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Manufacturing Scheme of Spherical Grinding Bodies from Abrasion-Resistant Cast Iron Free of Shrinkage Defects

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Abstract

This work presents a scheme for the manufacture of spherical grinding bodies used in grinding and crushing machinery as a grinding medium from abrasion-resistant cast iron CHKH16 (according to GOST 7769-82) free of shrinkage defects produced by casting into single sand molds with a vertical joint and by usingcoolers. The grinding efficiency in terms of material destruction and energy consumption has been studied according to a wide range of operating parameters and new scheme for calculating the sprue and supply system has been developed by the authors of the article. Its functionality has been substantiated, particularly the use of a central riser acting as a head and the use of coolers. The conducted numerical simulation has shown the dependence of a solid phase formation over time, which characterizes the direction of the system crystallization and determines the locations of the shrinkage defects concentration. The manufacture of the grinding body with a 100 mm diameter using the considered technology is presented in this paper.

Keywords: Grinding bodies, Abrasion-resistant cast irons, Shrinkage defects, Casting into single sand molds

1. Introduction

Grinding bodies are used in grinding and crushing machinery as a grinding medium. The grinding efficiency in terms of material destruction and energy consumption has been studied according to a wide range of operating parameters [1]. Specifically, changes in charge fill level, lifter shape (either by design or wear) and lifter pattern are analyzed. The effects of changes of the properties of the charge (ball fraction, ball and rock shape, type of ball and rock size distributions and the lower cutoff of the rock size distribution) can all be interpreted in terms of their effects on the shear strength of the charge [2]. The efficient operation of ball mills depends on the compliance with the specified trajectories of ball loading [3] and the ability to be easily spalled and wear out quickly. The first is achieved due to the high-quality reproduction of the required geometry on each ball. The second is achieved by both reducing the number of stress raisersand using a suitable material.

The following methods for grinding balls production are currently known:

- screw rolling;
- hot forging with flash formation;
- casting method.

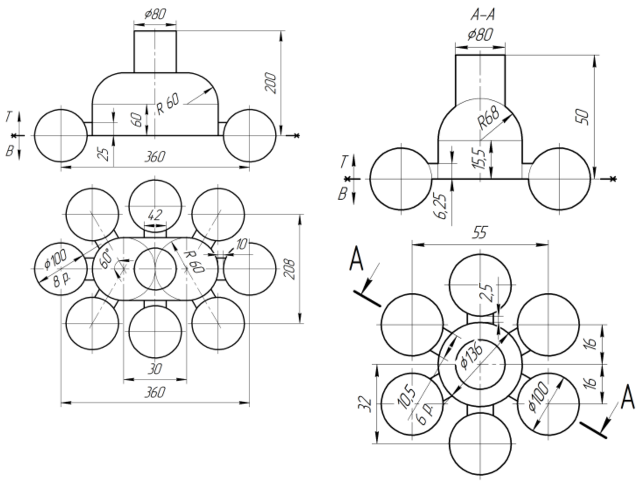
The most common method for producing balls is screw rolling. However, this method allows occurring ofan uneven strainedstructure in the balls. Moreover, it is not suitable for the production of bodies from high-chromium cast iron.

When producing the balls by hot forging, additional costs for subsequent processing occur, an uneven stressed structure arises and microcracks are formed.

The method ofchill mold casting or green sand casting provides shrinkage defects, which affect the performance properties. Moreover, a small coefficient of process yield ratio is observed.

The use of spherical grinding bodies from abrasion-resistant cast irons in the grinding and crushing machinery makes it possible to increase their useful life as a grinding medium. The manufacture of these bodies is possible only with casting since the cast iron is difficultfor machine processing and plastic deformation [5].

