UDC 621.926.3:664.71-62-412

STRUCTURE AND PROPERTIES OF BIMETALLIC CENTRIFUGALLY CAST MILLING ROLLERS

ZHENG ZHIBIN [1], *A. P. SHATRAVA* [2], *V. P. LIKHOSHVA* [2], *O. A. PELIKAN* [2], *ZHENG KAIHONG* [1]

[1] *Guangdong Institute of Materials and Processing, Guandong Academy of Sciences, PR China;*

[2] *Physico-Technological Institute of Metals and Alloys, National Academy of Sciences of Ukraine*

A way to increase the wear and crack resistance of the main working tools for roller mills is proposed. Bimetallic rollers (diameter – 252 mm, length – 1620 mm) were produced by sequential pouring of alloys with similar temperatures of the phase transformations. The microstructure, phase composition, redistribution of alloying elements and the properties of the bimetallic materials were studied. The results were taken as the basis for the development of a technological process for the production of bimetallic milling rollers by a centrifugal method of casting. The implementation of this method makes it possible to improve the reliability and durability of the rollers in the course of their operation.

Keywords: *structural phase analysis, iron-carbon low alloys, centrifugal casting method, transition area.*

Introduction. The increase in performance and durability of the grain processing mill complexes makes it necessary to steadily increase the requirements for the materials and the designs of modern equipments. The machines, such as roller mills are used for efficient grinding and milling of hard and soft wheat and are the most common machines for processing of corn, wheat, rye, barley or malt.

The main working tools of these units applied for grinding of grain are milling rollers operating in pairs, which have a grooved or smooth surface. A high requirement for physical and mechanical properties of the rollers makes it necessary to improve the durability of parts of the mill equipment of the leading manufacturers of plants such as: Bühler, Ocrim, Golfetto, MMW, etc. The roller mills are usually equipped with rollers with a diameter of 250 or 300 mm. The design features and operating conditions of the milling rollers define the need for a wear-resistant working layer on the surface while maintaining the viscosity and bearing properties of the core of these products [1]. Therefore, the milling rollers with bimetallic structures are considered to perform well and have a number of advantages: combination of the best characteristics of two different materials; wear-resistant working layer and a core that provides rigidity and toughness; simultaneous increase of the wear resistance and durability of the product [2].

Iron-carbon alloys are commonly used for the manufacture of rollers as wear resistance materials. The austenitic manganese irons and steels were used as a tribological material [3, 4]. The relationship of wear intensity with the structural-phase composition of the alloys and the load-speed characteristics are investigated.

The presence of antifriction additives in iron-carbon alloys in the form of graphite or copper inclusions reduces the friction coefficient and increases their wear resistance [5] too. The most effective method of producing bimetallic roller billets is centrifugal casting [6], which is far superior to stationary in quality and economic characteristics. It is demonstrated that the increase in the temperature of the contact surface between the working layer of chromium cast iron and the steel base promoted the formation of a me-

Corresponding author: О. П. ШАТРАВА, e-mail: shatrava@ptima.kiev.ua

tallurgical bonding layer. The adhesion strength between the working and base layers is also increased.

The pouring temperature and the preheating temperatures of steel base and the casting mold are key parameters [7]. It is established that high pouring temperatures and low cooling rates in the course of solidification result in the increase of flexural strength and the viscosity of the rollers material [8].

Although a few researches have been carried out to study the formation of the bimetal and the suitable manufacturing process of the bimetallic milling rollers [6–8], the interface between the two materials still remains mysterious. The structure of the working layer and the quality of the diffusion junction between the layers are still the most important indicators which determine the operational properties of bimetallic milling rollers. Therefore, the primary focus in this paper is on the study of these issues.

