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An Experimental Technique for Investigating the Skulling Behavior in the Blast Furnace Hearth

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Abstract: The skulling behavior in the blast furnace (BF) hearth has yet to be investigated as few (if any) industrial/experimental studies with particular focus on hot metal have been reported in the open literature. As a necessary first step towards a better understanding of the sophisticated behavior, an experimental technique is introduced in the present paper. The experimental apparatus, which mainly consists of a vertical tube furnace, a rotating and moveable pedestal and a moveable water-cooled probe covered with a multi-layer structured refractory sleeve, can utilize industrial coke, pig iron and BF hearth carbon brick as raw materials. The technique is shown to be capable of producing chemical, thermal and mechanical conditions similar to those in the real process. The feasibility and potential of the technique are demonstrated by a set of experimental runs. The results indicate that the air gap between the cooling device and the refractory lining plays a decisive role in both skull formation and lining erosion. Furthermore, the microstructure of graphite precipitated during solidification is influenced by the cooling rate, which in practice is affected by the BF hearth operating parameters. It is hoped that the current contribution will stimulate the growing research interest in this subject.

Keyword: blast furnace hearth, hot metal, cooling device, skull, microstructure

1. Introduction

The campaign life of a modern blast furnace (BF) considerably depends on its hearth integrity. Other furnace parts can be repaired or replaced in a relatively short period, but relining a broken hearth often requires much more efforts and sometimes could escalate to a complete revamp.^[1-2] The BF hearth is usually constructed of carbon (graphite) and ceramic refractories, which nevertheless cannot withstand the hostile in-hearth environment in the long run. As hearth walls are routinely cooled with embedded cooling device based on water circuits, the hot metal close to hearth walls may solidify to form a skull layer acting as an autogenous barrier (or referred to as freeze lining) to avoid direct contact between the construction refractories and the chemically and mechanically aggressive hot metal bath. It is therefore clear that the skulling behavior plays a crucial role in maintaining the hearth integrity.

The BF hearth phenomena have been investigated mainly based on mathematical and experimental modeling because the in-hearth variables cannot be directly measured during the continuous operation.^[3-11] As for the skulling behavior, Zhao and co-authors were among the first to put dedicated efforts into simulating skull formation utilizing a two-dimensional computational fluid dynamics (CFD) model.^[12] It should be stressed that for further development the CFD model still needs to be verified by the corresponding industrial or experimental results. To the best of our knowledge, however, few (if any) industrial/experimental studies with particular focus on hot metal have been reported. Keeping this in mind and as a first step to gaining a better understanding of the mechanisms, the current work is aimed at introducing an experimental technique for investigating the skulling behavior in the BF hearth. In the sections that follow, the

technique is presented in terms of apparatus arrangement, experimental procedure and materials, and the feasibility and potential of the technique are demonstrated by a set of experiments.

2. Experimental

2.1 Apparatus arrangement

The experimental apparatus, as schematically illustrated in Fig. 1, mainly consists of a vertical tube furnace, a rotating and moveable pedestal and a moveable water-cooled probe. The tube furnace is heated with MoSi₂ elements, and its inner diameter and maximum temperature are 140 mm and 1973 K, respectively. To produce a protective atmosphere, an inert gas can be delivered into the furnace through a replaceable heat-resistant steel pipe. The rotating pedestal, which provides a convective condition in the melt bath, is stacked with three refractory discs of successively decreasing diameters; the diameter of the uppermost disc is 110 mm. The pedestal can be lifted into the furnace from the bottom by a manual winch and its rotating speed is controlled by an electric motor (*i.e.*, EM1). The water-cooled probe, which represents an embedded cooling device, is built using two concentric stainless steel pipes. The pipes have the same wall thickness of 1 mm and outer diameters of 8 mm and 14 mm, respectively. The probe is insulated with a fire-proof rope starting about 100 mm above its tip and the remaining part is covered with a refractory sleeve of relevant interest. At the top of the furnace, the probe can be lifted or lowered, and the moving speed can be controlled by another electric motor (*i.e.*, EM2). Water flow rate of the probe is adjusted by tuning the water pressure with manual valves, while water temperature can be monitored using platinum resistance thermal sensors at different inprobe locations.



