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Application of Arc Furnace Flue Ash in Casting Heat Insulation Riser

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Abstract

Iron black commonly employs in thermal insulation riser sleeves due to its ability to react with aluminum powder, generating heat. However, the complex production process and unstable composition of iron black lead to high production costs. The potential of using arc furnace flue ash (AFFA) as a complete substitute for iron black and MnO_2 and KNO_3 oxidizing agents in conventional riser sleeves was investigated in this study. Waste material can be transformed into a valuable resource, while production costs can be reduced by utilizing arc furnace flue ash. The research examined the impact of varying types and amounts of arc furnace flue ash on riser sleeve temperature and holding time by conducting single-factor and orthogonal optimization experiments. The orthogonal optimization experiment determined that the optimum ratio of each oxidant was 6 % arc flue ash, 3 % MnO_2 and 6 % KNO_3. At this time, the highest temperature was 1512 ℃ and the holding time was 244 s. Results indicated that different types of arc furnace flue ash used as an oxidizing agent demonstrated superior holding capacity and heat generation performance compared to iron black. Additionally, a comparative analysis of factory casting experiments using ductile iron 600-3 (IS) revealed that both arc furnace flue ash and iron black risers effectively countered shrinkage. However, arc furnace flue ash risers exhibited improved mechanical properties, as evidenced by the hardness of the castings.

Keywords: Arc furnace flue ash, Iron black, Orthogonal optimization

1. Introduction

In foundry practice, the exothermic insulating riser could increase the temperature of the metal liquid through its heat combustion and delay the solidification of the metal liquid so that the feeding efficiency could be increased during casting [1-3]. A combination of aluminum powder and iron oxides typically serves as the heat-generating material in heat-retaining riser sleeve sets [4-6]. However, using iron black as the oxidizing agent in these heat and insulation bubble sets presents challenges such as high costs and casting defects [7]. To address these issues, this study proposes the application of arc furnace flue ash as an alternative oxidizing agent in the casting of heat-generating and insulating bubble sets.

Arc furnace flue ash dust is a significant byproduct of the arc furnace steelmaking process. It is mainly composed of iron, zinc, calcium, silicon, manganese and other oxides [8]. Unfortunately, elements such as zinc and chromium often surpass the permissible limits, rendering arc furnace flue ash a hazardous waste [9-10]. Aside from iron, this ash also contains many heavy metals like zinc, lead, chromium, and cadmium. Improper storage of the ash outdoors, combined with rainfall, can result in the leaching of these harmful elements into the soil, posing a threat to animals, plants, and the overall environment [11]. Arc furnace flue ash treatment options include pyrometallurgical, hydrometallurgical, and chemical stabilization/vitrification [12-13]. However, these approaches often generate secondary waste and have limited potential for high-value utilization. Given the increasingly stringent environmental regulations, exploring resource-based secondary utilization of arc furnace flue ash is imperative.

This innovative approach transforms arc furnace flue ash into a valuable resource and offers a novel and unique utilization method. The research introduces a new type of heated and insulated riser sleeve, building upon the conventional design, with arc furnace flue ash, MnO_2, and KNO_3 as oxidants. By analyzing the thermophysical properties of the riser sleeve, such as heat generation and insulation, and conducting orthogonal experiments to optimize the oxidant ratio in the riser sleeve, the study showcases the significant potential of arc furnace flue ash as a complete replacement for iron black.

2. Experimental

2.1. Materials and instruments

The materials used in this study include three types of arc furnace flue ash, whose composition is detailed in Table 1. aluminum powder with a particle size of 0.075mm; aluminum chips with a particle size ranging from 0.18-0.60mm and a purity exceeding 99%, oxidizers such as iron black, KNO_3, and MnO_2 in powder form, Na_3AlF_6 powder as the flux, phenolic alkali resin, and hollow drift beads with a particle size of 0.150-0.425 mm. All four powder reagents employed possess analytical purity.

