In-Situ Quantitative Study of Heat Transfer Performance of Mold Flux by Using Double Hot Thermocouple Technology

Zhe Wang, Guanghua Wen, Wenbo Jiang, Ping Tang, and Shuheng Huang

Abstract The heat transfer ability of the mold flux is crucial for balancing the heat flux between the slab and mold. The double hot thermocouple technique (DHTT) is widely used for the qualitative determination of the heat transfer performance of the mold flux due to its advantages of rapid in-situ testing. However, the traditional DHTT cannot determine heat flux quantitatively, which limits the development of DHTT in the field of heat transfer measurement. In the current study, the in-situ quantitative investigation method based on DHTT was, for the first time, proposed to determine the heat transfer performance of mold flux. Herein, the heat flux of four mold fluxes with different Al_2O_3/SiO_2 mass (A/S) ratios was estimated by using the new DHTT. The result showed that the heat flux decreases with increasing A/S ratio, which is consistent with the result of the parallel-sided plate method.

Keywords Mold flux · Heat flux · Thermal resistance · Double hot thermocouple technique · In-situ quantitative method

Introduction

In continuous casting process, the mold flux plays an essential role in controlling the heat transfer between the billet/slab and the mold [1]. For many steels, especially advanced high strength steel (AHSS) [2], twin-induced plasticity (TWIP) [3], and transformation induced plasticity (TRIP) steels [4], controlling the heat transfer of film is critical to improving the quality of billet/slab. For instance, the thermal mismatch between ferrite and austenite phases can cause the longitudinal cracking problem in casting AHSS steel. It is therefore important to determine the heat transfer properties of the mold flux.

Z. Wang · G. Wen (✉) · W. Jiang · P. Tang · S. Huang
Chongqing University, Chongqing 400044, P. R. China
e-mail: wengh@cqu.edu.cn

Z. Wang
e-mail: zhewang@cqu.edu.cn

TMS 2021 150th Annual Meeting & Exhibition Supplemental Proceedings,
The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-65261-6_29

Currently, there are four main approaches to determine the heat transfer performance of the mold flux: the parallel plate method, the cold finger method, the infrared emitter technique (IET), and the double hot thermocouple technique (DHTT). Many groups take up with the research of the heat transfer properties of mold flux. Cho et al. [5] compared the heat transfer properties of low carbon steel (LC) and medium carbon steel (MC) mold fluxes by using the parallel plate method. The results showed that the interfacial thermal resistance is found to be about 50% of overall thermal resistance for the heat transfer. By using the cold finger method, Qi et al. [6] investigated the heat transfer performance of fluoride-free and titanium-bearing mold fluxes. The results suggested that the heat flux of fluoride-free mold fluxes reduces with increasing basicity (CaO/SiO_2 mass ratio). By employing the IET and the DHTT method, Wang et al. [7] explored the radiative heat transfer behavior and the heat transfer capability of the LC and MC mold fluxes. The results showed that glassy samples behave similar radiation heat transfer capability and the thermal diffusivity of fully crystalline LC mold flux is higher than MC mold flux under the same condition.

The hot thermocouple technique (HTT) is a kind of high-temperature measurement method which uses intermediate frequency chopper technology to realize both heating and temperature measurement [8]. Based on the HTT, the DHTT is further developed by doubling the U-shaped B-type thermocouple and its associated controlling system [9]. The simplicity and versatility of DHTT should make it very useful, especially for in-suit observation of the crystallization and heat transfer properties of mold flux for different temperature gradient. However, all DHTTs used to analyze the heat transfer of mold flux are qualitative analysis and cannot keep a stable temperature field (need the temperature pulse) [7, 9]. Thus, it is crucial to quantify the heat flux by using the DHTT.

Based on the new DHTT, this research provides a new approach to investigate the heat transfer performance of mold flux. The results suggested that the new DHTT results were consistent with results of the parallel plate method.

Experimental

Pre-Melted Samples Preparation

The compositions of mold fluxes are listed in Table 1, which is the same as a previous Reference [10]. The mold fluxes for this study were made of pure chemical reagents. After mechanically mixed in a ball mill, these reagents were melted in an induction furnace at 1773 K for 20 min to homogenize their chemical compositions. Subsequently, the molten mold fluxes were quenched in a water cooled copper plate and crushed for the DHTT experiments.

