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CASTING OF ALLOYED CAST IRON IN SAND-CLAY MOLDS.

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Annotation: This article focuses on producing high-quality castings from alloyed cast iron using sand-clay molds. It provides details regarding the laminar and turbulent flow of molten metal during the casting process. The paper emphasizes the importance of correctly selecting the alloy composition, flowability, mold filling behavior, furnace type, and casting system to achieve optimal casting quality.

Keywords: chromium, manganese, molybdenum, casting system, alloyed, riser, sand-clay, mold, feeder, pouring basin, laminar, turbulent, ladle.

Currently, one of the key challenges in manufacturing and processing industries is the reliable supply of various parts produced through high-quality casting methods. Achieving such casting quality requires not only high-standard molds, but also careful control over several critical factors: the temperature and type of furnace used to melt the alloy, proper selection of the casting system and pouring temperature of the molten alloy [1], as well as consideration of the alloy's flowability, mold-filling capability, and the geometric shape and dimensions of the desired casting.

According to statistical data collected by professors of the "Foundry Technologies" department, many components currently used in abrasive operational conditions at mining-metallurgical, chemical machinery manufacturing, and other similar enterprises are increasingly being produced from alloyed cast iron using casting methods. In such applications, cast iron grades like ChX16, ChX16M2, ChX22, ChX22S, ChX28D2, ChX32, ICh290Kh12M, 280Kh29NL, and similar compositions are commonly utilized.

As specified in GOST 7769-82 standards, alloyed cast iron compositions are marked with the letter "Ch," followed by symbols denoting alloying elements: Kh – chromium, S – silicon, G – manganese, N – nickel, D – copper, M – molybdenum, T – titanium, P – phosphorus, and Yu – aluminum. These alloyed cast irons are predominantly used in the production of components operating under highly aggressive environments and conditions

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with severe abrasive wear [2, 3]. As a result, there is a growing interest in such materials across Uzbekistan's manufacturing and processing industries [4].

Although alloyed cast irons possess high operational properties, achieving high-quality cast components from them remains a process that continues to improve. This is largely due to the influence of alloying elements—particularly chromium—on the casting characteristics of the iron. The foundry behavior of alloyed cast iron improves in proportion to the chromium content [5, 6].

In addition, the wear resistance of alloyed cast iron is highly sensitive to the formation of its microstructure. Therefore, when producing castings from alloyed cast iron, it is essential not only to ensure the overall quality of the casting but also to form a microstructure that guarantees the material's resistance to wear [7].

The wear resistance of cast iron is primarily ensured by the formation of carbides with the structure $(Cr, Fe, Mn)_7C_3$. This is because such carbides are approximately 1.5 to 2 times harder than cementite carbides [8]. One of the associated challenges, however, is that for these $(Cr, Fe, Mn)_7C_3$ carbides to form effectively, the cast iron must contain about 3% carbon, and the chromium content must fall within a relatively high range—between 12% and 27%.

When studying the foundry properties of white cast iron, the optimal composition of carbon and chromium content within the alloy was identified. Specifically, carbon should be within the range of 1.53–4.15%, and chromium should range from 12.84–31.5%. In addition, other alloying elements should be maintained within the following intervals: molybdenum (Mo) – 1.4–1.6%, silicon (Si) – 0.4–0.7%, and manganese (Mn) – 0.4–0.7%, as indicated in Table 1 [9, 10].

During the casting process, the alloy is heated to a temperature approximately 100 °C above its melting point, typically reaching up to 1500 °C.

Figure 1 illustrates the effect of increasing carbon content on the fluidity of high-chromium cast iron. As the carbon percentage rises, notable changes in the alloy's flow characteristics can be observed.

