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GRAPHITIZING MODIFICATION OF THE AXIAL ZONE OF CAST IRON ROLLING ROLLS IN THE LIQUIDUS-SOLIDUS TEMPERATURE RANGE

Purpose. To develop a method for calculating a process of graphitizing modification of unsolidificated liquid-solid zone to reduce transcrystallinity of the macrostructure and the amount of cementite in the center of castings.

Methodology. The duration of solidification of the castings was determined by the kinetic curves of liquidus, solidus and pouring boundary in coordinates of relative thickness of the solidified metal layer – the parametric criterion of Gulyaev.

Findings. A methodology for the process of modification of the axial zone of rolling was developed, the mass and time of adding aluminum were determined according to the amount of liquid-solid phase that remains after the solidification of the working layer. On the example of a rolling roll weighing 1115 kg, 0.488 kg of aluminum was added into liquid-solid zone after the working layer solidified. Movement of aluminum to the front of crystallization is provided by centrifugal forces and adding of aluminum along the height of the roll.

Originality. For the first time, the kinetic curves of liquidus, solidus and pouring boundary have been plotted in coordinates of the relative thickness of the solidified metal layer x/R and τ/R^2 – the parametric criterion of Gulyaev for rolled cast iron alloys cooled in chill-sand molds of various sizes. A methodology was developed for calculating the process of aluminum modification of the axial zone of rolling rolls after solidification of the working layer in the barrel which was set at the pouring boundary. The amount of aluminum depends on the remains of the liquid-solid phase.

Practical value. Graphitizing modification reduces transcrystallinity of the macrostructure and the amount of cementite in the axial zone of castings. A promising direction for further development is the development of new methods for manufacturing castings due to physical and mechanical effects on the two-phase zone, deoxidation and alloying of the central zones of castings.

Keywords: *cast iron, modifications, rolling rolls, hardening, chill-sand mixture*

Introduction. The main performance characteristics of many cast products are determined mainly by the physical and mechanical properties of their surface layers [1, 2], macro- and microstructure [3, 4].

Thus, the main volume of boring is performed by three-ball drill bits [5]. Plate-shaped castings are used mainly in mills of medium and fine grinding at mining and processing plants; armor plates, which do not have pronounced protrusions or lifters, protect the inner walls of the mill drum, "lift" the grinding ball during the rotation of the mill, sort the grinding balls in the mill by size and "advance" the crushed material for unloading, and castings in ball shape – for grinding minerals of various kinds at concentrators, for the manufacture of Portland cement, gypsum, powder of the required dispersion for use in paints, pyrotechnics, ceramics, and cast iron rolls are used to grind flour or rolled balls.

The most common material that provides high hardness of the working layer compared to steel is cast iron [6, 7], but increasing the operational stability of such castings also depends on the strength and toughness of metal layers, which are located after the wear-resistant working layer for cast iron rolls; unsatisfactory macro- and microstructure of the axial zone is the cause of failure during operation. According to Krivosheev O. E. (1957), the rolling roll must have a solid wear-resistant working layer, whose properties are determined mainly by the amount of cementite and microhardness of the matrix, and starting from the transition zone and in the axial should be a structure with minimal brittle structural components that reduce roll strength when working on a rolling mill.

Therefore, in the production of cast iron rolls they limit the presence of carbide mesh in the necks and clubs, as well as carbides in the axial zone, which reduce the strength of the rolls [8]. However, the formation of internal chill hard spots in the central parts of cast iron castings of different chemical composition is known. Thus, when barrels of rolled rolls with a working layer of bleached cast iron (C – 3.75 %; Si – 0.44 %; Mn – 0.39 %; P – 0.38 %; S – 0.14 %; Cr – 0.73 %; Ni – 1.81 %, pour temperature 1305 °C) are cooled in a mold with a diameter of 431 mm, formation of chill hard spots was found (Fig. 1) in the axial zone, according to Kutafin A. K. (2000).

