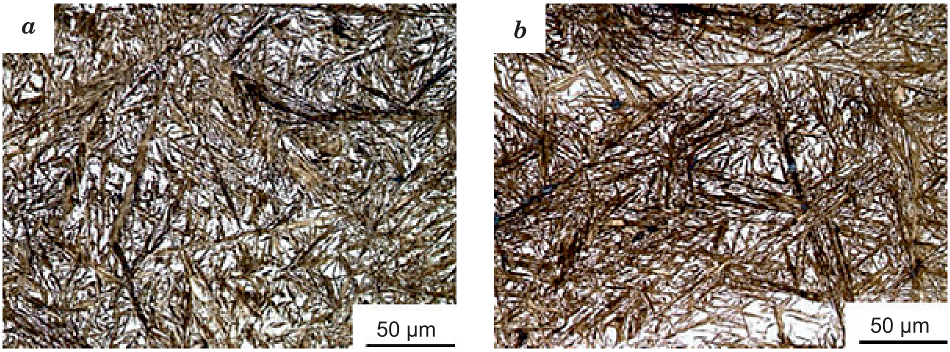

Fig. 9. Microstructure of the samples of the bearing steel 100Cr6 obtained in the conventional rolling process, cooled in water: *a* – left edge of the sample, *b* – right edge of the sample

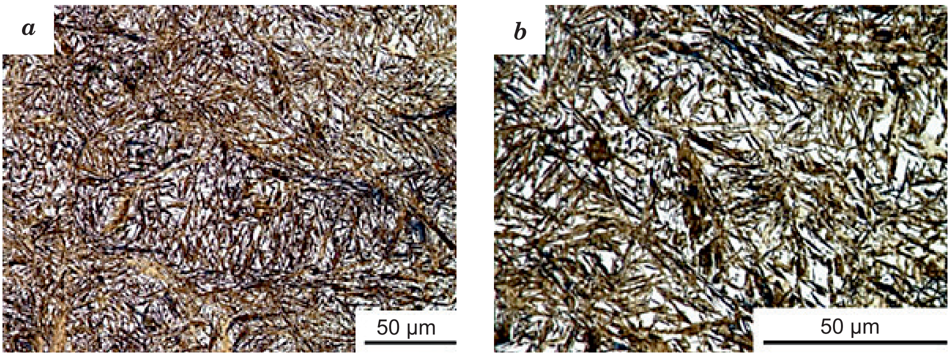

Fig. 10. Microstructure of the samples of the bearing steel 100Cr6 obtained in the modified rolling process, cooled in water: *a* – left edge of the sample, *b* – right edge of the sample

which lower the temperature M_s and M_f; moreover, it is stabilized by chromium dissolved in austenite. Light-colored, non-etched stripes are visible (high content of retained austenite), which may be due to chromium dissolved in austenite.

In the case of the balls made of the rail steel (Fig. 11, 12), formed in the cross wedge rolling mills after the heat quenching treatment, the size (length) of the martensite platelets is smaller, which may indicate a finer austenite grain. The microstructure of the steel from scrap rails, after quenching in water,

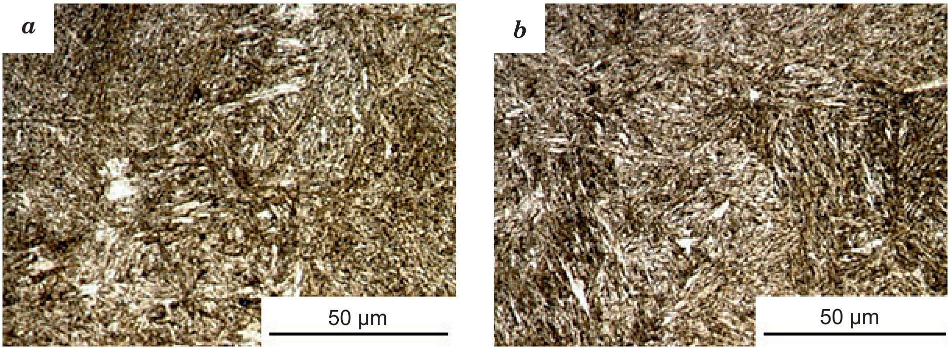

Fig. 11. Microstructure of the samples of the rail steel obtained in the conventional rolling process, cooled in water: *a* – left edge of the sample, *b* – right edge of the sample