Table 1.
Chemical analysis of three different kinds of arc furnace flue ash

Element	Ignition loss	Fe_2O_3	ZnO	CaO	SiO_2	MnO_2	K_2O	MgO	Eles
AFFA1	8.04	47.32	13.66	7.66	5.91	5.71	2.77	2.9	6.03
AFFA2	8.21	55.52	6.96	6.24	4.21	5.08	5.42	3.48	4.88
AFFA3	5.19	66.29	1.99	10.85	0.21	6.05	0.79	4.04	4.59

The experimental apparatus utilized in this study consisted of the following instruments: JS3-01 electronic balance with an accuracy of 0.01 g, the sand mixer (JJ-5), the SAC riser sleeve hammer sampler, the electrothermal blowing dry box (XGQ-2000), the high-temperature resistance furnace (SRJX-4-13), the 99% corundum tube, the type B platinum-rhodium thermocouple, the paperless recorder for temperature measurement (SIN-R5000C), the strength tester (SWX), and the Thermo ICP spectrometer (ICAP 7000).

2.2. Sample preparation and measurement

To prepare the riser sleeve samples, the heating material (20%-26%) , insulation material (45%-55%) , oxidizing agent (8%-20%) , and flux (3%-4%) were meticulously measured and placed into the sand mixer according to their respective proportions. The mixture was then blended at a low speed for approximately 5 minutes. Next, a specific amount of binder was added based on the total weight of the dry materials, and the mixing process continued at high speed for around 9 minutes. Once thoroughly mixed, 75g of the resulting mixture was placed into a mold. A hammering machine was used to shape the mixture into a cylindrical sample measuring Ø50*50 mm. Finally, the sample was carefully removed from the mold and dried in an oven set at 180 ℃ for 25 minutes. The temperature was then reduced to 130 °C for 30 minutes, resulting in the final riser sleeve sample.

In order to assess the combustion performance of the specimens, a Ø10 mm * 35 mm hole was carefully drilled at the top midpoint of each cylindrical sample to accommodate the thermocouple. Furthermore, a corundum tube was inserted into the test rod, leaving a margin of 45 mm. The paperless recorder (SIN-R5000C), designed for temperature measurement, accurately recorded the maximum temperature reached by the specimens and the duration during which the temperature remained above 1200°C, considering the holding time.

2.3. Experimental methods

After determining that arc furnace flue ash is a suitable substitute for iron black, a subsequent analysis to evaluate how three common oxidizing agents, namely arc furnace flue ash 1 (A), MnO_2 (B), and KNO_3 (C), affect the maximum temperature and holding time of the riser sleeve set.Single-factor experiments were conducted by using different amounts of each oxidizing agent within the range specified in Table 2. to prepare test bars for testing.

Table 2.
Variation range of Oxidizer additives

Oxidizer Additives	Content variation range (%)				
AFFA1	2	4	6	8	10
MnO_2	1	2	3	4	5
KNO_3	2	4	6	8	10

Oxidizer orthogonal optimization experiment: Based on the single-factor experiments, the orthogonal experiments were done with the content of oxidants as three factors with three levels per factor, and the orthogonal table L9 (3^3) (scheme shown in Table 4) was selected. Other materials were fixed, and the riser sleeve samples were prepared. The samples' ignition time and secondary heat generation time were used as the analysis index. Data analysis was performed using Minitab 20 software.

3. Results and analysis

3.1. Feasibility experiment of arc furnace flue ash as an oxidant

The investigation of arc furnace flue ash on a heated and insulated riser sleeve set was carried out based on a heated and insulated riser sleeve set. An experimental comparison was made by adding 6% MnO_2, 8% KNO_3, and 6% iron black to create a heated and insulated riser sleeve and by completely replacing 6% iron black with arc furnace flue ash to make a riser sleeve.