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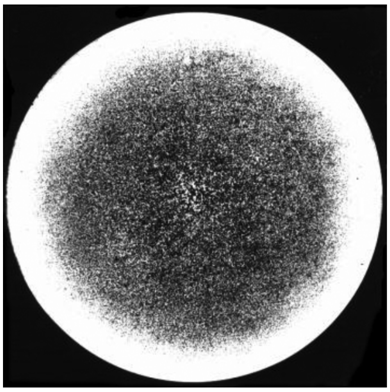


Fig. 1. Macrostructure of gray cast iron rolling mill with a working layer with cementite on the surface and carbides in the axial zone during cooling in an iron mold of ∅431 mm

In cast iron castings with a spherical shape of graphite (C – 3.10 %; Si – 1.41 %; Mn – 0.58 %; P – 0.214 %; S – 0.010 %; Cr – 0.34 %; Ni – 0.91 %, Mg – 0.04 %, temperature pouring 1320 °C) a columnar macrostructure forms not only in the working layer, but also in the axial zone (Fig. 2), which reduces the strength of the roll during its operation [9].

In addition, quantitative analysis of structural components on the depth of the roll barrel showed an increase in cementite area from 18 % at a depth of 130 mm to 22 % in the center of the casting despite heating the mold during curing and casting as well as the decreasing cooling rate of the alloy in the liquidus-solidus temperature range. Solidification of necks and clubs of rolls in sandy-clay elements of a foundry form promotes formation of a fragile cementite component in structure of insignificant quantity.

Literature review. For different rolling mills and stands, the rolls must have different hardness, micro- and macrostructure [8], which provide maximum operational stability under conditions of friction forces under high temperature, shock and bending loads that change cyclically. Known technologies of melting metal in order to obtain a working layer of the barrel with the required physical and mechanical properties provide, first of all, high wear resistance of the working layer [10]. Therefore, only after pouring the melt into the mold and crystallization of a given thickness of the working layer, it is possible to intervene in the process of hardening of the axial zone to reduce the transcrystalline macrostructure and the amount of cementite.

An effective process of obtaining a given structure of cast iron is the modification of the melt [11], including in the casting system in the process of pouring the mold to obtain two-layer castings. However, the proposed technologies are designed for shaped small castings and cannot be used for massive castings, which are cast iron rolls, because the duration of hardening of the working layer is much longer. It is not always possible to calculate the hardening kinetics of such castings using mathematical modeling [12, 13].

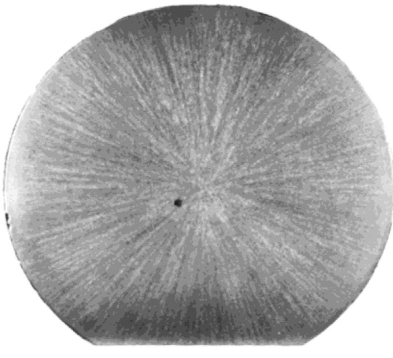


Fig. 2. Columnar macrostructure of a rolling mill barrel made of ductile iron cooled in a ∅450 mm mold [9]

In [10], the modification of the axial zone of the roll was studied when a graphitizing modifier – aluminum was introduced into the lower neck (Fig. 3).

In the process of filling the mold cavity with metal, the crystallization of the working layer begins in the barrel of the roll, which cools down rapidly in the chill-mold. After the formation of a working layer of the required thickness, the fixator *7* is turned off, the bar *5* with the modifier in the lower part, thanks to the guide pipe *4*, sinks into the liquid metal until the limiter is fixed on the upper part of the bar *5*. The low-melting modifier melts, having a lower density, rises in the column of liquid metal and modifies it. After melting of the modifier, bar *5* is removed from the casting.

It was found that the modification of cast iron with aluminum in the mold allowed eliminating transcrystalline and reduce the amount of cementite. The fracture of the barrel of the experimental roll by mass of 534 kg (Fig. 4, *b*) has a pronounced “two-layer”, and the fracture of the control roll (Fig. 4, *a*) – the same nature throughout the cross section of the barrel.

The amount of cementite in the center of the barrel of the experimental roll is 10 % less than in the control one, and the mechanical properties (σ_R^{prod}, σ_R^{mod}) of the material of the barrels of the rolls modified by the new technology by 3–18 %, and the upper and lower necks – by 10–30 % higher compared to mass-produced rolls. The content of cementite in the lower neck from a depth of 60 mm decreases by ≈ 3 %. In the upper neck, the reduction of cementite begins at a depth of 80 mm and reaches ≈ 2.5 % at a depth of 100 mm from the surface.