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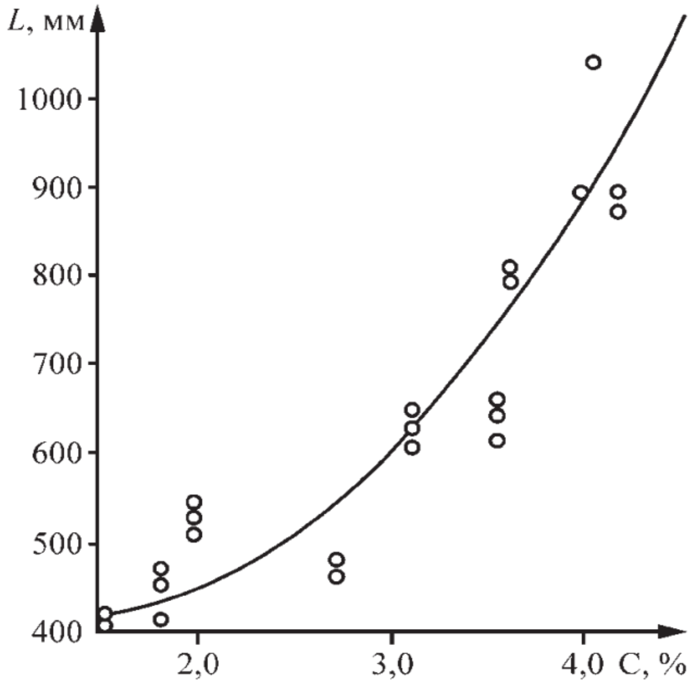

Figure 1. Effect of carbon content on the fluidity of chromium cast iron containing 12–14% Cr.

Table 1.
Effect of Carbon (C) and Chromium (Cr) Content on the Foundry Properties of High-Chromium Cast Iron [11]

Content (%)		**Temperature, °C**				
C	Cr	**Liquidus**	**Solidus**	**Pouring temperature**	**Linear penetration (%)**	**Fluidity, mm**
1,53	12,6	1410	-	1490-1500	-	415,410
1,53	13,0		-		2,18	-
1,8	12,2	-	-	1440-1460	1,91	470, 460, 420
2,19	13,5	1335	1220		-	-
1,96	13,1	1370	-		1,8	550, 530, 520
1,98	13,6	1340	-		-	-
3,02	12,84	1265	1220	1370-1380	-	-
3,03	13,2	1285	1220		-	-

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3,10	13,7	1280	-		1,74	650, 640, 610
3,6	13,0	1210,	1210		-	-
3,55	12,9	-	-	1310-1330	-	660, 650, 610
3,57	14,2	1230	-		1,64	820, 800
3,67	13,5	1225	-		-	-
3,94	12,1	1230	-		-	1050, 900
4,15	13,8	-	-	1320-1330	1,78	880, 900
4,0	12,3	1220	1180		-	-
2,86	18,1	1280	-		-	765, 610
2,78	18,8	1290	1230	1390-1400	-	-
2,84	17,9	1275	1250		-	-
2,85	16,4	-	-		2,13	520, 500
2,72	24,5	1280	-		1,99	850, 700
2,79	23,8	1280	-	1380-1400	2,0	-
2,84	24,3	-	-		1,98	930, 900, 850
2,80	29,3	1300	-		-	1100, 1000
2,84	31,5	1260	1260	1390-1400	2,12	-
2,92	29,0	-	-		2,08	1000, 1020, 1050

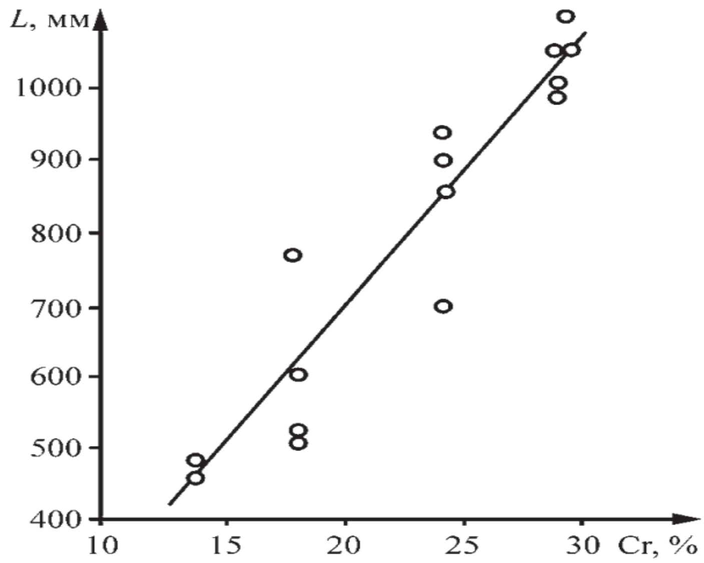

Figure 2. Effect of varying chromium content on the fluidity when carbon content is within 2.8–3.2%.

