

Improving Surface Wear Resistance of Gray Cast Iron via Casting Integrated Alloying

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In this study, we explore an innovative approach to enhance the surface properties of gray cast iron, a material widely used in industrial applications due to its excellent castability and damping capacity, but often limited by poor wear resistance in abrasive environments. The method, known as casting integrated with surface alloying, involves applying alloying powders to the mold surface before casting, allowing the molten metal to dissolve and fuse with these powders during solidification, thereby forming a thick, wear-resistant layer on the cast component. This technique offers a cost-effective and efficient means to achieve deep surface alloying, potentially extending the service life of components in sectors such as mining, agriculture, and transportation machinery. Our focus is on gray cast iron, a ferrous alloy characterized by its graphite flake structure, which provides good machinability but compromises hardness and wear resistance. By incorporating elements like molybdenum (Mo), tungsten (W), and copper (Cu) through this process, we aim to significantly improve the surface hardness and 耐磨性 of gray cast iron, addressing the need for enhanced durability in wear-prone parts.

The fundamental principle behind casting integrated alloying lies in the rapid diffusion and alloying that occur in the 液态 metal state. Unlike conventional surface treatments such as chemical heat treatment or coating, which rely on solid-state diffusion and often result in thin layers (typically 0.02–0.08 mm), this method leverages the high diffusion coefficients in liquids, on the order of $10^{-5} \text{ cm}^2/\text{s}$, compared to $10^{-8} \text{ cm}^2/\text{s}$ in solids. This allows for deeper penetration of alloying elements, forming a composite surface layer that is integrally bonded to the gray cast iron substrate. The process can be summarized by Fick's first law of diffusion, where the flux J of alloying atoms is given by:

$$J = -D \frac{\partial c}{\partial x}$$

Here, D is the diffusion coefficient, c is the concentration of the alloying element, and x is the distance from the surface. During casting, the high temperature and 液态 state maximize D , enabling substantial alloy uptake. In our work, we further enhance this by post-casting heat treatment, which promotes additional diffusion into the gray cast iron matrix, increasing the effective alloyed layer thickness.

To illustrate the microstructure of standard gray cast iron, which serves as our base material, consider the following image that shows its typical graphite flakes in a ferritic or pearlitic matrix. This structure is key to understanding the need for surface modification:



Our experimental methodology began with the selection of gray cast iron as the base material, specifically HT200 grade, with a composition as detailed in Table 1. This grade of gray cast iron is commonly used in engineering applications due to its balanced properties. For the alloying agents, we chose Mo, W, and Cu powders, based on their ability to form hard carbides and solid-solution strengthen the iron matrix. The 铸渗剂 (casting infiltration agent) was prepared by mixing these powders with a binder and flux to ensure proper adhesion and protection during casting.

Table 1: Chemical Composition of Base Gray Cast Iron (HT200) and Alloying Powders

Material	Element	Content (wt.%)	Remarks
Gray Cast Iron (HT200)	C	3.4	Balance Fe; typical flake graphite structure
	Si	2.2	
	Mn	0.6	
	S	<0.10	

Material	Element	Content (wt.%)	Remarks
Alloying Powders	P	<0.15	Mixed in ratio for 铸渗剂; 200 mesh size
	W	45	
	Mo	45	
	Cu	10	

The 铸渗剂 formulation involved several steps to optimize performance. We used powders of 200-mesh fineness to balance between adhesion and minimal 烧损. A binder, such as 合脂油, was added to improve wetting between the 液态 gray cast iron and the alloy paste, while a small amount of borax (2%) served as a flux to prevent oxidation. The paste was applied uniformly to the mold cavity wall at a thickness of 1.5 mm, then dried at 200–230°C for 4 hours to remove moisture. The [casting process](#) employed a sand mold with bottom gating to avoid 冲刷 of the alloy layer, and the pouring temperature was set at 1335°C to ensure proper fluidity of the gray cast iron melt.

We prepared three sets of specimens to evaluate the effects of casting integrated alloying and subsequent heat treatment on gray cast iron, as outlined in Table 2. This systematic approach allowed us to compare the microstructural evolution, hardness, and wear resistance across different conditions.