Modern sprue and supply systems (Fig. 1) [4] for the grinding bodies production by casting methods are mainly intended for the manufacture using gray cast iron.



a b

Fig. 1. Diagrams of sprue and supply systems for casting spherical grinding bodies into a sand mold with a horizontal joint

The use of gray iron in the manufacture of grinding bodies allows one to neglect the shrinkage of the alloy as a result of preshrinkage expansion, which occurs due to the release of lamellar graphite. Production of grinding bodies from white abrasion-resistant cast irons using sprue and supply systems leads to the formation of pores and holes inside the shrinkage of the casting body due to the high volume shrinkage of these alloys [6 – 8]. Fig. 2 schematically shows the successive formation of a solid phase in the process of casting solidification. This process leads to the formation of shrink shells when pouring in existing production diagrams of sprue and supply systems with single sand molds or permanent moldswith a vertical joint.

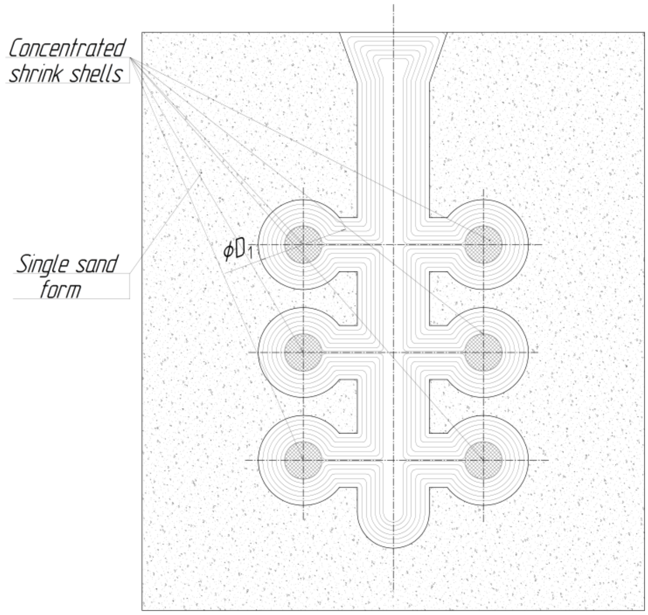


Fig. 2. Isotherms of the process of solidification of the system upon contact of the melt with the form

Fig. 3 shows the distribution of shrinkage defects for this system.

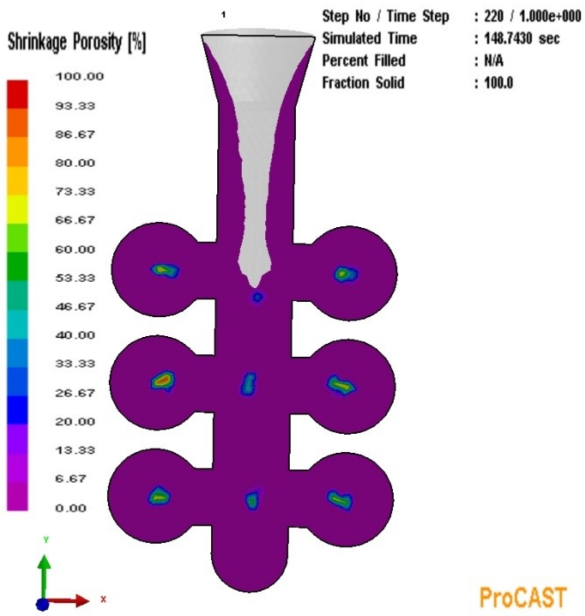


Fig.3. The result of the distribution of shrinkage defects across the section

These defects (Fig. 4) affect the total mass of the ball, and also shift the center of mass of the grinding body, thereby having a negative impact on its performance [9].

Fig. 4. Shrinkage and gas defects in castings of grinding bodies

Fig. 5 presents a diagram of parameters affecting the formation of shrinkage defects.