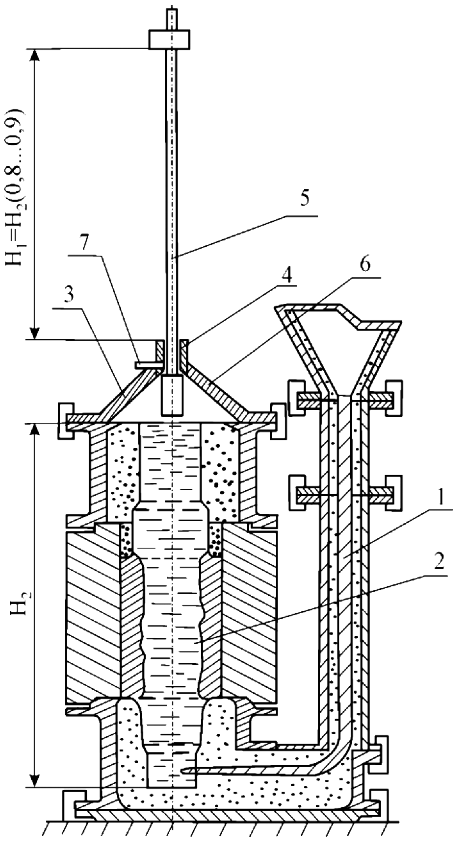


Fig. 3. Foundry mold of a rolling roll weighing 534 kg with a device for modification. The device is located in the lower roll neck:

1 – gating system; 2 – liquid metal after outer working layer has solidified; 3 – the device for planting of modifier; 4 – guide pipe; 5 – a bar with a modifier on the bottom; 6 – support; 7 – bar movement lock

Fig. 4. Macrostructure of the rolls of the control (a) and experimental (b), cast with modification of the axial zone by aluminum (Hitko O. Y., 2009)

However, the results of studies [10] are not realized due to the lack of data on quantitative assessment of the duration of solidification of the lower and upper necks for rolls with different sizes of barrels and necks. Without knowing the volume of liquid metal in the axial zone of the necks and barrels of the roll at the end of the solidification of the working layer of the required thickness according to the consumer's order, it is impossible to calculate the amount of modifier. In addition, exceeding the amount of aluminum above 0.1 % leads to the appearance of gas holes in iron castings.

The placement of aluminum is concentrated in the lower part of the roll (*5* in Fig. 3), which does not ensure its melting exactly at the time of crystallization of the working layer in the barrel, and to calculate the time of ascent of aluminum gradually into the lower neck, barrel and upper neck is impossible due to lack of data on the speed of convection flows in cast iron.

Purpose. To develop a method for calculating the hardening of the wear-resistant working layer of cast-iron rolls in combined chill-sand molds and to improve the technology of graphitizing modification of the non-solidified liquid-solid zone with aluminum to reduce the transcrystallinity of its macrostructure and the amount of cementite in the center of massive castings.

Methods. The duration of hardening of cast iron castings was determined by experimental measurements of crystallization temperatures [14] using thermocouples with simultaneous establishment of the pouring limit, which were processed according to the method of B. B. Gulyaev (1960) in the coordinates of the relative thickness of the solidified layer of metal x/R and τ/R^2 – parametric criterion, in which τ is curing time; R is the radius of the casting.

Implementation of experimental cooling curves by this method allowed establishing the kinetics of hardening fronts liquidus, solidus, casting for rolled cast iron alloys and calculating the solidification time of the working layer of barrels and necks of rolling rolls of different sizes in combined chill-sand molds.

Findings. To improve the modification process, the technology of introducing aluminum into the axial zone after curing the required layer of metal in the roll barrel was developed (Fig. 5). However, the location of the entire mass of aluminum in the lower part of the roll in the above process (*5* in Fig. 3) does not provide rapid melting, and it is impossible to set the time of its ascent in the lower neck, barrel and upper neck due to lack of speed liquid-solid zone of convective flows that fall down near the crystallization front and rise up through the center of the casting.