Materials, methods and experimental procedure. The working layer of the bimetallic milling roller was cast from synthetic low-alloy cast iron. The inner layer was cast from gray iron. The melting and pouring process was implemented according to the method indicated in our former work [9]. Chemical composition of the working layer (wt.%): C – 3.3…3.5, Si – 0.05…0.35, Mn – 0.4…1.0, Cr – 0.3…0.5, Ni – 1.4…2.0, P – 0.15…0.4, S – up to 0.02 and the inner layer (wt.%): C – 3.3…3.5, Si – 1.4…2.4, Mn – 0.7…1.0, P – up to 0.2, S – up to 0.15.

The bimetallic milling roller billets were made by the sequential pouring of molten masses of the working and inner layers into a rotating casting mold of a centrifugal machine. The casting mold rotation speed of the was 618 rpm. The casting process was carried out in the following stages: *1* – pouring the melt of the working layer; *2* – pouring the melt of the inner layer; *3* – ejection of the billet.

An induction crucible furnace was used as a melting unit, which made it possible to obtain the alloys with preset chemical compositions and ensured precise control of the liquid metal temperature, high-temperature overheating and the holding of the molten mass.

In order to reduce metal loss and increase the absorption rate of carburizer during the cast Cr/Ni iron melting for the working layer, the initial charging materials were loaded in the following sequence: steel scrap (15…20% of the total amount of charge); ferrophosphorus; ferrochrome; carburizer; steel scrap (60…70% of the total amount of charge); nickel; steel scrap (the remaining amount); ferromanganese (5…8 min prior to the start of casting).

The initial charging materials for the melting of cast iron for the inner layer were loaded in the following sequence: cast pig iron (15…20% of the total amount of charge); ferrosilicon; steel scrap; cast pig iron (the remaining amount); ferromanganese (5…8 min prior to start of casting).

The microanalysis was carried out on samples (templates) cut from the middle and end parts of the billets of rollers. An optical microscope was used to study the microstructure. The microhardness of the phase components was determined on a hardness tester according to the standard method (by Vickers) with automatic recording of readings with a load of 0.5 N. The hardness of the working layer was measured by the Rockwell method. The local chemical composition of the structural components, the redistribution of atoms of the alloying elements in the area of diffusion interaction between the layers was investigated on an electronic raster-type analyzer.

Results and discussion. It is clear that the microstructure of cast iron of the working layer (Fig. 1) of the studied billet rollers has a columnar structure with a fine texture throughout the layer thickness. It is associated with an increased rate of cooling (1.4…1.5°C/s) and the direction of its solidification [10]. It consists of finely-dispersed pearlite which is the eutectoid mixture of ferrite (solid solution of carbon and alloying elements in α-iron) and cementite (Fe_3C), secondary alloyed cementite $(FeCr)_3C$ of skeletal type or in the form of thin needles, as well as ledeburite eutectics which is the eutectic mixture of austenite (solid solution of carbon and alloying elements in γ-iron) and cementite as marked in Fig. 1.

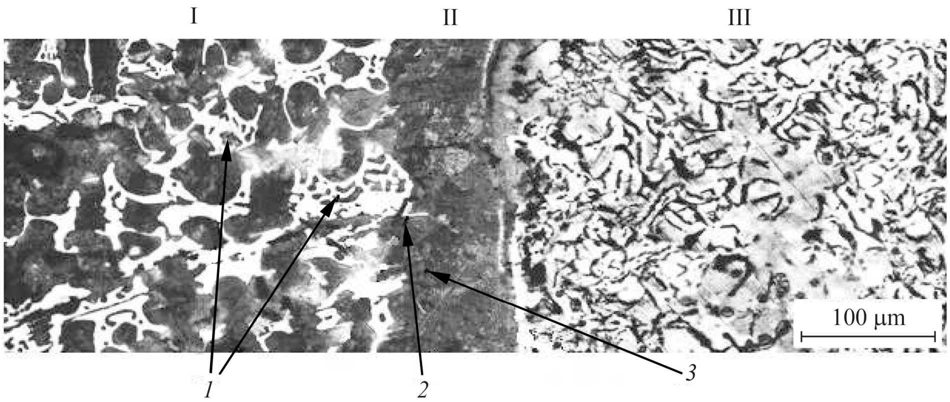

Fig. 1. Microstructure of the working and inner layers, transition area of the bimetallic billet. I – working layer; II – transition area; III – inner layer. *1* – phosphide eutectic ($HV_{0.05}$ = 925); *2* – cementite ($HV_{0.05}$ = 1450); *3* – perlite ($HV_{0.05}$ = 400).