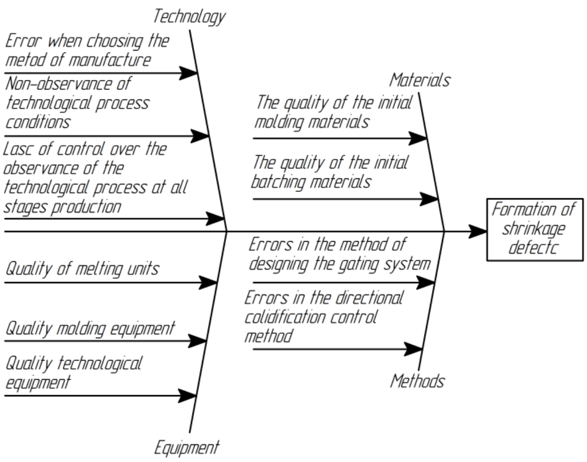


Fig. 5. Diagram of parameters affecting the formation of shrinkage defects

2. Research problem description. Sprue and supply system design method

The purpose of the work is the development of manufacturing technology for casting spherical grinding bodies from abrasion-resistant cast iron CHKH16 without shrinkage defects into single sand molds.

The object of the study is agrinding ball with a diameter of 100 mm, produced by the castingof high-alloyed iron CHKH16 into single sand molds. The CHKH16 chemical composition percentage in the alloy according to GOST 7769-82 is given in Table 1.

Table 1.
The chemical composition of alloy CHKH16 according to GOST 7769-82, %.

C	Si	Mn	S	P	Cr
1.6−2.4	1.5−2.2	up to 1	up to 0.05	up to 0.1	13−19

In the process of developing the manufacturing technology, a new scheme for calculating sprue and supply systemaimed to obtain spherical grinding bodies without shrinkage defects was created. Thermal processes of solidification using the ProCAST software were considered.

A new scheme for producing grinding bodies without shrinkage defects by casting intoa single sand mold is proposed and is shown in Fig. 6.

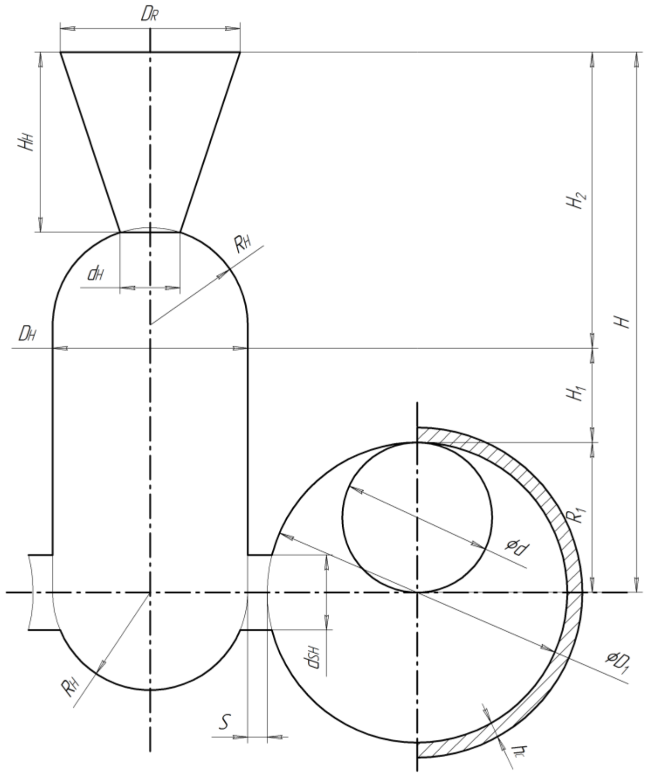


Fig. 6. Sprue and supply system: D_R − upper diameter of the riser; H_H − height of the hood; d_H − bottom diameter of the hood; D_1 − diameter of the ball; D_H− diameter of the head; R_H− radius of the head; d_1 − diameter of the inscribed circle in the thermal node; d_{SH} − diameter of the supply hole; S− supplier length; H_1− head height, compensating for the shrinkage of the thermal unit of the cast section; H_2 − height of head, compensating for shrinkage of head, compensating, in turn, for shrinkage of the cast section; H − total system height; h_C − thickness of the cooler.