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As seen in Figure 2, an increase in chromium content leads to improved fluidity of cast iron. When the chromium content ranges between 18% and 30%, it does not negatively affect the mold penetration characteristics in practical casting applications [12–15]. In this alloy system, increasing both carbon and chromium content results in enhanced fluidity and thermal resistance.

Important Properties of Gating Systems

One of the simplest gating systems is the **side gating system**. In this method, molten metal is poured into the pouring basin located on the side of the mold. This technique is commonly used for producing small to medium-sized castings [16–18]. A notable advantage of this system is that the volume of additional metal required in the feeders is significantly reduced, which makes it more material-efficient. Furthermore, it ensures rapid filling of the mold cavity and promotes even temperature distribution, both of which are critical for achieving high-quality castings.

However, in many cases, a separate **metal pouring basin system** is used. In such systems, the mold cavity is filled with molten metal through feeders. The main characteristics of a typical gating system are illustrated in Figure 4. The molten metal is first poured into the pouring basin, from where it flows downward through a vertically positioned conical sprue. Then, it passes through the runner and gradually fills the sand-clay mold cavity via feeders.

Depending on the shape and volume of the casting, one or more feeders may be incorporated to ensure proper mold filling [19]. In addition to these core functions, the gating system often includes non-metallic components that assist in regulating flow and preventing defects during casting.

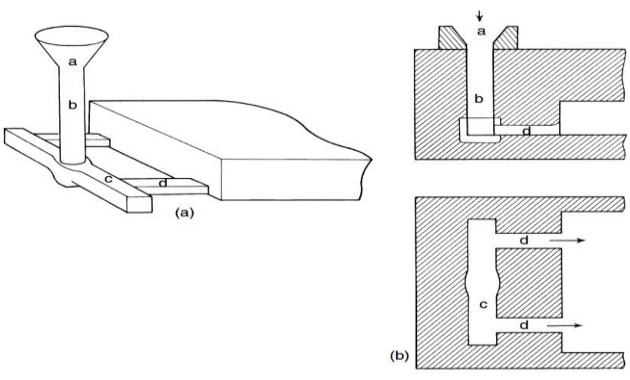

Figure 3. Main Features of the Gating System
a) Pouring basin b) Sprue c) Runner d) Feeders

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Before evaluating a gating system, it is essential to consider the overall flow behavior of molten metal within the mold cavity. One of the key concerns in casting is **mold erosion**, which primarily occurs due to the **turbulent movement** of molten metal during the pouring process. This type of flow is significantly different from **laminar (smooth)** flow.

In turbulent flow, although the primary mass of molten metal moves in a general direction, it experiences multiple fluctuations and velocity variations in various directions. As a result, the flow becomes unstable and can cause increased wear on the mold surfaces. The nature and speed of this flow depend on both the physical properties of the molten metal and the geometry of the mold.

Importantly, laminar flow can transition into turbulent flow once it exceeds a specific **critical velocity**, which is determined by the material characteristics and mold dimensions. The **Reynolds number** is commonly used to define the flow regime—whether it remains laminar or becomes turbulent [20].

$$(Re) = \frac{Vd}{v} \qquad (1)$$

In this context:

- **V** = average flow velocity
- **d** = characteristic dimension of the mold channel
- **ν (v)** = kinematic viscosity of the molten metal

Turbulent flow is typically associated with higher **Reynolds numbers (Re)**, which in turn are influenced by increased flow velocity, larger flow channels, and, conversely, lower flow velocities in confined spaces. The **Re** value is largely dependent on the geometry of the system and generally ranges between **2000 and 4000**, although turbulent flow may occur at lower values under certain conditions.

