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Evaluating the heat transfer phenomena and the interfacial thermal resistance of mold flux using a copper disc mold simulator

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ABSTRACT

The new modified pouring method (copper disc mold simulator, CDMS) to investigate the interfacial thermal resistance and crystallinity for the mold fluxes was introduced. To make sure the formation of the air gap, the surface waviness was measured with the crystallinity. The interfacial thermal resistance increased with higher average waviness, which means the average height of air gap. However, the average waviness did not increase with the higher crystallinity. This result came from the different crystallization mechanisms and the contraction of the flux during the solidification and crystallization was varied based on the crystallization mechanism. Therefore, it is important to apply the mold flux which has optimum crystallization behavior because applying the strong crystallized mold flux to increase the interfacial thermal resistance does not always bring the high interfacial thermal resistance.

1. Introduction

The infiltration of mold flux between a water-cooled copper mold and partially solidified steel shell in the continuous casting machine consists of three disparate phases [1–4]. One is a solid glassy phase, another is a solid crystalline phase, and the other is a liquid phase. The existing ratio of these different phases are dependent on mold flux properties such as the break temperature [5,6] and crystallization behavior [2]. Furthermore, the heat transfer through the copper mold is affected by this infiltrated flux film and the total heat transfer can be expressed by the following Eq. (1) assuming negligible interaction between conduction and radiation [7].

$$q_{Tot} = q_{Rad.} + q_{Cond.} = q_{Tot}^{Glass.} + q_{Tot}^{Cryst.} + q_{Tot}^{Liq.} \quad (1)$$

where the total heat flux(q_{Tot}) through the glassy, crystalline, and liquid flux film ($q_{Tot}^{Glass.}$, $q_{Tot}^{Cryst.}$, $q_{Tot}^{Liq.}$, respectively) can be expressed by Eqs. (2)–(4) [2].

$$q_{Tot}^{Glass.} = q_{Cond}^{Glass.} + q_{Rad}^{Glass.} \quad (2)$$

$$q_{Tot.}^{Cryst.} = q_{Cond}^{Cyst} + q_{Rad}^{Cryst.} \quad (3)$$

$$q_{Tot.}^{Liq.} = q_{Cond}^{Liq.} + q_{Rad}^{Liq.} \quad (4)$$

where $q_{Cond.}{}^{k}$ and $q_{Rad.}^{k}$ correspond to the heat transfer through the phase '*k*' via the conduction and radiation mechanism, respectively.

In addition, the total thermal resistance, $R_{Tot.}$, can be expressed by Eq. (5) [1].

$$R_{Tot.} = R^{Glass.} + R^{Cryst.} + R^{Liq.} + R^{Int.} \quad (5)$$

where $R^{Glass.}$, $R^{Cryst.}$, and $R^{Liq.}$ are the resistance in the glassy, crystalline, and liquid phase flux film, respectively. $R^{Int.}$ is the interfacial thermal resistance between the copper mold and flux film.

According to previous works, the crystallization of mold flux is a key factor in controlling the heat transfer in the mold [8–12]. Higher crystallization in fluxes has been speculated to lower the heat transfer through the infiltrated mold flux film due to the increase in the thermal resistance at the interface of the copper mold and flux by forming air gaps due to volumetric contraction [8–10]. In addition, greater crystal phases within the flux lowers the transmissivity by scattering and reflecting the exposed heat, which can inhibit radiative heat transfer [11,12].

With respect to the thermal conductivity, Ozawa et al. [13] reported a higher thermal conductivity with greater crystallinity due to the increased packing density and regularity, when the flux is crystallized. Considering the effect of crystallization on both radiative and conductive heat transfer, crystallization of the flux can reduce radiative heat transfer, but promote conductive heat transfer [13,14].

Therefore, understanding the crystallization behavior of mold fluxes is essential *in* controlling the overall heat transfer in the mold. Several research techniques have been utilized to study

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Nomenclature

q^k_{Rad}	radiative heat flux through the phase 'k', W/m^2	n	refractive index of the flux
$q_{Cond.}{}^k$	conductive heat flux through the phase 'k', W/m^2	σ	Stefan-Boltzmann constant, W/(m^2·K^4)
q^k_{Tot}	total heat flux through the phase 'k', W/m^2	α	absorption coefficient of the flux, m-1
R^k	thermal resistance of the phase 'k', (m^2·K)/W	ε	emissivity of the flux
$R^{Int.}$	interfacial thermal resistance between the copper mold and the flux, (m^2·K)/W	k	thermal conductivity of the material, W/m·K
$T_{FT\text{-}1}$	temperature of the thermocouple, FT-1, K	r	roughness of the material, nm
$T_{FT\text{-}2}$	temperature of the thermocouple, FT-2, K	Wa	average waviness the material, µm
T_f	temperature at the bottom of the flux, K	ρCP	volumetric heat capacity of the material, J/m3·K
T_m	temperature at the top of copper mold, K		

the crystallization behavior of mold fluxes such as the mold simulator [15,16], differential thermal analysis (DTA) [17,18], single and double hot thermocouple technique (SHTT, DHTT) [19,20], and confocal laser scanning microscope (CLSM) [21–23]. Each method has its pros and cons, but have commonly provided important information in the fundamental understanding of mold flux crystallization.

