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論文内容要旨

1. Introduction

In modern large scale integrated iron and steel plants, casting and hot rolling of steel slabs have been connected directly as HDR (Hot direct rolling) process to save energy and increase productivity. High speed casting is essential in this process because the cast slabs must be transferred to hot rolling without reheating. However, increased heat flux in mold at the higher casting speeds tends to cause more longitudinal cracks on the slab surface especially for peritectic medium carbon steel the solidifying shell of which grows irregularly due to enhanced shrinkage on $\delta \rightarrow \gamma$ transformation. Therefore, casting speed should be limited to sustain heat flux to be less than a threshold value, for example, 2.4MW/m^2 for low carbon steels and 1.6 MW/m^2 for peritectic medium carbon steels. Basic mold fluxes are known to be effective to reduce the occurrence of surface cracks by decreasing the heat flux. However, the reason for the decrease has not been made clear as yet.

Major objective of this study is to determine the contribution of each factor which influences the heat transfer from steel shell to mold across the film of mold fluxes which are in commercial use. Thermal properties of conduction and radiation in mold flux have bee observed, and interfacial thermal resistance between mold and mold flux film has been determined. In addition, numerical calculation has been carried out by taking into consideration the data on the conduction, radiation and interfacial thermal resistance. The difference in the thermal properties between the mold fluxes for low carbon steels and those for medium carbon steel has been investigated as a function of their basicity.

2. Effect of thermal and optical properties of mold flux on the radiative heat transfer across mold flux film

Absorption coefficient and extinction coefficient of commercial mold fluxes have been determined to evaluate the radiative heat transfer through infiltrated film of these fluxes in continuous casting mold. The absorption coefficient is found to be less than $1000m^{-1}$ for glassy films whereas the extinction coefficient is ca. $3000\sim30000m^{-1}$ for crystalline ones. Comparison of observed with calculated radiative heat flux has shown that gray gas approximation is valid for evaluating the radiative heat flux across the mold flux film as shown in **Fig.1**. Numerical calculation for both radiative and conductive heat transfer has been carried out for a given total thickness of the flux film. Despite little difference in optical properties among these mold fluxes, the radiative heat flux through molten layer of the flux films for low carbon and ultra low carbon steels is found larger than that for medium carbon steels, owing to increasing thickness ratio of molten layer to crystalline layer of the flux films as shown in **Fig.2**. Behavior of solidification and crystallization of the mold fluxes is found to be a key factor to control the radiative heat transfer in continuous casting mold, accordingly.

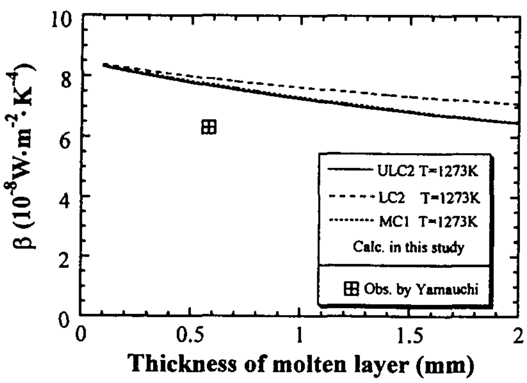

Fig. 1 Calculated β for molten layer of flux film under gray gas approximation

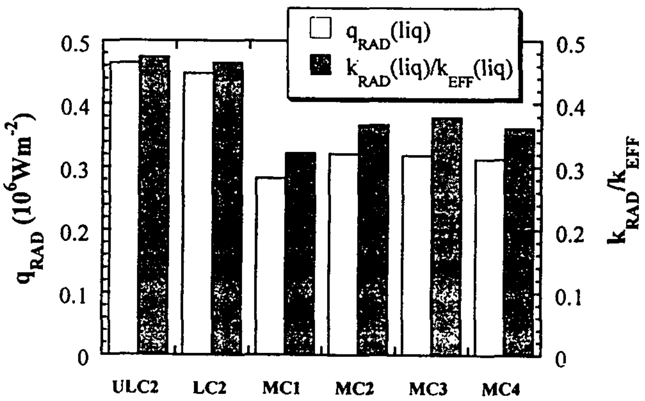

Fig. 2 Amount and ratio of radiative heat flux in molten layer of flux film when total flux film thickness is fixed at 1.5mm