Even slight changes in mold cavity geometry, such as bends, dimensional transitions, or variations in flow direction, can disrupt the smooth movement of molten metal and result in localized turbulence. In such scenarios, Reynolds numbers tend to be lower, yet turbulence may still arise due to these flow disturbances.

In many casting processes, the dimensions of the gating system are critical. When minimum flow velocities are not maintained, turbulent motion is likely to occur. Therefore, the **primary function of the gating system** is to ensure complete and consistent filling of the mold cavity by molten metal at an optimal temperature. If the number and placement of **feeders** (risers) are sufficient to uniformly distribute the metal, the gating system can be considered **ideal** in terms of casting performance.

Designing of Gating Systems

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Numerous modern studies on gating system design indicate that the process must consider two fundamental principles of fluid dynamics. The first of these is the continuity equation, which states that the flow rate of a fluid remains constant throughout the system. It is mathematically expressed as:

$Q = A \times V$

where:

- Q = flow rate (volume per unit time),
- A = cross-sectional area of the flow channel,
- V = velocity of the fluid (molten metal).

This principle ensures that the amount of molten metal entering and exiting each section of the gating system remains consistent, allowing for uniform mold filling. Proper application of the continuity equation is essential for maintaining laminar flow and avoiding turbulence, metal splashing, or mold erosion during casting.

$$Q=A_1V_1 = A_2V_2 \quad (2)$$

Here:

- **Q** = flow rate (volume per unit time)
- **A** = cross-sectional area of the flow
- **V** = linear velocity of the flow

According to **Bernoulli's equation**, the linear velocity of the flow within the system is also related to other factors, assuming the specific weight of the fluid remains constant throughout the system. Bernoulli's principle is expressed as:

$$P + \frac{1}{2}\varrho V^2 + \varrho gh = \text{constant}$$

where:

- **P** = pressure energy
- **ϱ** = fluid density
- **V** = linear velocity
- **g** = acceleration due to gravity
- **h** = elevation head (height)

This equation illustrates the conservation of energy within a flowing fluid and shows the relationship between pressure, velocity, and elevation. In casting processes, applying Bernoulli's equation allows for a more accurate design of gating systems by predicting the

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flow behavior of molten metal, helping to minimize turbulence and ensure smooth, controlled mold filling.

$$\frac{V_1^2}{2g} + h_1 + \frac{P_1}{\rho} = \frac{V_2^2}{2g} + h_2 + \frac{P_2}{\rho} \quad (3)$$

Here:

- **V** = linear velocity of the flow
- **h** = height (elevation)
- **P** = pressure
- **ϱ** = density

The terms in Bernoulli's equation respectively represent **kinetic**, **potential**, and **pressure** energy. Based on this principle, it is essential to consider energy losses due to **friction**, **sudden directional changes**, and **abrupt cross-sectional transitions** within the flow path when calculating fluid motion. These disruptions can lead to deviations from ideal flow behavior.

To correct such deviations, **experimentally determined loss coefficients** must be incorporated into calculations. Research shows that although these losses may seem negligible at first glance, they can significantly impact flow behavior and should not be ignored [21].

These principles are especially useful when calculating flow velocity in specific sections of a gating system. As molten metal descends from the initial pouring basin, it encounters **resistance**, which causes a reduction in the linear velocity of the flow at the lower parts of the gating channel. In such cases, **atmospheric pressure** can be treated as potential energy, while the remaining flow behavior can be analyzed in terms of **kinetic energy** at different points in the system.

Thus, flow dynamics in gating systems can be described using Bernoulli's equation as presented in formula (3), allowing for more accurate modeling and optimization of molten metal movement.

$$h = \frac{V^2}{2g} \quad (4)$$

Thus, the velocity of molten metal flowing from an initial height can be expressed as **$V = (2gh)^{1/2}$**, indicating that the flow velocity depends directly on the vertical distance from the starting point.