Table 1 Chemical compositions of mold fluxes (wt%)

No	CaO	SiO_2	Al_2O_3	Na_2O	CaF_2	A/S ratio	Heat flux / MWm^{-2}	Thermal resistance / $10^{-2}K^2W^{-1}$
R1	20	45	5	10	20	0.11	0.449	0.246
R2	20	35	15	10	20	0.43	0.393	0.285
R3	20	25	25	10	20	1.00	0.368	0.302
R4	20	15	35	10	20	2.33	0.321	0.343

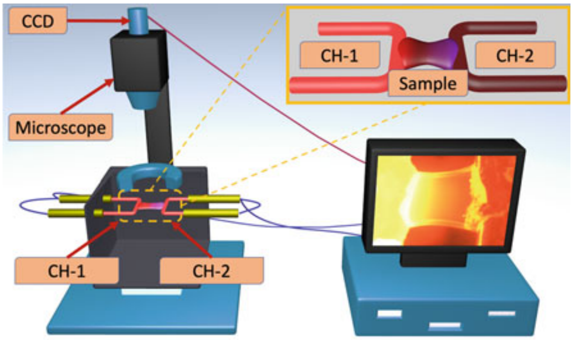


Fig. 1 Schematic of new DHTT. (Color figure online)

Experimental Procedure

Figure 1 shows the schematic diagram of the DHTT device. The details of DHTT have been described by Kashiwaya [11]. Based on the traditional DHTT, we add the duty cycle sensor in each channel, which can collect the output duty cycle. And the sample is heated by the lamps to keep the ambient temperature stable [12].

To test the heat transfer performance of mold flux, a temperature control curve was first designed. As shown in Fig. 2, the temperature of CH-1 and CH-2 was raised rapidly to 1773 K and keep 30 s to homogenize its composition. Then, the temperature of CH-1 and CH-2 rapidly cool down to 1673 K and 1073 K, respectively, remaining in agreement with the temperature gradient in the mold. Secondly, the pre-melted mold fluxes were added on the B-type thermocouple (between CH-1 and CH-2) and heated according to the temperature control curve (Fig. 2). When the temperature gradient is stable, the distance between CH-1 and CH-2 was kept constant at 2 mm. Finally, the duty cycle of CH-1 and CH-2 was collected.

In order to obtain the heat transfer performance of samples, the low-temperature channel (CH-2) was chosen as comparison criteria. In the comparison, if the duty cycle of low-temperature channel (CH-2) was assumed to be lower, estimating the heat flux was higher, and vice versa. In the quantitative study, each sample was repeated three times, and the mean duty cycle value (150 - 230 s of Fig. 2) was taken as the original parameters. However, the results are presented here only to provide

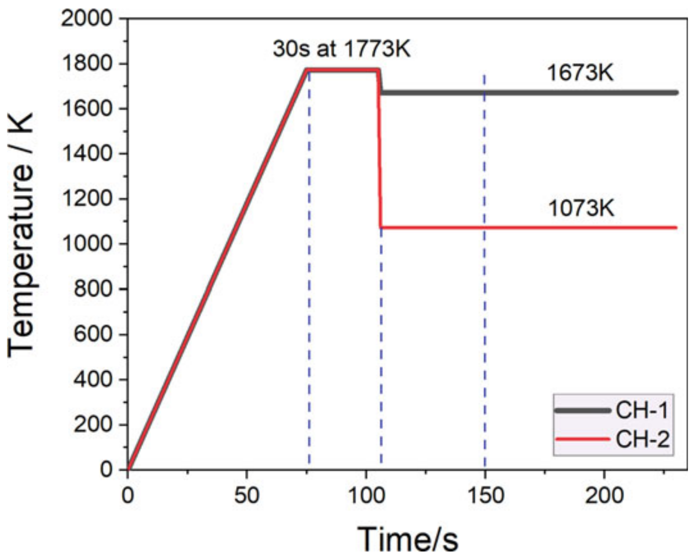


Fig. 2 Temperature control for DHTT test. (Color figure online)

a qualitative value of the heat transfer performance of mold flux. Therefore, further research is needed to quantify these parameters. Since the heat fluxes and thermal resistance of samples are known (Table 1), the conversion function can be obtained by the fitting.