Fig. 1 Schematic illustration of experimental apparatus for investigating skulling behavior under BF hearth conditions

2.2 Procedure and methods

Before each experiment, the lower part of the probe was covered with a refractory sleeve of relevant interest and a crucible holding the raw materials (for the liquid bath) was fixed on the rotating pedestal.

All the experiments were conducted in accordance with the following steps:

- The inert gas flow was turned on, followed by lifting the pedestal into the furnace and capping the furnace with a fire-proof (alumina) fiber blanket.
- (2) EM1 was switched on and the furnace was heated at a heating rate of 4 K/min. After reaching the experimental temperature, the furnace was allowed to stabilize for 20 min.
- (3) The water flow and the temperature monitoring of the probe were turned on, and the furnace cap was moved aside. EM2 was carefully controlled to lower the probe down to a position where its tip was approximately 5 mm above the melt bath in

the crucible. Then, the furnace was recapped and the system (*i.e.*, furnace and probe) was left stabilizing for 10 min.

- (4) The probe was lowered further till its tip was submerged about 40 mm into the bath. After an immersion interval of 10 min, the furnace cap was moved aside and the probe was lifted up quickly from the furnace. The incandescent hot section of the probe was then quenched in tap water.
- (5) The furnace was powered off, while the inert gas flow and EM1 were still kept on.Melt samples were collected at different points in the crucible.

If a shell was found on the sleeve surface after quenching, it was removed for preparation of the skull sample using the conventional metallographic methods. The shell was firstly filtered using a funnel and filter paper, followed by a 10 min drying with a hot air blower. The dry shell was then cast into an epoxy resin and sliced along its axial plane. A skull sample was finally obtained by grinding and polishing the revealed cross-sections with silicon carbide papers and diamond pastes, respectively.

After each experiment, the melt samples were sent for chemical analysis and the skull sample cross-sections were examined using a scanning electron microscope (SEM) equipped with an energy-dispersive spectroscopy (EDS) detection module. In order to cover the entire thickness, backscattered electron (BSE) images with a single magnification were taken in a sequence along a horizontal line throughout a cross-section. After that, a microstructure panorama can be obtained by stitching the sequences.

2.3 Materials

In the present experiments, dry nitrogen gas with a purity of 99.99 (vol.) % was delivered into the furnace to avoid oxidation at high temperatures. Industrial coke particles and pig

iron were used as the raw materials for the hot metal bath: Coke particles of diameters less than 10 mm were screened for use and small pieces of pig iron were prepared by crushing an ingot obtained from a local ironworks. In order to simulate the multi-layer structured BF hearth walls, the refractory sleeves were made using alumina cement and a commercial BF hearth carbon brick delivered by the same ironworks.

3. Results and discussion

Since no similar experiments have been reported in the open literature, the feasibility of the experimental technique was firstly proven by performing a set of preliminary runs where the functioning of the rig was tested and experimental parameters were varied within relatively wide ranges. After a few trials, dense magnesia crucibles with an inner diameter of 92 mm were chosen as the hot metal container.

In order to demonstrate the potential of the technique, results of two experiments are presented and discussed in this section. In these experiments, the raw materials consisted of 30 g of coke particles and 3 kg of pig iron pieces, yielding a hot metal bath with a depth of more than 60 mm. The experimental temperature, nitrogen gas flow rate and water flow rate in the probe were 1783 K, 5 L/min (STP) and 1.5 L/min, respectively. The rotational speed of the pedestal was 1 rpm, corresponding to a linear velocity of hot metal in the sleeve vicinity of about 1.5 mm/s. It should be noted that in a normal BF hearth operation the hot metal velocity varies within the range of 0.1 mm/s to 0.4 mm/s except for regions near the taphole.^[12] As depicted in the left part of Fig. 1, the refractory sleeves were identical in those two experiments. Each sleeve had an inner layer of carbon brick and an outer layer of alumina cement. The thicknesses of the layers were 5 mm and 1 mm, respectively. The only difference lies in the contact between the sleeve and the probe: The

sleeve was mounted directly on the probe surface in Exp. 2, leaving a thin air gap and hence an elevated heat resistance due to the tolerance needed for assembly. In Exp. 1, however, the air gap was filled by graphite fines.