In addition to these phases, steadite that is made up of three phases: Fe3P + Fe3C + Fe, is present in the structure, which is formed between the cementite plates.

The mass fractions of different phase components are analyzed and the result (as shown in Table 1) indicates that the main structural components of the working layer are pearlite and cementite with high microhardness, which has a significant impact on the overall hardness of the working layer.

Table 1. Phase components of the cast iron of the working layer and their microhardness

Phase component	Fraction, mass%	Microhardness, HV
Cementite	30…35	1450
Ledeburite	5…8	–
Phosphide eutectic	2…5	780…925
Pearlite	55…60	400…410

The microstructure of the working layer on the outer and inner surfaces of the billets differs by dispersion and the number of structural components. Near the billet outer surface, the pearlite dendrites, cementite plates, and the areas of phosphide eutectics are mostly oriented towards heat dissipation, perpendicular to the outer surface. As the distance to the outer surface of billet increases due to the decrease in the rate of solidification and the increase in carbon and phosphorus segregations, the microstructure coarsens slightly. The amount of ledeburite and phosphide eutectics increases and the inclusions of cementite coarsen. These changes have little effect on the change in the hardness of the working layer in depth. Near the outer surface, the hardness of the working layer is 55 HRC. As the distance from the surface increases, the hardness slightly decreases to 54 HRC, which indicates the uniformity of hardness over the cross section of the layer. This has a significant impact on the service life of the rollers with the possibility of repeated re-cutting of riffles as they age.

The microstructure of the transition area as shown in Fig. 1 consists of pearlite of low-alloy cast iron of the working layer (400 HV) with ribs of cementite, partially dissolved cementite needles, triple phosphide eutectics, and pearlite of gray iron of the inner layer (330 HV).

In the course of manufacturing the roller billets, after pouring the inner layer, the inner surface of the hardened working layer was heated to a temperature of 1150…1160°C that resulted in partial dissolution of the secondary cementite and cementite contained in ledeburite. At the same time, in the adjacent layer of gray iron, the numerous eutectic austenite-graphite colonies were formed, inside and along the boundaries of which the pearlite was generated as a result of the eutectoid transformation. The pearlite layer fringing the eutectic grains formed the pearlite layer of the transition area on the side of gray iron.

An increase in the temperature and mass rate of pouring of the working layer, a decrease in the holding time in between pouring of layers resulted in the increase in the temperature of the working layer inner surface, an increase in the scope of its melting with gray iron. This also contributed to an increase in width and change in the phase composition of the transition area. The formation of the transition area in this case occurred in a similar way. However, the graphite was formed instead of cementite. The process of graphitization was promoted by a change in the thermophysical state in the transition area. The crystallization rate decreased while both the amount of the liquid phase and the content of silicon and phosphorus therein increased. The carbon diffused better during this process. In this case, the decomposition rate of cementite was higher than the diffusion rate of carbon, resulting in the in-situ graphitization. The width of the transition area increased to 300…450 μm.

The formation of pearlite on the side of working layer was caused by the fact that carbon formed as a result of the cementite dissolution diffused through the austenite solid solution and was released at the graphitization centers (on the graphite plates of austenite-graphite colonies of the border layer of gray cast iron). The impurities segregated to the boundary of the pearlite layers of the transition area, especially phosphorus, which had a low melting point. Therefore, the transition area crystallized last. When the transition area was saturated with phosphorus and silicon, the part of the carbon was pushed into austenite, and some were transformed into cementite of phosphide eutectics. The width of such a transition area was about 100 μm.