3. Thermal Resistance at the Interface between Mold Flux Film and Mold for Continuous Casting of Steels

A model system consisting of mold/mold flux film/steel shell was built to determine the thermal resistance, R_{INT}, at the mold/mold flux interface. The R_{INT} increases with increasing flux film thickness in contrast to previous observation by others who assumed that the interfacial thermal resistance is constant for different flux film thickness. The R_{INT} is found to be about 50% of overall thermal resistance for the heat transfer at the near meniscus position in mold. Observed lower heat flux for MC2 mold flux with higher crystallization temperature is than attributed not due to reduced radiative heat transfer but to higher interfacial thermal resistance at the same flux film thickness as LC2. This arises from the difference in crystallizing behavior, particularly growth rate of crystalline layer, between the two fluxes. This difference in R_{INT} is the major reason why heat flux for MC2 mold flux is lower than that for LC2 as shown in **Fig.3**.

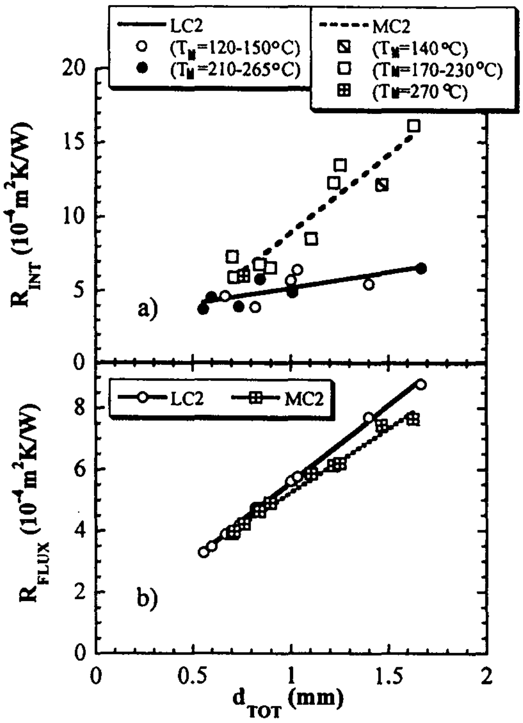

Fig.3 Change of observed interfacial and through thickness thermal resistances with thickness of mold flux film

To apply these observations to the numerical analysis of overall heat transfer in continuous casting mold, relation between R_{INT} and the thickness of crystalline layer (d_{CRY}) in the mold flux film has been derived as follows:

R_{INT} ($10^{-4}m^2K/W$)= 16.4 x d_{CRY} (mm) for MC2 where $0.4 \leqq d_{CRY}(mm) \leqq 0.9$

R_{INT} ($10^{-4}m^2K/W$)= 2.94 x d_{CRY} (mm) + 3.52 for LC2 where $0.3 \leqq d_{CRY}(mm) \leqq 1.0$

4. Heat Transfer from Solidifying Shell to Mold across Mold Flux Film during Initial Solidification in Continuous Casting of Steel

Numerical analysis of heat transfer near the meniscus in mold for continuous casting of steel has been carried out by taking into account the conductive and radiative thermal resistances of infiltrated mold flux film and the thermal resistance at the copper mold/solidifying mold flux film interface. Thermal conductivities, absorption coefficients and interfacial thermal resistances of these fluxes have been determined by laser flash method (Ch.2), high temperature cell FTIR test (Ch.2) and contacting thermal resistance test (Ch.3), respectively.