Therefore, the graphitizing modifier – aluminum wire (*7* in Fig. 5), was distributed along the height of the axial zone on the steel reinforcement *5*, and after curing the working layer ($X_{P\text{-}C}$) steel reinforcement was immersed in the axial zone through feeder. To ensure the movement of molten aluminum to the crystallization front, the steel reinforcement was rotated by an electric motor *6*.

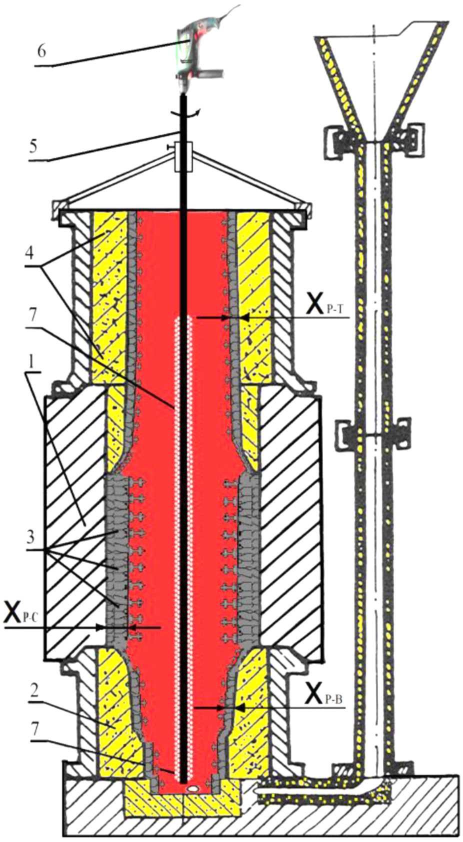


Fig. 5. Scheme of the process of curing the working layer in the mold and the introduction of aluminum in the axial zone of the roll to the crystallization front:

1 – chill mold; 2 – the shape of the lower neck; 3 – layer of cast iron ($X_{P\text{-}C}$), solidified in the barrel of the roll; 4 – shape of the upper neck and feeder; 5 – steel reinforcement; 6 – electric motor; 7 – aluminum wire distributed along the height of the axial zone on the steel reinforcement; XP-B, XP-T – a layer of solidified metal in the lower and upper necks, respectively

To calculate the mass and time of introduction of the graphitizing modifier according to the amount of liquid phase remaining after curing of the working layer in the barrels and necks of rolls of different sizes, a technique was developed, which consists of stages:

1. Determining the relative thickness of the working layer of the roll barrel, taking into account the allowances for shrinkage and machining.
2. Calculating the time of penetration of the pouring limit to a given thickness of the working layer of the barrel.
3. Calculating the thickness of the solidified layer of cast iron, and then the volume and mass of the liquid-solid two-phase axial zone in the barrel of the roll.
4. Calculating the thickness of the hardened layer of cast iron in the lower and upper necks.
5. Calculating the volume and mass of the liquid-solid two-phase axial zone in the lower and upper necks at the time of completion of solidification of the working layer of the barrel.
6. Calculating the total mass of liquid solid metal in the axial zone of the roll.
7. Calculating the mass of the graphitizing modifier (aluminum) for introduction into the axial liquid-solid zone of the barrel, lower and upper necks of the roll.

The hardening time of the working layer ($X_{P\text{-}C}$) in the barrel of the roll, which is cooled in the mold, was recognized by the kinetic curves of hardening in the coordinates of x/R and τ/R^2 (Fig. 6).

