The production practice of Nb enhanced GCI cylinder head

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Abstract: Ferromolybdenum prices are expensive and highly volatile, while ferroniobium maintains stable prices and consistent supply. This experiment has achieved cost-effective alloy optimization by partially substituting molybdenum with niobium (Nb:Mo=0.7:1) to reinforce grey iron cylinder heads. This substitution strategy decreases reliance on price-sensitive molybdenum and enhances corporate economic efficiency, demonstrating a viable pathway for industrial cost control under volatile raw material markets.

Keywords: niobium; microallying; GCI; cylinder head;

1 Introduction

Grey Cast Iron(GCI) is widely applied in diesel engine cylinder heads due to its perfect balance of outstanding casting properties, high thermal conductivity, good mechanical properties, and low cost[1-3]. Under the dual-carbon goals and increasingly stringent environmental regulations, diesel engines are continuously improving thermal efficiency while reducing carbon emissions and pollutant emissions[4-5]. The combustion temperature and peak cylinder pressure of engines are gradually increasing, imposing more demanding requirements on the tensile strength and fatigue resistance of cylinder heads[6-9]. Gray cast iron remains a proven material for diesel engine cylinder heads through long-term practice: Its flake graphite structure effectively absorbs vibrations, reducing engine noise and vibration during operation; The excellent fluidity and low shrinkage rate make it suitable for casting complex-shaped cylinder heads; Through micro-alloying treatment, the thermal fatigue resistance of gray iron can be significantly enhanced, reducing cracks caused by thermal cycling.

Alloyed cast iron, developed by adding alloying elements (such as chromium, copper, niobium, etc.) to gray cast iron, demonstrates improved strength, wear resistance, and thermal stability, making it suitable for high-load diesel engines[10-11]. Both molybdenum and niobium are commonly used strengthening elements in gray iron engine cylinder heads. Although molybdenum significantly enhances material strength, heat resistance, and wear resistance, its frequent price volatility creates substantial cost pressures and operational risks for foundries. Exploring the partial substitution of molybdenum with niobium—an element with stable pricing and supply—can significantly improve enterprise economic efficiency while reducing dependence on price-sensitive molybdenum. This paper comprehensively elaborates and summarizes the principles and practices of substituting niobium for molybdenum.

2 Mechanism and experiment

2.1 Mechanism of niobium strengthening in GCI

CITIC Metal Co., Ltd. and Companhia Brasileira de Metalurgia e Mineração (CBMM) collaborated through the Joint Foundry Laboratory of Shanghai University to conduct extensive research on the existence form and function of niobium in gray iron. The strengthening mechanism of niobium in gray iron was clarified, and industrial verification was carried out using passenger vehicle brake discs[12-16]. Through refinement effects, niobium in gray cast iron reduces eutectic cell size, pearlite lamellar spacing[17-18], and graphite lamella length, thereby improving strength. The strengthening mechanism of molybdenum in high-grade gray iron cylinder heads and blocks is similar to that of niobium in gray iron, with a recommended molybdenum addition range of 0.2%–0.6%[19–20]. According to research data published by the American Foundry Society, niobium exhibits higher strengthening efficiency in cast iron compared to molybdenum[21]. Therefore, theoretically, substituting higher amounts of molybdenum with lower quantities of niobium could potentially reduce alloy element additions while maintaining mechanical properties, thereby lowering alloy costs. This study was conducted based on these theoretical premises.

2.1 Experiment method

Parallel comparative tests were conducted at an engine foundry using an in-house 8-ton medium-frequency melting furnace and hot core process, following the production line's routine manufacturing procedures. The target product was an engine cylinder head made of HT300 gray iron, produced via vertical casting with two castings per mold. Ferro-molybdenum and ferro-niobium were added directly into the furnace to ensure complete melting and absorption.

2.2.1 Raw Material Selection

High-quality raw materials form the foundation of successful smelting, with stable and superior inputs critical for ensuring accurate test comparisons. Based on the characteristics of induction furnace melting, the following premium materials used in daily production were selected:

(1) Pig Iron: Low-impurity pig iron with consistent elemental composition (e.g., Z10, Z14 grades).

(2) Scrap Steel: Stable and continuous supply of scrap steel (e.g., Q235).

(3) Returned Material: Shot-blasted and crushed recycled castings, sorted by grade, with molybdenum-free material chosen to ensure compositional control.

(4) Carburizer: Graphitized, low-nitrogen carburizer with reliable sourcing.

(5) Ferro-Niobium: To ensure recovery efficiency, 65% niobium ferroalloy (particle size <5mm) produced by CBMM (Companhia Brasileira de Metalurgia e Mineração) was used.

(6) Ferro-Molybdenum: Commercially available Chinese-made 60% molybdenum ferroalloy (particle size <5mm) was selected for consistent recovery rates.

Fig.1 The package and appearance of ferroniobium (FeNb)

2.2.2 Composition Design

The chemical composition design for the niobium-strengthened HT300 cylinder head in this trial was as follows: niobium content was set at 0.16%-0.21%, replacing the original 0.25%-0.3% molybdenum with a Nb:Mo ratio of 0.7:1. Other chemical compositions were kept consistent with the molybdenum-strengthened HT300 cylinder head, including carbon (C), silicon (Si), manganese (Mn), sulfur (S), phosphorus (P), etc., to minimize compositional changes and ensure the accuracy of verification results. The compositions of the original molybdenum-strengthened HT300 cylinder head produced by conventional process and the trial niobium-strengthened HT300 cylinder head are presented in Table 1.