After quenching, it was observed that a hollow cylinder shaped shell with an average thickness of about 3 mm had formed on the sleeve surface in Exp. 1. Nevertheless, no shell was generated in Exp. 2, but instead the alumina layer was eroded to some extent. It is therefore clear that when an air gap exists (as in Exp. 2) the heat extracted by the water flow is insufficient to balance the heat transferred by convection from the bath and the latent heat released due to solidification of the hot metal. This argument can be substantiated by analyzing the heat flow rate (Q) of the system.

$$Q = \rho c_{\rm p} \dot{V} (T_{\rm out} - T_{\rm in}) \tag{1}$$

where \dot{V} , T_{out} and T_{in} are the measured water (volumetric) flow rate, and water temperatures at the probe outlet and inlet, respectively. The temperature-dependent density (ρ) and specific heat capacity (c_p) of water are estimated based on the arithmetic mean of T_{out} and T_{in} .

The heat flow rates are compared in Fig. 2, where it is clearly seen that heat transfer through the probe-sleeve system is effectively enhanced when the air gap in Exp. 2 is filled with graphite fines in Exp. 1. The major difference between the heat flow rates suggests that the air gap with poor thermal conductivity dominates the whole heat transfer process, leading to a high temperature within the sleeve. This explains the erosion of the alumina layer that is brought into direct contact with the hot metal in motion. More importantly, the results demonstrate why internal cracking of the BF hearth lining must be avoided in practice.^[13] It can also be seen in Fig.2 that the heat flow rates of both

experiments evolve in a similar way during the period when the probe was located 5 mm above the bath: The heat flow rates rise abruptly within about 2 min in the beginning and then stabilize. During the period when the probe was submerged 40 mm in the bath, the heat flow rate of Exp. 2 shows similar behavior, but a noticeable increase appears initially in the heat flow rate of Exp. 1 associated with the release of latent heat due to solidification. However, the rate declines gradually in a negative exponential manner that is intimately related to the variation of skull growth rate.^[14]



Fig. 2 Comparison between heat flow rates of Exp. 1 and Exp. 2

The microstructure at the mid-height of the skull sample from Exp. 1 is visualized in Fig. 3(a), where the 3 mm long panorama beginning from the sleeve surface and ending at the melt bath is divided into three continuous strips of 1 mm in length. To facilitate the comparison, a typical BSE image (with the same magnification) of the hot metal ingot used in the experiments is also shown in Fig. 3(b). According to the EDS detection, the black flakes in both figures are the same species of graphite. It can be seen from the uppermost strip in Fig. 3(a) that most graphite flakes are precipitated in a thin layer next

to the (cold) sleeve surface, while the other two strips are relatively 'clean' because of the quenching in tap water. This feature indicates that the actual skull is only about 1 mm thick under the conditions of Exp. 1. In the actual skull layer (*cf.* the uppermost strip in Fig. 3(a)), the graphite flakes are short and tend to form lumps locally owing to a high cooling rate guaranteed by the uninterrupted heat transfer between the sleeve and the probe. It is worth noticing that the characteristic graphite structures in the experimental skull can also be observed in a core-drilled skull sample from an industrial BF hearth^[15] and the graphite precipitations are comparable in size. In the ingot cooled in air, however, the randomly oriented flakes are long and uniformly distributed as a result of a limited cooling rate. Considering that the thermal and mechanical properties of a material are determined by its microstructure, the aforementioned observation implies that the properties of skull formed in hot metal may vary with the BF hearth operating parameters that can alter the cooling rate.



(b) Ingot cooled in air

Fig. 3 Microstructure of graphite in different samples

4. Concluding remarks

As a necessary first step towards a better understanding of the skulling behavior in the BF hearth, an experimental technique has been introduced, and the feasibility and potential of mimicking skull formation conditions have been accessed. The results of two pilot-scale experiments were presented and discussed. It has been demonstrated that the air gap between the cooling device and the refractory lining plays a decisive role in both skull formation and lining erosion. The microstructure of graphite precipitated during solidification was found to be influenced by the cooling rate, which in practice is affected by the BF hearth operating parameters. However, a large number of issues still remain unexplored, so more systematic and detailed studies will be carried out putting special

attention on skull growth kinetics and characterization of the physical and thermal properties of the material. Also, mathematical modeling of the skulling process will be used to plan more experiments and to analyze the observed thermal behavior of the system.

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