Table 2: Experimental Groups for Gray Cast Iron Specimens

Group	Treatment Process	Objective
1	Casting with alloy paste, as-cast condition	Assess initial alloying layer without diffusion
2	Casting with alloy paste, followed by heat treatment at 960°C for 2 hours and air cooling	Evaluate effect of diffusion on layer thickness
3	Casting without alloy paste (plain gray cast iron)	Baseline for comparison

After casting, we conducted metallographic analysis to examine the alloyed layers. For Group 1 specimens, the gray cast iron surface showed a distinct alloyed zone of approximately 1.5 mm thickness, comprising a hardened layer (0.8–1.0 mm) and a diffusion layer (0.4–0.6 mm). The microstructure revealed significant changes: the presence of W and Mo, both strong carbide formers, led to the precipitation of alloy carbides such as $(Fe,W)_6C$, $(Fe,W)_{23}C_6$, and Mo_2C , which caused partial whitening of the matrix. This reduced the graphite flake content in the gray cast iron surface, with remaining flakes becoming shorter and straighter. In contrast, the core of these specimens retained the typical gray cast iron structure of pearlite, ferrite, and 片状 graphite.

Group 2 specimens, subjected to post-casting heat treatment, exhibited a much thicker alloyed layer. The hardened surface layer extended to about 3 mm, characterized by a hypereutectic white iron structure with primary carbide dendrites and ledeburite. The diffusion layer reached 4 mm, where alloy

carbide precipitation was less dense. The core of these gray cast iron samples showed coarser graphite flakes and larger grains due to grain growth during the high-temperature holding, compared to the as-cast Group 1 core. This demonstrates how heat treatment can further enhance the alloy penetration in gray cast iron, effectively increasing the functional depth of the wear-resistant surface.

To quantify the mechanical improvements, we performed **显微硬度** measurements using a HX-1000 tester. The results, presented in Table 3, highlight the substantial hardness gradient induced by the alloying process in gray cast iron. The hardened layer in Group 2 showed an average hardness over three times that of the plain gray cast iron core, while the diffusion layer was about twice as hard. This enhancement is directly attributable to the dispersion of hard carbides and the reduction of graphite, which typically softens gray cast iron.

Table 3: Microhardness (HV) Results for Gray Cast Iron Specimens

Group	Region	Measurement 1	Measurement 2	Measurement 3	Average	Hardness Increase vs. Core
Group 2 (Alloyed + Heat Treated)	Hardened Layer	752	724	747	741.0	~3.8x
	Diffusion Layer	434	466	448	449.3	~2.3x
	Core	196	202	186	194.7	Baseline
Group 3 (Plain Gray Cast Iron)	Surface Region	218	204	213	211.7	~1.1x
	Mid-Region	197	204	202	201.0	~1.0x
	Core	196	201	198	198.3	Baseline

Wear resistance was evaluated using a SKODA-SAVIN rapid wear tester under controlled conditions: a rotation speed of 675 rpm, a normal load of 150 N, a **硬质合金** wheel with radius 15 mm and width 2.5 mm, and a total of 6000 revolutions. The wear volume was calculated from the **磨痕** length, and the results are summarized in Table 4. Group 2 specimens, with the alloyed and heat-treated gray cast iron surface, exhibited a wear volume nearly 50% lower than that of plain gray cast iron (Group 3), indicating a doubling of wear resistance. This confirms that casting integrated alloying can dramatically improve the durability of gray cast iron in abrasive scenarios.

Table 4: Wear Test Results for Gray Cast Iron Specimens

Group	Wear Scar Length (arb. units)	Average Length	Wear Volume ($\times 10^3 \text{ mm}^3$)	Relative Wear Resistance

Group	Wear Scar Length (arb. units)	Average Length	Wear Volume ($\times 10^3 \text{ mm}^3$)	Relative Wear Resistance
Group 1 (As-cast alloyed)	627, 624, 619	623.33	78.394	1.88x
Group 2 (Alloyed + heat treated)	631, 616, 620	622.33	78.207	1.89x
Group 3 (Plain gray cast iron)	801, 794, 807	800.67	147.243	1.00x (baseline)

The role of individual alloying elements in modifying gray cast iron is critical to understanding the observed enhancements. Molybdenum (Mo) acts as a石墨化 inhibitor and a potent carbide former, refining the microstructure and increasing strength. Tungsten (W) primarily dissolves in cementite to form stable carbides, improving the morphology and distribution of hard phases, which boosts wear resistance. Copper (Cu), while not a strong carbide former, provides solid-solution strengthening and grain refinement, counteracting excessive grain growth during heat treatment and maintaining toughness in the alloyed gray cast iron. The combined effect of these elements can be modeled using a rule-of-mixtures approach for hardness, where the composite hardness H_c of the alloyed layer is given by:

$$H_c = f_m H_m + f_c H_c$$

Here, f_m and f_c are the volume fractions of the metal matrix and carbides, respectively, and H_m and H_c are their respective hardness values. In gray cast iron, the matrix hardness is typically low due to graphite, but the introduction of carbides via alloying increases f_c and H_c , leading to overall hardness elevation.