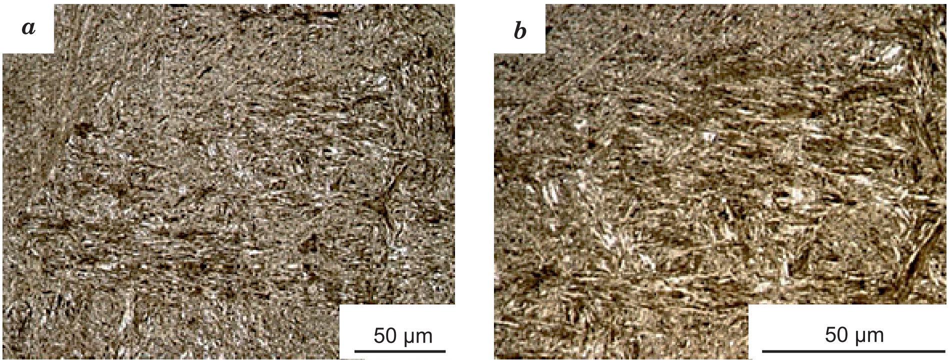

Fig. 12. Microstructure of the samples of the rail steel obtained in the modified rolling process, cooled in water: *a* – left edge of the sample, *b* – right edge of the sample

is composed of lath and plate martensite as well as retained austenite. Compared with the microstructure of hardened bearing steel, the content of austenite is much lower. Martensite with small-sized plates is better – there are smaller residual stresses. Retained austenite reduces the hardness but, on the other hand, it favorably affects the properties of steel such as wear resistance and fatigue strength, as well as reduces its tendency to brittle fracture. The hardness of the bearing steel should be slightly higher due to the carbon content. In the case of the steel from scrap rails, there are no major differences in the microstructure of the balls formed in the conventional and modified rolling processes.

As a result of the cooling process, after the deformation in oil, the martensitic transformation occurred (Fig. 13÷16). The microstructure of the balls formed from the bearing steel (Fig. 13, 14) consisted of: plate martensite and retained austenite (light-colored areas). In some places (light-colored spots), it could be associated with the segregation of chromium dissolved in austenite. The share of retained austenite is much higher than in the case of rail steel (higher carbon content).

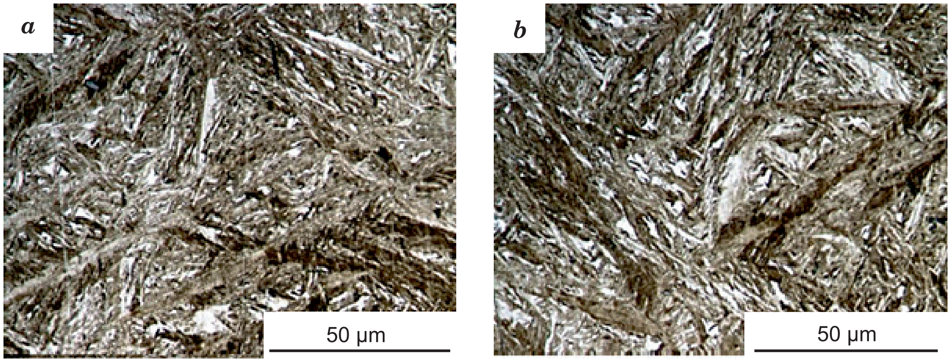

Fig. 13. Microstructure of the samples of the bearing steel 100Cr6 obtained in the conventional rolling process, cooled in oil: *a* – left edge of the sample, *b* – right edge of the sample

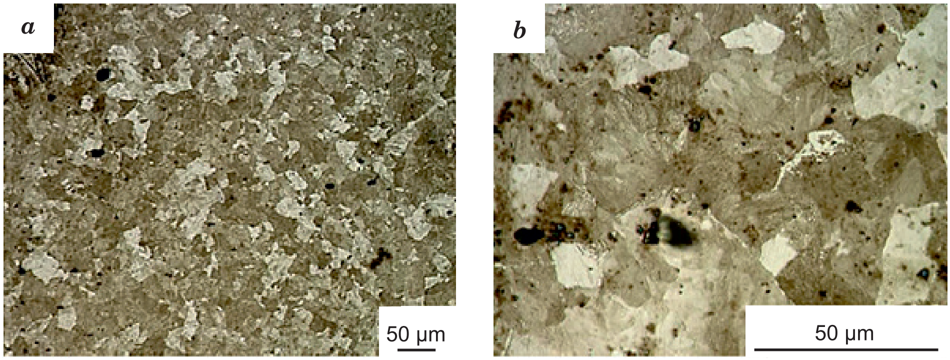

Fig. 14. Microstructure of the samples of the bearing steel 100Cr6 obtained in the modified rolling process, cooled in oil: *a* – left edge of the sample, *b* – right edge of the sample

In the case of rail steel (Fig. 15, 16), the microstructure is composed of lath and plate martensite (to a lesser extent) and retained austenite (light-colored areas).