Table 3.
Performance comparison of Iron black and arc furnace flue ash

Riser sleeve	Maximum temperature(°C)	Holding time (s)	Ignition time （s）	Secondary combustion time(s)
IB	1470	220	43	58
AFFA1	1489	210	42	52

The comparative analysis presented in Table 3. demonstrates notable distinctions in two critical performance parameters, namely the maximum combustion temperature and insulation duration, between using iron black and arc furnace flue ash as oxidizing agents in preparing the heating and insulation riser sleeve set. Remarkably, arc furnace flue ash can entirely replace iron black as an oxidizing agent, offering a promising alternative for achieving optimal combustion temperature and insulation performance. Nevertheless, the precise quantity of flue gas ash required and its potential synergistic influence with other oxidizing agents in the arc furnace domain still remains undisclosed. Consequently, additional investigations will be carried out to refine the oxidizer ratio for riser sleeves.

3.2. Single-factor experimental results of oxidant

Modifying the composition of various oxidants within the riser sleeve makes it possible to regulate the test bars' maximum temperature and holding time. A higher maximum temperature signifies an increased heat contribution from the aluminothermic reaction, consequently elevating the temperature of the test bars. On the other hand, an extended holding time allows for a more substantial reaction between the heating agent and the oxidizing agent following secondary combustion ignition, ensuring a more prolonged curing duration for the metal liquid during the aluminothermic reaction.

Figure. 1. depicts the relationship curve between arc furnace flue ash content and the highest temperature/holding time. As the amount of arc furnace flue ash increases, the maximum temperature and holding time initially increase before trending downwards. At a content level of 4%, the maximum temperature and insulation time peaked at 1498 °C and 217 s, respectively. To achieve optimal results, the amount of arc furnace flue ash added should thus be within the range of 2-6%.

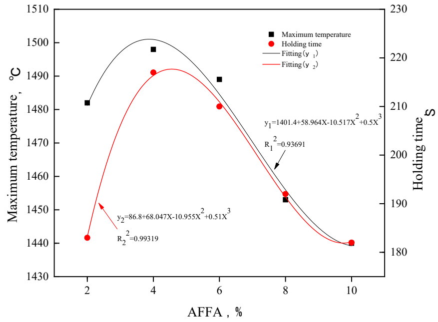

Fig. 1. Relationship between arc furnace flue ash and maximum temperature and holding time

Figure. 2. presents the relationship curve between MnO_2 content and the maximum temperature and holding time. Initially, as the amount of MnO_2 increases, both the maximum temperature and holding time exhibit an upward trend until reaching a peak at a content level of approximately 3%, where the peak values were 1489 °C and 210 s, respectively. On either side of the peak, there is little significant difference in temperature or holding time. However, an apparent downward trend in the highest temperature and holding time appears once the MnO_2 content surpasses the optimal zone. Therefore, adding about 3% MnO_2 to the mixture achieves the best results.

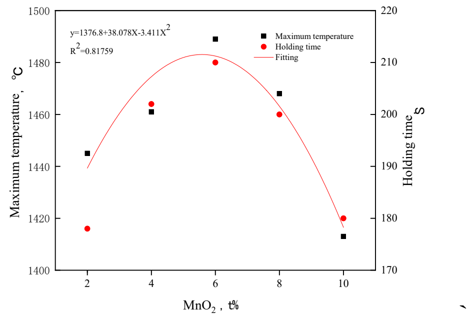

Fig. 2. Relationship between MnO_2 and maximum temperature and holding time

Figure. 3. depicts the relationship curve between the KNO_3 content and the corresponding highest temperature and holding time. As observed in previous cases, an initial increase in the arc furnace flue ash content leads to an upward trend in both the maximum temperature and holding time, followed by a subsequent decline. When the KNO_3 content reaches 6%, it achieves the maximum temperature and holding time peak values, which measure 1494°C and 230s, respectively. Beyond this point, while the maximum temperature gradually declines, the holding time shows a more noticeable downward trend. Consequently, it is crucial to ensure that the amount of KNO_3 added is not less than 4% to optimize the performance of the riser sleeve set.