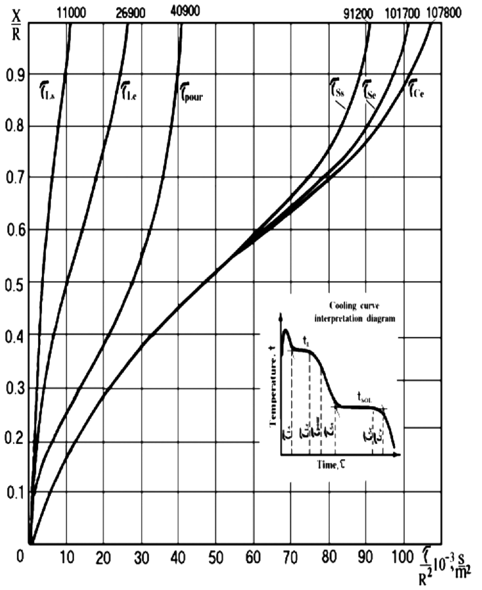


Fig. 6. Kinetic curves of hardening of cylindrical iron castings in the mold:

τ_{Ls} and τ_{Le} – the beginning and end of the temperature liquidus "pause", s; τ_{pour} – pouring boundary, s; τ_{Ss} and τ_{Se} – the beginning and end of the temperature solidus "pause", s; τ_{Ce} – the end of the crystallization of 100 % solid phase according to the scheme of estimation of the cooling curve, s; R – the radius of the cylindrical casting, m

In the necks of the roll, which are cooled in sand-clay mold, the solidification of cast iron is much slower due to the fact that its heat storage capacity of 1377 $W \cdot s^{0.5}/m^2K$ is 8 times smaller than in the chill mold 11,000 $W \cdot s^{0.5}/m^2K$. Therefore, according to the results of experimental temperature studies [14], kinetic curves were constructed (Fig. 7), which were used to calculate the layer of solidified metal in the lower and upper necks ($X_{P\text{-}B}$, $X_{P\text{-}T}$ in Fig. 5).

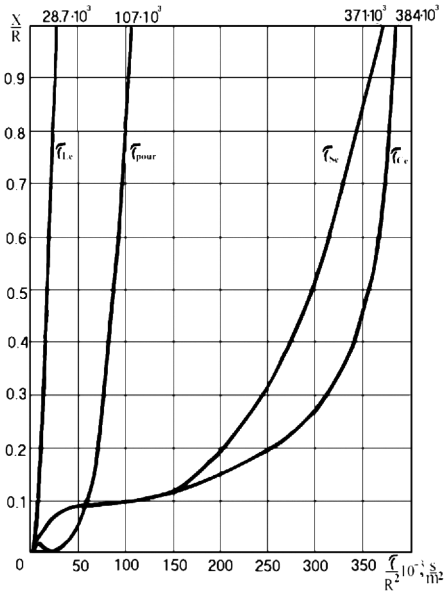


Fig. 7. Kinetic curves of hardening of cylindrical iron castings in sand-clay molds:

τ_{Le} – time of the end of the temperature liquidus "pause", s; τ_{pour} – pouring boundary, s; τ_{Se} and τ_{Ce} – time of the end of temperature "pause" of solidus and crystallization of 100 % of solid phase, s; R – radius of the cylindrical casting, m

An example of calculating the time of modification of the axial zone in the temperature range of liquidus-solidus is given for the roll SPHN-65 [8] with a barrel diameter of 320 and a height of 630 mm (Fig. 8, *a*).

According to the technical conditions, the hardness of the working layer on the barrel must be obtained of 65–75 units by Shore (466–577 HB), and the chemical composition is within, mass %: 2.7–3.8 C; 0.4–0.8 Si; 0.3–0.8 Mn; $P \leq 0.50$; $S \leq$ ≤ 0.12; 0.5–1.3 Cr; 0.8–2.5 Ni. The net weight of the roll is 980 kg, the rough weight – 1115 kg, the pouring temperature of cast iron – 1320 °C. The diameter of the lower neck, taking into account the allowances and casting slopes at the lower end is 210 mm, at the transition to the barrel – 230 mm. The diameter of the upper neck on the border with the barrel is 240 mm, and at the upper end of the feeder – 210 mm.