According to the presented scheme, the production of the grinding body without shrinkage defects is provided by installing a segmented outdoor cooler into the mold, which affects the solidification parameters in such a way that the entire system hardens sequentially: first the ball hardens, then the supply hole and then the raiser acting as a head.

The key part of the work is the determination of the parameters of the used cooler, which is carried out on the basis of the compiled thermal balance equation (1) [10], which determines the mass of the cooler G_c. Then, using the mass of the cooler and the density of the alloy of the cooler determine the cooler volumeV_c. Using the cooling area of the ball Fch determine the thickness of the cooler h_c.

$$c_1 \cdot G_{sn} \cdot \left(T_{av} + T_{liq}\right) + L_{lat} \cdot G_{sn} = c_c \cdot G_c \cdot \left(T_{sol} + T_{ic}\right) \qquad (1)$$

where c_1 – specific heat of the alloy, $c_1 = 450 \,{}^{J}/_{kg} \cdot$ °C;
G_{sn} – mass of the supplied node.
T_{av} – average temperature of the melt during casting, °C:

$$T_{av} = \frac{T_{cast} + T_{liq}}{2}, \text{°C} \qquad (2)$$

where T_{cast} – temperature of the melt when casting forms, $T_{cast} = 1400$ °C;
T_{liq} – liquidus temperature,$T_{liq} = 1336$ °C;
L_{lat} – latent heat of solidification, J/kg:

$$L_{lat} = L_1 + k \cdot c_1 \cdot \left(T_{liq} - T_{zc}\right), J/kg \qquad (3)$$

where L_1 – specific heat of crystallization, $L_1 = 268 \cdot 10^3 \, J/kg$;
k – coefficient for the ball, $k = 3/4$;
T_{zc} – temperature of zero castability, °C:

$$T_{zc} = T_{liq} - T_{\Delta c}, \text{°C} \qquad (4)$$

$$T_{\Delta c} = \frac{\Delta T \cdot 80}{100}, \text{°C} \qquad (5)$$

with 80-80% of the solid phase.

$$\Delta T = T_{liq} - T_{sol}, \text{°C} \qquad (6)$$

where T_{sol} – solidus temperature,$T_{sol} = 1112$ °C.;
c_c – specific heat of the alloy of the cooler, $c_c = 560 \,{}^{J}/_{kg} \cdot$ °C;
G_c – mass of the cooler, kg;
T_{ic} – initial temperature of the cooler, $T_{ic} = 20$ °C.;.

$$V_c = \frac{G_c}{\rho_c}, m^3 \qquad (7)$$

whereρ_c – density of the cooler material, $\rho_c = 7200 \, kg/m^3$.

$$F_{chc} = \frac{1}{2} F_{ch}, m^2 \qquad (8)$$

$$F_{ch} = \pi \cdot {D_1}^2, m^2 \qquad (9)$$

$$h_c = \frac{Vc}{F_{chc}}, mm \qquad (10)$$

According to the results of calculations, a 3-D model of a cooler with 10 mm thick wall was built, which is shown in Fig. 7.

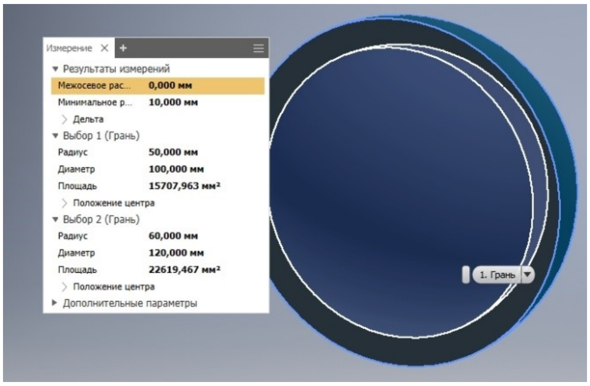


Fig. 7. A 3-D model of gray cast iron cooler with a wall thickness of 10 mm

3. Modeling the system solidification process

The next step is a numerical simulation of the solidification process of the entire system in the ProCAST software package for estimating the entire system and identifying possible sites of shrinkage defects.