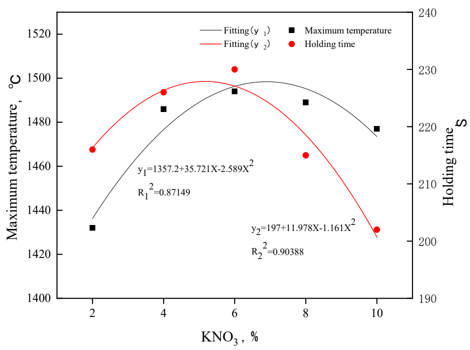

Fig. 3. Relationship between KNO_3 and maximum temperature and holding time

3.3. Oxidant orthogonal optimization

The results obtained from the single-factor experiments indicate an optimal range for the content of each oxidant, beyond which both the maximum temperature and holding time of the specimen decrease. It is important to note that achieving a higher temperature sometimes results in a longer holding time. For the heated insulation riser sleeve, it is generally recommended to maintain a temperature above 1450°C and a holding time of at least 210s. Therefore, it is necessary to strive to increase the maximum temperature and extend the holding time. Utilizing a single oxidant poses challenges in meeting the combustion performance requirements of the riser sleeve set. Hence, a combination of oxidants is required, and their ratios must be further optimized using orthogonal experiments, as outlined in Table 4.

Table 4.
Orthogonal test protocol and results

NO	Factors			Experimental results	
	A: AFFA(%)	B: MnO_2 (%)	C: KNO_3 (%)	Maximum temperature (°C)	Holding time (s)
1	2	2	4	1431	210
2	2	3	6	1456	211
3	2	4	8	1458	212
4	4	2	6	1463	213
5	4	3	8	1448	214
6	4	4	4	1447	215
7	6	2	8	1467	216
8	6	3	4	1491	217
9	6	4	6	1481	234

The signal-to-noise ratio analysis of the different oxidant blends was analyzed using a polar difference analysis, as shown in Table 5. The ranking of the polar differences shows that the effect of oxidant A is much more significant than that of oxidants MnO_2 and KNO_3. This indicates that the effect of oxidant A content on the maximum temperature was the most significant. However, the difference between oxidant MnO_2 and KNO_3's effects was insignificant.

Table 5.
Signal to noise ratio response table

Indicator	Level	A: AFFA	B: MnO_2	C: KNO_3
Maximum temperature and Holding time	1	49.4	49.49	49.52
	2	49.53	49.53	49.73
	3	49.85	49.77	49.53
	R	0.44	0.28	0.2

Table 6. displays the mean values and the extreme differences (Δ) of the mean values for each level of every factor. The ranking of the polar differences provides insights into the extent of influence that each factor has on the mean values. Based on the analysis of the magnitude of the polar differences, the optimal combination of proportions was determined as A3, B2, and C2, corresponding to 6% arc furnace flue ash content, 3% MnO_2 content, and 6% KNO_3 content, respectively. When employing these optimized oxidant ratios, the riser sleeve specimens exhibited a maximum temperature of 1512°C and a holding time of 244 s.

Table 6.
Mean Response Table

Indicator	Level	A: AFFA	B: MnO_2	C: KNO_3
Maximum temperature and Holding time	1	829.7	833.3	835.2
	2	833.3	839.5	843
	3	851	841.2	835.8
	R	21.3	7.8	7.8

4. Performance comparison of different arc furnace flue ash riser sleeves

Based on the optimized formula of the arc furnace flue ash riser sleeves, which includes an oxidant content of 15% (comprising 6% arc furnace flue ash, 3% MnO_2, and 6% KNO_3) , further experiments were conducted to validate the results of the oxidant optimization. Homemade riser sleeve test rods with identical specifications were prepared for combustion tests to compare the effects of different types of arc furnace flue ash additions. The riser sleeve test rods' heat combustion performance and temperature change curves were measured, as depicted in Figure 4.