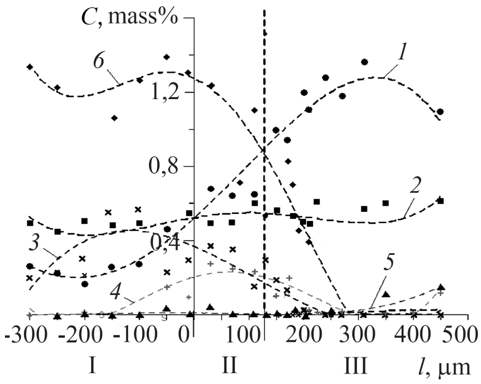

Fig. 2. Redistribution of alloying elements in the transition area, the working and inner layers of roller billets: I – working layer; II – transition area; III – inner layer. *1* – Si; *2* – Mn; *3* – Cr; *4* – P; *5* – S; *6* – Ni.

Thus, the width, phase composition and kinetics of the transition area formation are determined by the temperature conditions for the manufacture of bimetallic billets. Thus, the change in the concentration of elements (Fig. 2) in the transition area depends on their initial content in the cast iron of the working and inner layers.

The mass fraction of silicon droningly increases from 0.25% in the transition area of the working layer to 1.3% in the transition area of the inner layer. The nickel content within the transition area changes significantly, a decrease in its content during the transition from the working to the inner layer is found. Through diffusion processes, its partial presence is observed at the boundary of gray cast iron. The amount of sulfur and manganese across the width of the transition area remains almost unchanged. In the course of casting transition area formation, the phosphorus segregation is intensified at the interface of the layers due to an increase in the temperature of the inner surface of the working layer and its melting. As a result, the number of inclusions of phosphide eutectics increases in transition area, which is expressed as a maximum on the phosphorus distribution curve.

Table 2. Service condition of the bimetallic rollers during the process of grain milling in the milling machine lines

System	Rifle height, mm							Degree of wear	
	Before operation	1st period of operation 71 days Milling 16,000 tons (I f. s. –2,666 tons)	2nd period of operation 87 days Grinding 76,555 tons (I f. s. –12,759 tons)	3rd period of operation 152 days Grinding 141,127 tons (I f. s. –23,521.17 tons)	4th period of operation 134 days Grinding 198,922 tons (I f. s. –33,153.67 tons)	5th period of operation 80 days Grinding 238,425 tons (I f. s. –39,737 tons)	6th period of operation 145 days Grinding 299,734 tons (I f. s.–49,956 tons)	Δ, mm	%
I f. s.	0.70…0.87	0.70…0.87	0.70…0.75	0.66…0.72	0.66…0.71	0.65…0.70	0.65…0.69	0.05…0.18	7…21
II f. s.	0.44…0.55	0.43…0.52	0.42…0.51	0.40…0.50	0.40…0.50	0.40…0.47	0.39...0.47	0.03…0.14	7…26
III f. l. s.	0.30…0.39	0.24…0.37	0.23…0.35	0.19…0.33	0.19…0.32	0.19…0.31	0.19…0.31	0.07…0.12	18…37
III f. f. s.	0.25…0.32	0.23…0.30	0.22…0.28	0.22…0.28	0.20…0.24	0.20…0.24	0.19…0.23	0.06…0.09	22…28
IV f. l. s.	0.16…0.28	0.14…0.26	0.14…0.22	0.12…0.21	0.12…0.21	0.12…0.21	0.12…0.21	0.04...0.12	19…43
IV f. f. s.	0.20…0.21	0.18…0.20	0.17…0.18	0.16….0.17	0.15…0.16	0.15…0.16	0.15…0.15	0.05…0.06	25…29

I f. s. – the 1st fluted system; II f. s. – the 2nd fluted system; III f. l. s. – the 3rd fluted large system;
III f. f. s. – the 3rd fluted fine system; IV f. l. s. – the 4th fluted large system; IV f. f. s. – the 4th fluted fine system.