Crystallization properties of mold flux can also affect the interfacial thermal resistance by producing air gaps [24] as a result of the contraction of the steel during solidification. This interfacial thermal resistance plays a dominant role in casting since it accounts for about 50–78% of the total thermal resistance in the mold [1,2,25]. The interfacial thermal resistance (R_{int}) was reported to be highly affected by the solid slag thickness and the crystallinity as the R_{int} is increased with increasing thickness of the air gap during transformation of the glass phase into a denser crystalline phase [6].

The thickness and the crystallization ratio (crystallinity or crystalline film thickness) of the solid flux film have been reported to be major factors in forming air gaps according to previous published literature [1,6,9,11,24,26,27].

Many researchers have analyzed the surface roughness of solidified flux adjacent to the contact surface of the mold to correlate and qualitatively evaluate the air gap formation. Shibata et al. [28] suggested the average air-gap thickness of various commercial mold fluxes for three steel grades corresponding to the medium, low, and ultra-low carbon steel to be 73–167 µm from pouring tests. Yamauchi et al. [29] reported the air gap to be 20–50 µm using the contact method and Tsutsumi et al. [12] reported that the surface was approximately 10–30 µm in the crystalline area, which was 10 µm larger than the glassy region using the confocal laser scanning microscope combined with an infrared image furnace. Cho et al. [1] measured the surface roughness using a stylus surface profiler and the r_a was under 10 µm with an r_{MAX} approximately 50–150 µm.

Yamauchi et al. [30] correlated the surface roughness with the solidus temperature of mold fluxes, where increased surface roughness was obtained for higher solidus temperatures. Tsutsumi et al. [12] related the surface roughness with the cooling rate in Na_2O or Li_2O containing calcium-silicate slag systems, where a critical rate results in a drastically reduced surface roughness suggesting the slag to be fully glassy. Cho et al. [1] mentioned the effect of the primary crystalline phase growth rate on the surface roughness, where a faster growth rate instigates greater shrinkage. However, the crystallization mechanism with different growth rates have yet to be fully clarified.

In the present study, to evaluate the interfacial thermal resistance, a copper disc mold simulator (CDMS), which is based on a modified pouring method, was applied. Four kinds of commercial mold fluxes were investigated to understand the bulk crystallization phenomenon using the CDMS. The detailed morphology of the obtained disc sample was observed with a back scattered scanning electron microscope (SEM) and X-ray diffraction (XRD) results to establish the crystalline phases.

2. Experimental

2.1. Materials and sample preparation

Commercial mold powders were decarburized at 898 K (625 °C) for 24 h under air using a Mo-Si$_2$ box furnace. The residual carbon was measured with a C/S analyzer (CS-300; LECO, USA) and was less than 0.1 wt% after decarburization. The post-chemical compositions of the samples were analyzed by XRF (S4 Explorer; Bruker AXS GmbH, Germany), as provided in Table 1.

2.2. Developed copper disc mold simulator and experimental procedure

To implement rapid crystallization behavior similar to the continuous casting mold, spent copper molds were machined to a specified concentric disc shape (diameter: 50 mm, height: 5 mm). Two 1 mm dia. T-type thermocouples (CT-1, CT-2) were embedded inside the copper mold 5 mm and 10 mm from the *hot* surface. Additional T-type thermocouples (WT_{in}, WT_{out}) were installed at the inlet/outlet of the cooling water. To measure the temperature of the poured molten flux during cooling in the CDMS, two 1 mm dia. K-type thermocouples (FT-1, FT-2) were placed above the copper mold surface. Thermocouple FT-1 was placed 1.015 mm above the copper mold surface and the thermocouple FT-2 was placed 0.965 mm above FT-1. These TC's are 6 mm from the inner periphery of the Al_2O_3 insulator aligned horizontally, but not vertically aligned. Dual layers of Al_2O_3 insulators are used to minimize horizontal temperature gradients. These TC's were purposely unaligned vertically for optimal sample retrieval without affecting temperature measurements. The temperature acquisition rate was 10 Hz per thermocouple using the LabVIEW software (National Instrument, USA). A general schematic of this apparatus and a sample of the flux after solidification are provided in Fig. 1(a). The 20 g of flux samples were melted at 1823 K (1550 °C) under 0.3 L/min Ar for 5 min. Before pouring the mold flux, the halogen spot heater (HSH-1, Inflidge Co. LTD, Japan) was turned on and the flux was poured into the concentric disc groove of the CDMS using a supply slide constructed from an Inconel 600 alloy. According to the manufacturers specifications, the spot heater can provide a constant heat flux to a high temperature of about 1573 K (1300 °C) from a distance of 8 cm using a steel sample measured with a direct contact thermocouple. Preliminary work with slag samples using the spot heater at a distance of 10 cm using mold fluxes can be up to 1273 K (1000 °C) at steady state under the con-