Figure 17 illustrates a special case of the microstructure obtained by the conventional rolling process combined with the cooling in oil. Near the surface, it is composed of pearlite and cementite at the grain boundaries (as after the cooling in air), and farther from the surface, martensite (brown color) and dark areas – pearlite can be observed. This effect may be due to the fact that during the deformation, as a result of the contact with a tool, the temperature dropped (diffusional transformation), but inside the material, where the transformation did not occur (there was austenite in the structure), as a result of the cooling in oil, the martensitic transformation occurred where, in addition to perlite, there is martensite.

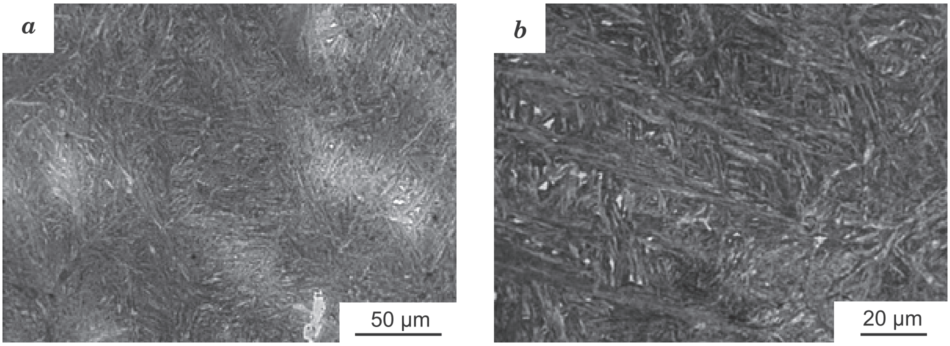

Fig. 15. Microstructure of the samples of the rail steel obtained in the conventional rolling process, cooled in oil: *a* – left edge of the sample, *b* – right edge of the sample

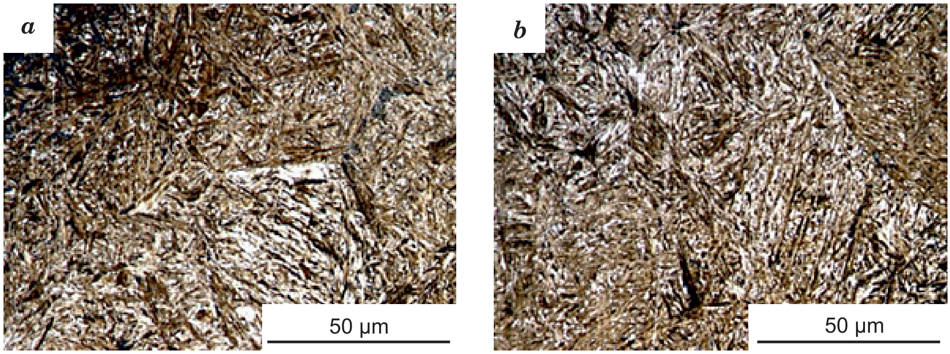

Fig. 16. Microstructure of the samples of the rail steel obtained in the modified rolling process, cooled in oil: *a* – left edge of the sample, *b* – right edge of the sample

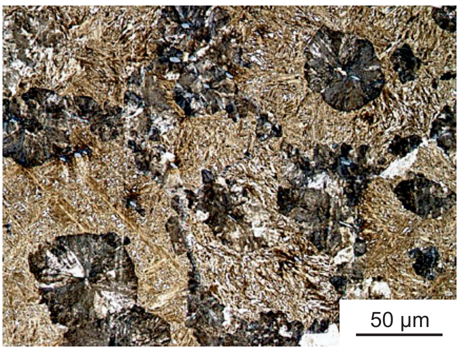

Fig. 17. Microstructure of the sample of the rail steel obtained in the conventional rolling process, cooled in oil (specific case)

Summary and conclusions

Numerically analyzed processes of skew rolling of the balls (DOBRZAŃSKI 1993) were verified experimentally in the laboratory conditions of the Department of Metal Forming, Faculty of Metals Engineering and Industrial Computer Science of AGH University of Science and Technology in Krakow, using the skew rolling mill installed at this laboratory. The physical tests were performed on two stock materials: bearing steel 100Cr6 and rail steel.

After the rolling process, the balls were subjected to quenching treatment in three cooling media: they were placed in water, in oil and they were left in the air. The analyses of the physical test results allowed to formulate the following conclusions:

– despite a relatively long shaping time, the temperature of the material is maintained within the range appropriate for hot plastic working and it is sufficient to carry out the quenching process immediately after the rolling of the balls;

– the roll pass method of the working roller does not affect either the hardness or the microstructure of the obtained balls.

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