The simulation of the solidification of the entire system was carried out with the following initial and boundary conditions: temperature of the poured metal t_{pour} = 1400°C; form temperature t_f = 20°C; cooler temperature t_c = 20°C; heat transfer coefficient at the "casting-form" border $h_{c\text{-}f}$ = 300 W/m^2·K; heat transfer coefficient on the border "casting-cooler" $h_{c\text{-}c}$ = 3000 W/m^2·K; heat transfer coefficient at the "cooler-form" border $h_{c\text{-}f}$ = 300 W/m^2·K; air cooling system parameter at 20°C; pouring speed v_{pour}=0.6 m/s. The thermophysical parameters of the pouring metal were generated by the internal module of the ProCAST based on the chemical composition of the alloy according to the Scheil model. The thermophysical parameters of the material of the mold are taken as "single sand mold" (silica sand), the thermophysical parameters of the cooler material are taken as "cast iron", in accordance with the material base of ProCAST software.

4. Simulation results of the system solidification

The simulation showed that the use of the cooler provided directional solidification: the ball began to harden before the head-riser. The supplier freezes when the ball is solidified. The time dependence of the formation of a solid phase is shown in Fig. 8.

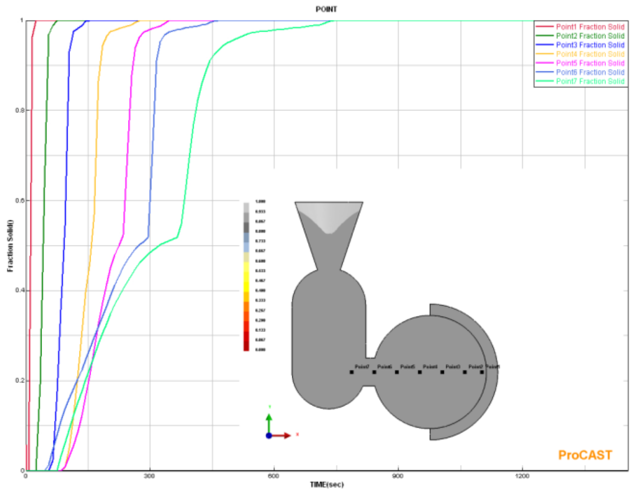


Fig. 8. The dependence of the formation of a solid phase in the body casting time

Also, according to the simulation results, no shrinkage defects were detected directly in the casting body (Fig. 9).

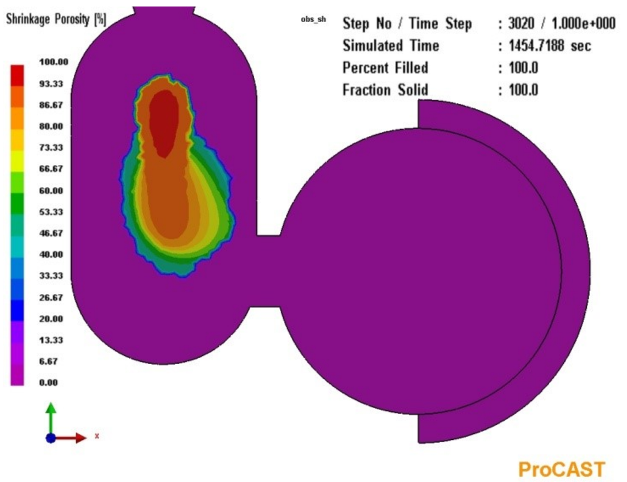


Fig. 9. Porosity distribution in casting over the section

5. A full-scale experiment inproducing a spherical grinding body according to the given scheme

The next step was a full-scale experiment,which resultedin the production of a casting mold according to a givena sprue and supply system. Then the metal was formedinto a single sand mold with a vertical connector, melted and poured, with the finalknockout and clearance.