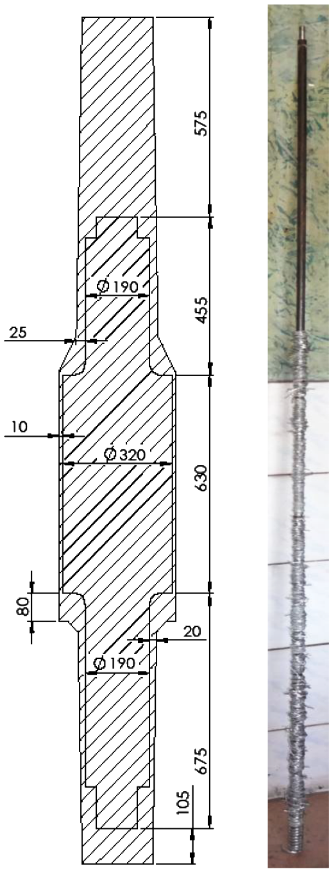
Calculation sequence is as follows:

1. In the barrel of the roll the working layer is equal to 50 mm according to the requirements of the customer, and taking into account the allowance for shrinkage and machining of 10 mm took $X_{P\text{-}C} = 60$ mm. When the radius of the barrel $R = 170$ mm, the relative size of the working layer will be

$$\frac{X_{P-C}}{R} = \frac{60}{170} = 0.353.$$

2. According to the kinetic diagram of solidification of the roll barrel (Fig. 6), from the *y*-axis ($X/R = 0.353$) a line is drawn to the intersection with the curve τ_{POUR}, and on the abscissa axis we get the value

$$\frac{\tau_{pour}}{R^2} = 17{,}785.$$



a *b*

Fig. 8. Net and rough dimensions of the milling roll (a) SPHN-65 and general view of steel reinforcement made with aluminum wire weighing 0.488 kg (b), intended for in-mold graphitizing modification of the axial liquid-solid zone

3. Thus, boundary of pouring out in the barrel will reach a thickness of 60 mm through: $\tau_{pour} = (0.17)^2 \cdot 17{,}785 = 514$ s = = 8 min 34 s.

4. The diameter of the axial liquid-solid zone (D_M) in a barrel with a height of 71 cm (Fig. 8, *a*) after the solidification of the working layer after 8 min 34 s will be: D_M = 340 mm – (60 mm · 2) = 220 mm.

5. The calculated mass of the metal in the liquid-solid zone, (m_M) that needs to be modified, with D_M = 22 cm, a height of 71 cm and a density of liquid cast iron of 6.9 g/cm^3, is $m_M \approx 186.1$ kg.

6. According to the kinetic diagram of cast iron solidification in sand-clay form (Fig. 7), the position of the pouring point was calculated for the value $\tau_{pour}/R^2 = 17{,}785$ s/m^2, which corresponds to the parametric criterion by B. B. Gulyaev for the working layer of the barrel. A perpendicular to the intersection with the τ_{pour} curve was laid up on the abscissa axis and then a horizontal curve to the intersection with the ordinate axis at $X/R = 0.01$. Then the layer of solidified metal in the lower neck ($X_{P\text{-}B}$ in Fig. 5) with an average radius $P_{P\text{-}B}$ = 110 mm will be: $X_{P\text{-}B} = 0.01 \cdot 110 = 1.1$ mm.

7. The diameter of the axial liquid-solid zone ($D_{M\text{-}B}$) in the lower neck 70 cm high, after the working layer solidified, in the barrel will be: $D_{M\text{-}B}$ = 220 mm – (1.1 mm · 2) = 217.8 mm.

8. The mass of liquid-solid metal in the lower neck after 8 min 34 s is calculated to be $m_{M\text{-}B}$ = 179.86 kg.

9. The diameter of the liquid-solid axial zone $D_{M\text{-}T}$ = = 225 mm – (1.13 mm · 2) = 222.7 mm, and the mass of metal in the upper neck ($m_{M\text{-}T}$) with a height of 45.5 cm after solidifying of the working layer of the barrel will be $m_{M\text{-}T}$ = 122.29 kg.

10. Thus, in the axial zone of the roll, the total mass (m) of liquid-solid metal that must be modified is 488.25 kg

$$m = m_M + m_{M\text{-}B} + m_{M\text{-}T}.$$

11. 0.1 % aluminum is sufficient for graphitizing modification of liquid-solid cast iron [10]. An increase in aluminum to 0.3 % leads to the appearance of gas hole in cast iron castings. Therefore, the mass of aluminum (m_{Al}), which must be introduced into the axial zone after the solidifying of the working layer in a 60-mm-thick barrel, taking into account the metal layer on the sand elements of the casting mold, will be m_{Al} = 0.488 kg.