The depth of the alloyed layer in gray cast iron is influenced by several factors, including powder粒度, binder type, pouring temperature, and diffusion conditions. We derived an empirical relationship for the effective layer thickness L based on our experiments:

$$L = L_0 + \alpha \sqrt{Dt}$$

where L_0 is the initial thickness from casting (about 1.5 mm in our case), D is the effective diffusion coefficient during heat treatment, t is the diffusion time, and α is a material constant dependent on gray cast iron composition. For Group 2, with $t = 7200$ s at 960°C , L increased to 6 mm, demonstrating the synergistic effect of liquid-state alloying followed by solid-state diffusion. This two-stage process offers a significant advantage over conventional methods for surface hardening of gray cast iron.

To further analyze the wear mechanisms, we consider the Archard wear equation, which relates wear volume V to load F , sliding distance S , and material hardness H :

$$V = k \frac{FS}{H}$$

Here, k is a wear coefficient. For alloyed gray cast iron, the increased hardness H directly reduces wear volume V , as observed in our tests. Assuming k remains relatively constant for similar sliding conditions, the improvement factor can be approximated as the ratio of hardness values. From Table 3, the hardened layer hardness (741 HV) versus plain gray cast iron (198 HV) gives a ratio of about 3.74, which correlates well with the near-doubling of wear resistance (since wear resistance is inversely proportional to wear volume). This consistency validates the effectiveness of casting integrated alloying for enhancing gray cast iron performance.

In practical applications, this technique can be tailored for various service environments by adjusting the 铸渗剂 composition. For instance, adding chromium (Cr) or nickel (Ni) could improve corrosion resistance alongside wear resistance, making gray cast iron suitable for harsh chemical exposures. The process is particularly advantageous for components that undergo minimal machining, such as pump housings, valve bodies, or agricultural tillage tools, where a thick, integral wear layer is more beneficial than a thin coating. Our field tests on power plant slag pipelines, made of gray cast iron, showed a lifespan increase of 1.5 times after treatment, highlighting the economic potential.

We also investigated the microstructural stability of the alloyed gray cast iron under thermal cycling. Using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), we mapped the distribution of Mo, W, and Cu across the alloyed layer. The results confirmed that these elements diffuse uniformly, forming a gradient that mitigates interfacial stresses between the hard surface and the ductile gray cast iron core. This gradient structure is key to preventing spalling or delamination under load, a common failure mode in coated components.

From a manufacturing perspective, casting integrated alloying adds minimal cost to the production of gray [cast iron parts](#). The alloy powders, though containing expensive elements like W and Mo, are used in small quantities localized to the surface, reducing overall material costs compared to bulk alloying. The process can be integrated into existing foundry workflows with minor modifications, such as adding a paste application station and optimizing mold drying cycles. For high-volume production, automated dispensing systems could further enhance consistency and efficiency in treating gray cast iron components.

Looking ahead, we envision broader adoption of this method for gray cast iron in industries ranging from automotive to construction. Future research could focus on optimizing the 铸渗剂 formulations for specific wear mechanisms (e.g., adhesive vs. abrasive wear), exploring the use of nano-sized powders for finer microstructures, or combining casting integrated alloying with other surface treatments like shot peening for residual stress benefits. Computational modeling, using finite element analysis (FEA) to simulate diffusion and stress distributions, could also guide the design of alloyed gray cast iron parts for maximum durability.

In conclusion, our study demonstrates that casting integrated with surface alloying is a highly effective technique for improving the wear resistance of gray cast iron. By applying Mo, W, and Cu powders during casting, followed by optional heat treatment, we achieved a thick, hard surface layer with excellent bonding to the gray cast iron substrate. The hardened layer showed a hardness increase of up to 3.8 times and a wear resistance improvement of approximately 200% compared to untreated

gray cast iron. This process leverages the high diffusion rates in **液态** metal to achieve deep alloying, overcoming the limitations of traditional surface treatments. With its simplicity, cost-effectiveness, and adaptability, casting integrated alloying holds great promise for extending the service life of gray cast iron components in demanding applications, contributing to resource conservation and operational efficiency in various industrial sectors.

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