The carbides of the cementite type, which also include chromium, partially dissolve during the casting of the inner layer. In this case, the chromium is distributed between the γ-solid solution of the transition area of gray cast iron and phosphite eutectic cementite.

The results demonstrate that optimization of the chemical composition, melting and pouring conditions of synthetic low-alloy cast iron can improve the microhardness and dispersion of the carbide phase and the metal base. The appearance of structurally free graphite in the working layer can be eliminated, resulting in the increase of wear resistance. Moreover, high and uniform hardness along the length and cross-section of the working layer, both for rifled rollers of fluted systems and for smooth rollers of fine milling systems was achieved.

The bimetallic rollers resulted from the current method have been applied in the food industry. The state of service of bimetallic rollers in the process of processing 299734 tons of grain in the lines of the milling machine has been obtained.

In roller mill complexes there are several fluted and smooth systems of rollers, which are sets of rollers with riffled surfaces and without them. As the grain is crushed and milled to a state of flour – the height of the rifles changes from larger to smaller. Accordingly, the load on the working surfaces of the rollers decreases from the first fluted system to the fourth. The data (Table 2) show that each first most loaded fluted system (I f.s.) processed 49956 tons of grain prior to the first re-cutting of riffles without reducing the performance of the machines.

The obtained indicators of the service life of the produced rollers are comparable to the service life of the rollers manufactured by "Bühler", which occupies the advanced positions in the production of mill equipment. The results of production tests indicate high wear resistance, reliability and competitiveness of the rollers in the production of equipment for food industry in the world market.

CONCLUSIONS

Bimetallic material has been designed for the milling roller by the sequential pouring of molten masses of the working and inner layers into a rotating casting mold of a centrifugal machine. The main structural components of the working layer are pearlite and cementite with micro-hardness of 1450 HV and 400…410 HV, respectively. The hardness of the working layer outer surface was 55 HRC and it slightly decreased to 54 HRC in the inner surface of the working layer, which indicates the uniformity of hardness over the cross-section of the layer. The width, phase composition and kinetics of the transition area formation are determined by the temperature conditions for the manufacture of bimetallic billets. The bimetallic rollers produced by the current technological process showed good wear resistance during processing of over 299734 tons of grain in the milling machine lines.

РЕЗЮМЕ. Запропоновано спосіб підвищення зносо- і тріщиностійкості основних робочих органів вальцьових млинів. Біметалеві вальці (діаметр 252 mm, довжина 1620 mm) виготовляли шляхом послідовного заливання сплавів з подібними температурами фазових перетворень. Досліджено мікроструктуру, фазовий склад, перерозподіл легувальних елементів і властивості біметалевих матеріалів. Результати досліджень взято за основу під час розробки технологічного процесу виробництва біметалевих вальців методом відцентрового лиття. Реалізація цього способу дала можливість підвищити надійність і довговічність вальців під час експлуатації.

Ключові слова*:* *структурно-фазовий аналіз, залізовуглецеві низьколеговані сплави, метод відцентрового лиття; перехідна зона.*

РЕЗЮМЕ. Предложен способ повышения износо- и трещиностойкости основных рабочих органов вальцовых мельниц. Биметаллические вальцы (диаметр 252 mm, длина 1620 mm) изготавливали путем последовательной заливки сплавов с похожими температурами фазовых превращений. Исследованы микроструктура, фазовый состав, перерас-

пределение легирующих элементов и свойства биметаллических материалов. Результаты исследований взяты за основу для разработки технологического процесса производства биметаллических вальцов методом центробежного литья. Реализация этого способа позволила повысить надежность и долговечность вальцов в процессе эксплуатации.

Ключевые слова: *структурно-фазовый анализ, железоуглеродистые низколегированные сплавы, метод центробежного литья, переходная зона.*

Acknowledgments. This work was supported by the GDAS' Project of Science and Technology Development (2017GDASCX-0117), 2018 Guangzhou International Science and Technology Cooperation Project (201807010085) and Science and Technology Planning Project of Guangdong Province (2017A070701029).