Results and Discussion

Figure 3 shows the duty cycle result of each sample. It can be seen that the duty cycle and thermal resistance increase with increasing A/S ratio, while the heat flux decreases with increasing A/S ratio. These three parameters reflect the trend that the heat transfer performance of the mold flux reduces with the A/S ratio. Actually, this trend is related to the crystallization ratio of mold flux film. Figure 4 shows the in-situ observation results of mold flux film (R1 to R2) at 200 s in Fig. 2. It can be observed that the crystallization ratio increases with increasing A/S ratio. Therefore, the increase of crystallization of films inhibits the heat transfer, which is consistent with the previous studies [13–16].

For the purpose of quantification, the relationships between duty cycle and heat flux or thermal resistance was investigated to estimate the heat flow and thermal resistance of mold flux. As shown in Fig. 5a, it can be seen that the heat flux are significantly correlated with duty cycle, of which the R^2 is 0.992. Thus, the relationship between the heat flux and duty cycle can be estimated by fitting a linear regression model, which was expressed by the formula given below.

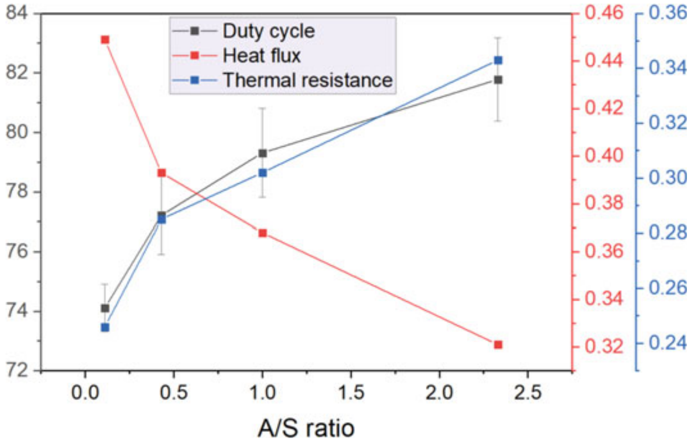
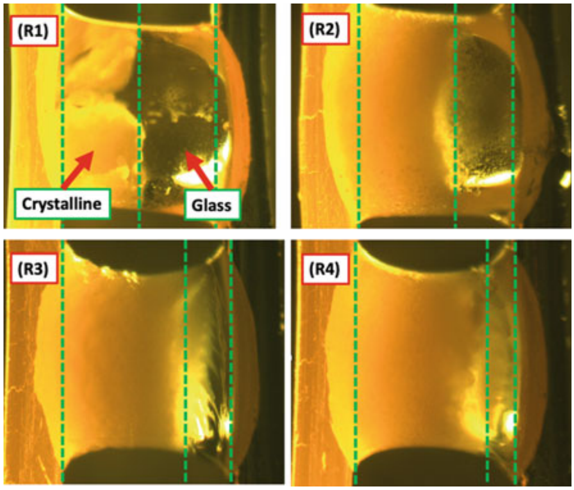


Fig. 3 Heat flux, duty cycle, and thermal resistance change with the A/S ratio. (Color figure online)

Fig. 4 In-situ DHTT observation of mold flux. (Color figure online)



$$q = -0.163\frac{w}{10} + 1.660 \quad (1)$$

where q is the heat flux (MWm^{-2}), w is the duty cycle (‰) obtained by new DHTT. As shown in Fig. 5b, the thermal resistance has an obvious positive correlation with the duty cycle ($R^2 = 0.980$). Thus, the conversion relationship between the thermal resistance and duty cycle is further established, as shown below.

$$R = 0.123\frac{w}{10} - 0.665 \quad (2)$$

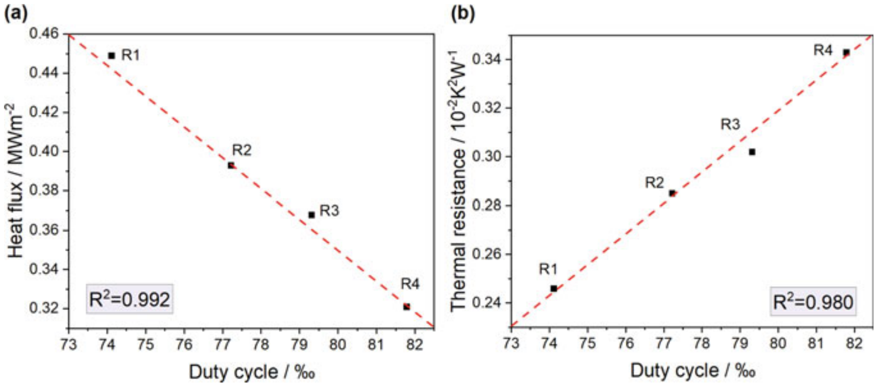


Fig. 5 Correlation analysis: **a** relationship between the heat flux and duty cycle, **b** relationship between the thermal resistance and duty cycle. (Color figure online)

where R is the thermal resistance ($10^{-2}K^2W^{-1}$). Thus, the new DHTT can be used quantitatively to evaluate the heat flux and thermal resistance of mold flux film by using Eqs. 1 and 2.