The implementation of the developed technique was performed in the foundry during the casting of the rolling mill with a rough weight of 1115 kg (Fig. 9). Aluminum wire (scrap) was attached to the ∅14 mm steel armature, which was distributed over a height of 1760 mm (Fig. 8, *b*) and heated with a burner flame to remove moisture. After curing of the working layer in the barrel of the roll after 8 min 34 s, it was immersed in the axial zone of the casting of steel reinforcement with aluminum.

Next, the electric motor (*3* in Fig. 9) was turned on, which ensured the rotation and movement of aluminum by centrifugal forces to the crystallizing metal layer. A heat shield *5* was installed on the metal structure of the device for modification (*4* in Fig. 9), which prevented heating of the electric motor from liquid metal.

After melting the aluminum, the steel reinforcement was removed from the melt (*2* in Fig. 9) and subsequently used as a component of the charge in the production of rolling rolls.

In the developed method of calculation, the working layer was set according to the position of the pouring boundary (τ_{pour} in Figs. 6 and 7) on the experimental cooling curve, and not after the end of the temperature stop "solidus" (τ_{Se} in Figs. 6 and 7), which corresponds to crystallization ≈ 100 % solid phase. This allowed increasing the accuracy of the calculation of the working layer, as evidenced by the example of the roll SPHN-65 with a rough weight of 1115 kg. Thus, the working layer in the barrel when calculating the limit of pouring is formed in 8 minutes 34 s, and the calculation at the end of the temperature "stop" solidus – after 13 minutes, which is 1.5 times more.

Fig. 9. Modification of the axial zone of a cast-iron rolled roll weighing 1115 kg with aluminum weighing 0.488 kg using a device with an electric motor:

1 – foundry mold; 2 – steel reinforcement with aluminum; 3 – electric motor; 4 – metal structure of the device for modification; 5 – heat shield

Chill hard spots working layer was 63 mm after mechanical restoration of the rolls at the end of the barrel (Fig. 8, *a*). It is only 5 % more compared to the calculation of the pouring limit, which confirms the feasibility of the adopted method.

The implementation of the proposed technology of graphitizing modification of the axial zone in the foundry form requires minimal capital and organizational costs, and the use of parametric criterion of B. B. Gulyaev (τ/R^2 and X/R) for different sizes of cast iron rolls, allows one in the first approximation to set the curing time of the working layer in the barrel, which is cooled in the mold, and the thickness of the hardened layer of metal in the necks, cooled in the sand mixture. Therefore, the calculation of the residue of the liquid-solid zone in the center of the casting allows you to set the amount of aluminum for graphitizing modification of cast iron rolls.

The effect of the modifier is limited in time unlike alloying [15]. Therefore, it is advisable to bring the moment of modification closer to the pouring of metal into the foundry mold, which is realized in casting by the in-mold process. The modification takes place in the gating system, in which the ligature is located in a special reaction chamber with a centrifugal slag catcher. During the pouring process, the metal current melts the ligature, non-metallic inclusions float into the upper part of the reaction chamber, and the modified metal enters the casting through the feeder in the lower part of the reaction chamber. During the in-mold process, the consumption of the modifier is reduced, the pyro effect and metal boiling are excluded, and the spherical shape of graphite ensures an increase in the physical and mechanical properties of castings [11].

However, the disadvantage of this technology is an increase in unproductive consumption of metal in the reaction chamber. The method for calculating the volume and mass of the liquid and liquid-solid zone in the center of the casting suggested in the work provides the possibility of physical and mechanical influence on the metal, for example, mixing. At the same time, fragments of dendrites become centers of crystallization, which increases the quality of the macro- and microstructure. At the same time, non-metallic inclusions float into the feeder.

In addition, the implementation of the scheme shown in Fig. 5 and methods of impact on the two-phase zone will ensure deoxidation and doping of the central zones of spills in the range of crystallization temperatures. This will make it possible to obtain bimetallic products in a cast form and increase their operational properties.

Conclusions.