1. *Technological* features of production of bimetallic (multilayer) castings of increased wear resistance / V. V. Shiryaev, O. A. Pelikan, I. O. Shinskiy, D. V. Glushkov, and Yu. N. Romanenko // Metal and casting in Ukraine. – 2009. – № 7–8. – P. 52–56. (in Russian).
2. *Dorin Eftimie and Aurel Ciurea* Installation for centrifugal casting of bimetallic jacks // The Annals of "Dunarea de jos" University of Galati fascicle XIV mechanical engineering. – 2002. – P. 39–42.
3. *Балицький О. І., Колесніков В. О.* Дослідження продуктів зношування аустенітних марганцевих чавунів // Фіз.-хім. механіка матеріалів. – 2004. – **40**, № 1. – С. 65–69.

   (*Balytskyi O. I., Kolesnikov V. O.* Investigation of wear products of austenitic manganese cast-iron // Materials Science. – 2004. – **40**, № 1. – P. 78–82.)
4. *Балицький О. І., Колесніков В. О., Кав'як П.* Триботехнічні властивості аустенітних марганцевих сталей та чавунів в умовах тертя ковзання // Фіз.-хім. механіка матеріалів. – 2005. – **41**, № 5. – С. 55–60.

   (*Balyts'kyi O. I., Kolesnikov V. O., Kawiak P.* Triboengineering properties of austenitic manganese steels and cast irons under the conditions of sliding friction // Materials Science. – 2005. – **41**, № 5. – P. 624–630.)
5. Структура та трибологічні характеристики литого гетерогенного сплаву до і після лазерної обробки / В. Г. Новицький, В. П. Гаврилюк, О. П. Шатрава, Д. Д. Панасенко, В. Я. Хоружий, М. О. Кальчук // Фіз.-хім. механіка матеріалів. – 2011. – **47**, № 1. – С. 87–93.

   (*Structure* and tribological characteristics of a cast heterogeneous alloy before and after laser treatment / V. H. Novyts'kyi, V. P. Havrylyuk, O. P. Shatrava, D. D. Panasenko, V. Ya. Khoruzhyi, and M. O. Kal'chuk // Materials Science. – 2011. – **47**, № 1. – P. 95–101.)
6. *Production* of copper-aluminum bimetal by using centrifugal casting and evaluation of metal interface / J. Nazari1, M. Yousefi, M. S. Amiri Kerahroodi, N. S. Bahrololoumi Mofrad, and S. H. Alavi Abhari // Int. J. Materials Lifetime. – 2015. – **1**, № 1. – P. 20–28.
7. *Optimization* of process parameters to improve combination in duplex roller sleeve / Zhihong Guo, Fu-ren Xiao, Su-ling Lu, Rui-ling Liu, and Bo Liao // Inter Metalcast. – 2017. – **11**, № 3. – P. 448–455.
8. *Identification* of metallurgical manufacturing factors with a significant effect on the flexural strength of mottled Ni-hard cast irons through a design of experiments approach / J. F. Álvarez Antolín, J. Asensio Lozano, and C. H. Álvarez Pérez // Inter Metalcast. – 2017. – **11**, № 3. – P. 467–474.
9. *Peculiarities* of melting and casting of synthetic cast iron in the working layer during centrifugal casting of two-layer blanks of milling rollers / O. A. Pelikan, G. D. Kostenko, D. G. Kostenko, V. V. Shiryaev, and D. V. Glushkov // Metal and Casting in Ukraine. – 2005. – № 1–2. – P. 70–72.
10. *Investigation* of thermophysical processes of solidification of two-layer blanks of milling rollers / G. D. Kostenko, O. A. Pelikan, A. G. Martynenko, E. L. Brechko, Yu. N. Romanenko, and D. G. Kostenko // Metal and Casting of Ukraine. – 2005. – № 6. – P. 38–42.

Received 31.01.2019