In this study, we prosed a new DHTT method to determine the heat transfer performance of mold flux. The results showed that the new DHTT not only solves the problem that traditional DHTT cannot be utilized in a quantitative study, but also establishes a stable temperature gradient in during the experiment (no need for a temperature pulse). Collectively, the new DHTT provides a new approach to investigate the heat transfer performance of mold flux at high temperature.

Conclusion

In this paper, a new DHTT method was, for the first time, employed to quantitatively estimate the heat transfer performance of mold flux. The duty cycle of the low-temperature channel increases with increasing A/S ratio, reflecting the heat transfer performance of mold flux reducing with the increase of A/S ratio, which consistent with the results obtained by the parallel plate method. The conversion formulas are further established, which enables the new DHTT can be used to estimate the heat flow and thermal resistance of mold flux.

Acknowledgements The authors greatly appreciate the funding from the Graduate Scientific Research and Innovation Foundation of Chongqing, China (Grant No. CYB19002).

References

1. Zhang SD et al (2019) Effect of substituting Na_2O for SiO_2 on the non-isothermal crystallization behavior of CaO-BaO-Al2O_3 based mold fluxes for casting high Al steels. Ceram Int 45:11296–11303
2. Jia N et al (2009) An in situ high-energy X-ray diffraction study of micromechanical behavior of multiple phases in advanced high-strength steels. Acta Mater 57:3965–3977
3. Luo ZC et al (2018) The effect of deformation twins on the quasi-cleavage crack propagation in twinning-induced plasticity steels. Acta Mater 150:59–68
4. Wang WL, Lu BX, Xiao D (2016) A review of mold flux development for the casting of high-Al steels. Metallurgical Mater Trans B-Process Metallurgy Mater Process Sci. 47:384–389
5. Cho J et al (1998) Thermal resistance at the interface between mold flux film and mold for continuous casting of steels. ISIJ Int 38:440–446
6. Qi X, Wen GH, Tang P (2008) Investigation on heat transfer performance of fluoride-free and titanium-bearing mold fluxes. J Non-Cryst Solids 354:5444–5452
7. Wang WL et al (2011) Radiative heat transfer behavior of mold fluxes for casting low and medium carbon steels. ISIJ Int 51:1838–1845
8. Wang Z et al (2019) Novel method for determining the interfacial properties of melt slags based on single hot thermocouple technique. ISIJ Int 59:1806–1810
9. Wang WL et al (2018) High-temperature properties of mold flux observed and measured in situ by single/double hot-thermocouple technique. Jom. 70:1248–1255
10. Yan W et al (2015) Effect of slag compositions and additive on heat transfer and crystallization of mold fluxes for high-Al non-magnetic steel. ISIJ Int 55:1000–1009
11. Kashiwaya Y et al (1998) Development of double and single hot thermocouple technique for in situ observation and measurement of mold slag crystallization. ISIJ Int 38:348–356
12. Wang Z et al (2019) A novel method of surface tension test for melt slags based on hot thermocouple technique. Springer
13. Hayashi M, Abas RA, Seetharaman S (2004) Effect of crystallinity on thermal diffusivities of mould fluxes for the continuous casting of steels. ISIJ Int 44:691–697
14. Ozawa S et al (2006) Lattice and radiation conductivities for mould fluxes from the perspective of degree of crystallinity. ISIJ Int 46:413–419
15. Wang W, Cramb AW (2010) Study of the Effects of the Mold Surface and Solid Mold Flux Crystallization on Radiative Heat Transfer Rates in Continuous Casting. Steel Res Int 81:446–452
16. Cho JW et al (2013) Assessment of CaO-Al2O3 Based Mold Flux System for High Aluminum TRIP Casting. ISIJ Int 53:62–70