Tab.1 Designed chemical composition (mass fraction , %)

C	Si	Mn	S	P	Sn
3.28～3.33	1.75～1.85	0.7～0.8	0.06～0.12	≤0.06	0.06～0.08

2.2.3 Test Procedure

Raw material was gradually charged into a 8-ton induction furnace for melting, following daily operational protocols. After all furnace charges were completely melted and chemical composition adjusted, complete slag removal, and temperature check.

Ferro-niobium (25 kg, particle size <5mm) was added into the induction furnace at temperatures ≥1450℃. The melt was then heated to 1520℃, held for 10 minutes, then sampled for spectrometric composition analysis. After passing quality inspection, the molten iron was tapped at 1480℃. Inoculation was performed in the ladle, with temperature measurement and spectrometric sampling conducted immediately before pouring. Pouring commenced at 1390℃. Subsequent production processes include mold opening, inspection, machining, etc., following standard operational procedures.

3 Results and discussion

A total of 12 castings were produced in this trial with 8 tons of molten iron, consuming 25 kg of ferro-niobium. Spectrometric analysis confirmed a niobium content of 0.19%. Calculations showed a ferro-niobium recovery rate of 92%. All 12 castings passed quality inspection. Metallographic examination results indicated:

- 100% Type A graphite distribution
- Graphite grading: 4
- Pearlite content: 96%
- Carbide content: 1.6%

Tab.2 Actual chemical composition (mass fraction , %)

C	Si	Mn	S	P	Sn
3.3	1.90	0.7	0.07	0.03	0.07

One cylinder head was sectioned for analysis. Tensile strength of the bulk sample reached 270–310 MPa, and hardness measured 202–213 HB. Both tensile strength and hardness of the bulk samples were comparable to or better than the original molybdenum-containing products, meeting product specification requirements. Sealing performance tests showed no leakage under high pressure for all cylinder heads. Hydrostatic pressure testing confirmed zero leakage across all units. Except for the sectioned cylinder head, all others underwent normal machining, assembly, and shipping processes. These components have been in normal service for one year.

The foundry conducted multiple subsequent trials, resulting in over 3,000 niobium-strengthened gray iron cylinder heads produced to date. With the recent surge in ferro-molybdenum prices, the cost of 60% ferro-molybdenum has become comparable to that of 65% ferro-niobium. By substituting niobium for molybdenum, the enterprise achieved significant alloy cost savings, yielding favorable economic returns.

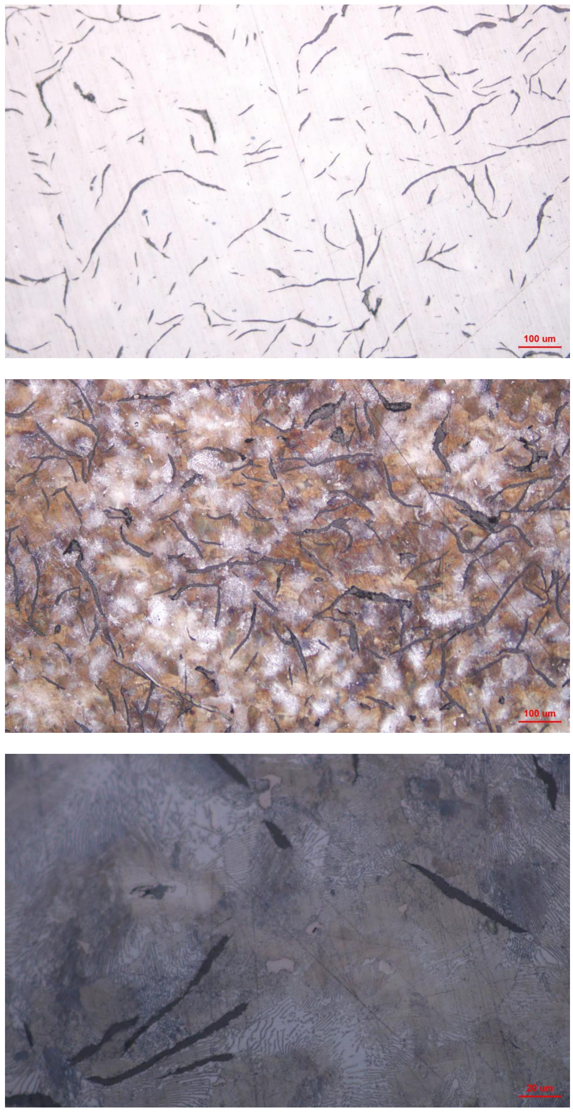

Fig.2 Morphology of cylinder head sample

4 Conclusions

Due to significant price volatility and high costs associated with molybdenum, foundries face substantial economic burdens. To address this, this trial successfully developed a more cost-effective strengthening solution by substituting molybdenum with a smaller amount of niobium at a Nb:Mo ratio of 0.7:1. The addition of niobium exhibits minimal impact on existing casting processes, facilitating large-scale production. Niobium's relatively stable pricing, combined with its reduced usage requirements while maintaining equivalent cylinder head performance, enables substantial cost savings in material expenses, resulting in favorable economic outcomes.

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Conflicts of interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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