The melt of high-alloyed iron CHKH16 was made in an induction RELTEC furnace UIP-16-10-0, 01-UKHL14 of the company RELTEC in an alumina crucible. Melting weight was 12 kg.

The burden materials used and their content in the burden obtained during the calculation are presented in Table 2.

Table 2.
Burden materials

Burden material	Material chemical content						Material content in the burden, %
	Key elements, %				Residual elements, % (not more than)		
	C	Si	Mn	Cr	S	P	
Pig iron Pl1 GOST 805-95	4.2	1	0.8	-	0.3	0.08	51
Melting steel St3sp GOST 380-94	0.18	0.2	0.95	0.03	0.04	0.03	28
Ferrochrome FeCr 80C01GOST 4757-91	0.015	1.5	-	80	0.053	0.052	21
Ferrosilicium FeSi 75 GOST 1415-93	0.1	77	0.4	0.3	0.02	0.04	1.6(over 100%)
Ferromanganese FeMn 90GOST 4755-91	0.05	1.8	90	-	0.02	0.05	1.1(over 100%)

The start-up of the furnace was carried out using a starting block of the required chemical composition weighing 1.5 kg. The blank was placed into a melting pot and melted. Afterwards, burden materials were loaded onto the liquid-metal surface and the furnace was turned off. Ferroalloys were poured after complete melting of the main mixture components. The metal in the furnace was overheated to a temperature of 1380°C, upon reaching this temperature, the furnace was turned off and samples were taken for chemical composition. With the furnace turned off, the metal was held for 15 minutes.

After that, the temperature of the melt was raised to 1400°C and the mold was cast. The temperature of the melt was controlled by an immersion thermocouple.

The molding mixture composition used is given in Table3.

Table 3.
The molding mixture composition.

Components	%
Silica sand $2K_3O_2O_2$	87
Bentonite $C3T_2$	13
Humidity	6-7

6. Results of the full-scale experiment

The conducted experiment resulted in the production of a grinding body from high-alloyed cast iron CHKH16 free from shrinkage defects.The macro section of the grinding body obtained is shown in Fig. 10.

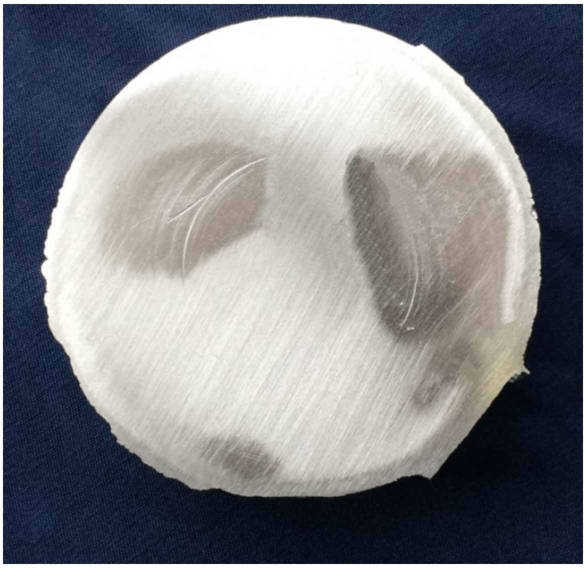


Fig. 10. Macro section of the resulting grinding body

7. Conclusions

The developed scheme of the system provides the conditionsfor directional solidification. Due to the application of the cooler, the accelerated hardening of the grinding body is achieved to the supply hole being completely frozen.

During the simulation, the dependence of the formation of a solid phase in the casting body over time was obtained and the place of formation of shrinkage defects in the system was determined.

A full-scale experiment of producing a grinding body confirmed the results of calculations and simulations.

This manufacturing scheme allows producing spherical grinding bodies from abrasion-resistant white cast iron in the single sand mold without shrinkage defects.

The use of this production scheme makes it possible to manufacture grinding bodies with a material utilization factor of 76%, while the existing systems have a material utilization factor the doesn't exist 55%, which, in turn, affects economic performance.

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