To ensure the production of high-quality castings, it is crucial to consider the **fluidity** of the cast iron. While **gray cast iron** is known for its high fluidity, the **chromium content** in its

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composition significantly affects this property. As the chromium level increases, it can alter the metal's ability to fill mold cavities effectively.

Therefore, to achieve the desired casting quality when working with such alloys, it is recommended to use a **side gating system** in **sand-clay molds**, as this configuration supports smoother metal flow and helps maintain optimal temperature and fill characteristics during casting.

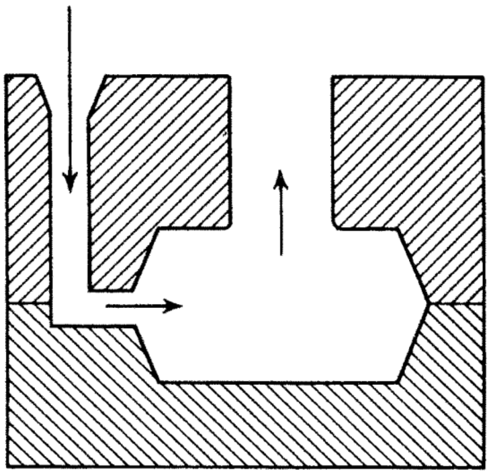

Figure 4. Side Gating System

The main purpose of selecting a **side gating system** is to ensure uniform filling of the mold cavity and to achieve effective **feeding** of the casting, especially in areas prone to shrinkage. This system enables improved **metal delivery** into the feeders, which in turn helps reduce **excess metal consumption**.

Moreover, for producing **large castings**, it is recommended to use **multi-branch feeder systems**, as they provide better metal distribution and support directional solidification, thereby minimizing casting defects and improving overall quality [22].

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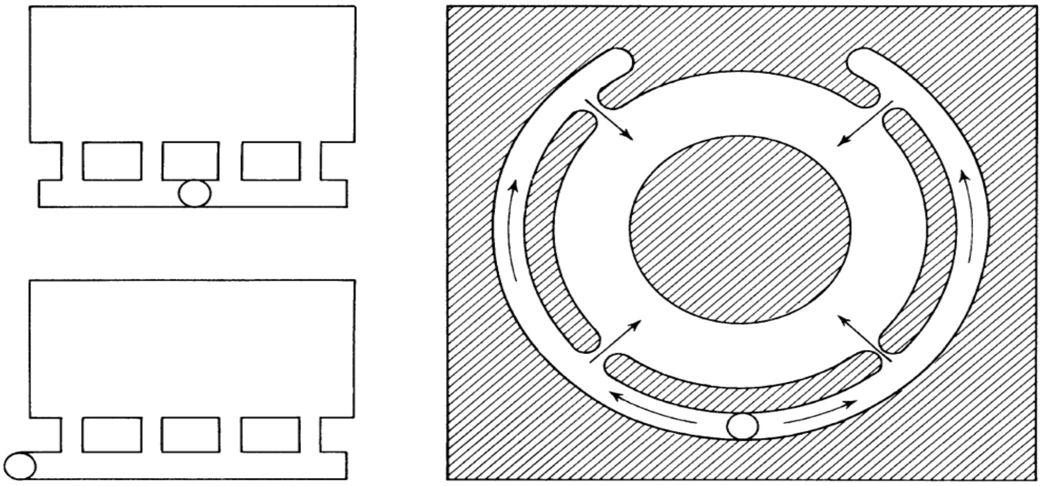

Figure 6. Multi-Branch Gating System

The reason for this is that the molten metal must fill the mold cavity effectively within a short period of time. To achieve this, it is advisable to utilize a **multi-branch feeder gating system**. This type of system ensures fast and uniform metal distribution throughout the mold, minimizing the risk of defects such as cold shuts or incomplete filling. By implementing this approach, it becomes possible to obtain the desired **high-quality casting**, even in complex or large-scale components. The multi-branch configuration not only enhances filling efficiency but also supports better temperature control and directional solidification.

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