1. The operational properties of cast iron rolls are mainly due to the wear resistance of the working layer of the barrel and the strength of the central zones, which are affected by the compressive forces when rolling metal. The required hardness and structure of the working layer is provided by the chemical composition of cast iron and the high cooling rate of the barrel in the mold. But in the axial zone, carbides and carbide mesh are also often formed, which can lead to breakage of the roll on the mill.

2. According to the results of laboratory and research-industrial experiments performed earlier, the reduction of cementite and transcrystalline macrostructure of the axial zone of the cast iron roll provides modification of aluminum up to 0.1 %. However, the results of the research are not realized due to the lack of data on the volume of liquid metal in the axial zone of the necks and barrels of the roll at the end of hardening of the working layer, which makes it impossible to accurately calculate the required amount of modifier for different sizes.

3. A methodology has been developed for calculating the process of advancing the pouring limit in the coordinates of the relative thickness of the solidified metal layer x/R and the parametric criterion τ/R^2 for different sizes of rolling rolls in this work. This made it possible to establish the time of solidification of the working layer in the barrel, which is cooled in the mold, and the metal layer in the necks, which are cooled in the sand mixture.

4. A practical test of the development was carried out during the casting of a roll with a rough weight of 1115 kg in the conditions of a foundry. Using the modifier – aluminum into the liquid-solid zone, according to the calculation, 8 min 34 s after pouring the melt into the mold made it possible to eliminate trans crystallinity, to reduce the amount of cementite in the axial zone and to send the roll to the customer for operation at the rolling mill. After the mechanical treatment of the experimental rolls, the whitened working layer is only ≈5 % more compared to the calculation at the pour point, which confirms the feasibility of the adopted methodology.

5. The process of melting aluminum and its distribution along the height of the roll has been improved due to the rotation of aluminum by an electric motor and its movement by centrifugal forces to the crystallization front of the barrel and necks. Setting the volume of the liquid-solid zone based on the relative thickness of the solid metal layer in the barrels and necks made it possible to increase the accuracy of the beginning of the modification by ≈1.5 times compared to the calculation after the end of the solidus temperature "stop".

6. A promising direction for further development of the obtained results is the development of new methods for manufacturing iron castings due to physical and mechanical effects on the two-phase zone, deoxidation and alloying of the central zones of castings during the crystallization process in order to improve the physical, mechanical and operational properties of cast products.

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Графітизуюче модифікування осьової зони чавунних прокатних валків в інтервалі температур ліквідус-солідус

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Мета. Розробити методику розрахунку процесу графітизуючого модифікування незатверділої рідко-твердої зони для зменшення транскристалічності макроструктури й цементиту у центрі виливків.

Методика. Тривалість твердіння виливків визначали по кінетичним кривим ліквідус, солідус і виливання в координатах відносної товщини затверділого шару металу й параметричному критерію Б. Б. Гуляєва.

Результати. Розроблено процес модифікування осьової зони валків, установлена маса і час уведення алюмінію в розплав, що залишається після твердіння робочого шару. На прикладі валка масою 1115 кг уведено 0,488 кг алюмінію в рідко-тверду зону після затвердіння робочого шару в бочці. Переміщення алюмінію до фронту кристалізації забезпечене відцентровими силами обертання й розподілом алюмінію по висоті валка.

Наукова новизна. Уперше побудовані кінетичні криві ліквідус, солідус і виливання в координатах відносної товщини затверділого шару металу x/R і τ/R^2 – параметричному критерію для валкових чавунних сплавів, що охолоджуються в кокільно-піщаних формах різних розмірів. Розроблена методика розрахунку процесу модифікування алюмінієм осьової зони валків після затвердіння робочого шару в бочці, яку встановлювали по межі виливання, а кількість алюмінію – залежно від залишків рідко-твердої фази.

Практична значимість. Графітизуюче модифікування зменшує транскристалічність макроструктури й кількість цементиту в осьовій зоні виливків. Перспективним напрямом подальшого розвитку є розробка нових способів виготовлення виливків за рахунок фізико-механічного впливу на двофазну зону, розкислення й легування центральних зон виливів.

Ключові слова: *чавун, модифікування, прокатні валки, твердіння, кокільно-піщана суміш*

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