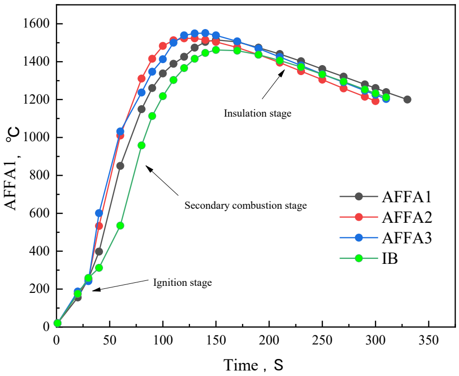

Fig.4.Temperature-time curves of AFFA and IB

Through analysis of performance data presented in Table 7. it was observed that adding different types of arc furnace flue ash in Table 1. resulted in varying degrees of influence on heated riser sleeve sets, as evidenced by differentiated maximum temperatures and holding times. Specifically, arc furnace flue ash1 displayed excellent heat generation and insulation properties, producing a 42℃increase in temperature and a 10.9% improvement in insulation compared to the conventional iron-black riser sleeve set. The mechanism underlying this outcome involves the ability of arc furnace flue ash to provide additional oxygen to supplement the higher oxygen content in the oxidizer. As a result, an adequate aluminothermic reaction occurs within the riser sleeve, leading to higher temperatures and longer insulation times.

Table7.
Performance comparison of different oxidizers

Riser sleeve	Maximum temperature （℃）	Holding time （s）	Ignition time （s）	Secondary combustion time （s）
Iron black	1470	220	43	58
AFFA1	1512	244	40	56
AFFA2	1524	223	47	54
AFFA3	1550	235	45	55

5. Analysis of the casting experiment of arc furnace flue ash riser sleeve

Three sets of comparative casting experiments was conducted on a model wheel casting using both the arc furnace flue ash riser sleeve and the iron black riser sleeve. Its casting dimensions are 800*1000mm. The casting process involved the use of ductile iron 600-3 (ISO) at a casting temperature of 1400℃, as per the requirements. As shown in Figure 5. To minimize differences in shrinkage effects, the castings were carefully examined after being cut. that the arc furnace flue ash riser and the iron black riser effectively compensated for shrinkage and facilitated the transfer of defects to the colanders. As a result, the casting yield improved, and the overall quality was enhanced.

Fig.5. Casting experiment: a) Arc flue ash riser sleeve, b) Iron black riser sleeve, c) casting profile, d) riser sleeve inner profile, e) wheel casting

Material hardness testing was performed a comprehensive indicator of elasticity, plasticity, strength, and toughness. Higher hardness values typically indicate better material performance. The hardness test results in Table 8 indicate that the hardness value of the casting profile at the position of the arc furnace flue ash riser in the flue of the arc furnace and the inner crown shape of the riser sleeve is about 210 HB, which is 10 HB higher than that of the same iron black riser sleeve, and all meet the requirements. Notably, the arc furnace flue ash riser sleeve set proved to be a suitable replacement for the black iron riser sleeve and demonstrated slightly higher strength properties.

Table 8.
Strength of castings at different riser sleeves

Position of the riser	Hardness（HB）	
	3-1/2-1	3/2
AFFA1 riser sleeve	208	210
Iron black riser sleeve	199	200

6. Conclusions

1) Experimental tests have revealed that arc furnace flue ash possesses a significant concentration of oxides, making it highly effective as an oxidizing agent in the heating and insulation of riser sleeves. This characteristic imparts excellent heating and insulation properties to the riser sleeve shell, resulting in superior performance.

2) Different arc furnace flue ash provides different oxidize depending on the total content of the oxidant, which affects the riser sleeve jacket's heat generation and insulation properties. The oxidant ratio was optimized by employing both the single-factor method and the orthogonal method, with arc furnace flue ash 1 comprising 6%, MnO_2 3%, and KNO_3 6%. As a result, the combustion temperature of the custom-made riser sleeve reached 1512°C, accompanied by a holding time of 244 s.
3) When used as an oxidiser, each type of arc furnace flue ash shows better heating and heat preservation performance than iron black. Specifically,arc furnace flue ash 1 demonstrated a 10.9% improvement in heat preservation effects compared to the riser sleeve set with iron-black oxidation.
4) The arc furnace flue ash and black iron riser sleeves were subjected to practical casting tests, including opening the castings for observation and conducting hardness experiments. The results indicate that both the arc furnace flue ash and black iron riser sleeves exhibit satisfactory quality and meet the required standards. Moreover, the arc furnace flue ash riser sleeves had shown potential for replacing conventional heat insulation riser sleeves in casting production.

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