Calculation with these data shows that the heat transfer is strongly influenced by the R_{INT} as shown in **Fig.4**. Slow cooling required for casting surface crack sensitive medium carbon peritectic steel slabs can be achieved by making the interfacial thermal resistance high, which is attainable by use of basic mold fluxes with high rate of crystallization. A flux film thicker than 0.25mm for LC2 or 0.4mm for MC2 is also found to be a requisite to prevent the occurrence of longitudinal surface cracks as shown in **Fig.5**. Reasonably high interfacial thermal resistance and a proper flux film thickness are concluded to be essential to reduce the surface defects and to increase the speed of continuous casting of these steel slabs.

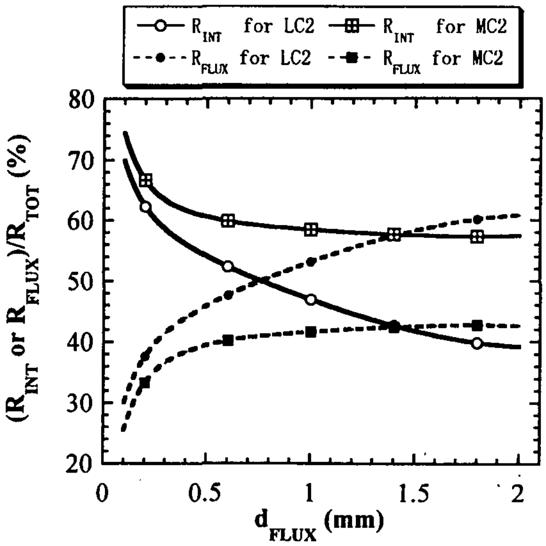

Fig.4 Change of thermal resistance ratio of interfacial (R_{INT}) or flux film (R_{FLUX}) to total (R_{TOT}).

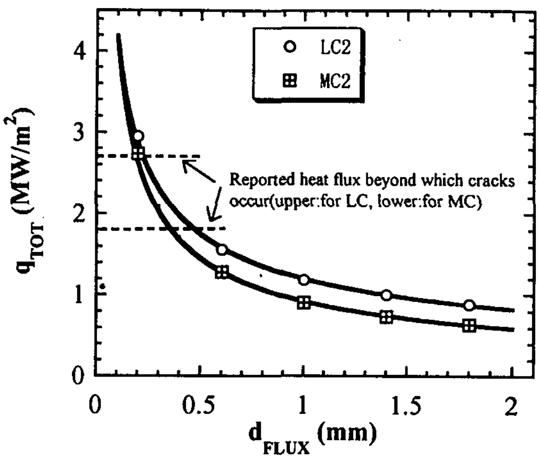

Fig.5 Heat flux in mold as a function of total mold flux film thickness.

5. In-situ observation of crystallization of mold flux by confocal scanning laser microscope

Crystallizing behavior of mold flux film has been observed with a confocal scanning laser microscope (CSLM). The crystallization of mold flux in the mold is expected to occur in two ways. One is in solidified glassy phase near the interface between flux film and mold, and the other is directly in liquid phase near the solidified steel shell. Observation on both cases has indicated that mold flux for peritectic medium carbon steels (MC2) starts crystallizing directly in liquid phase at higher temperature, and shows faster growth than the mold flux for low carbon steels (LC2). Dendritic growth of cuspidine as a primary phase has been observed in these two mold fluxes, nepherine appearing only in LC below 976K. Cross section of solidified fluxes shows that the shrinkage due to the crystallization is more in MC2 than in LC2. The crystalline phases formed in glassy flux was the same as those in liquid flux, cuspidine in MC2 and cuspidine + nepherine in LC2. The surface roughness of the flux film of LC2 increased due to the crystallization while that of MC2 hardly changed.

These results imply that thermal resistance at mold/mold flux film interface arises from the solidification and crystallization of flux film, routing of which is mainly direct crystallization in liquid flux for MC2 and low temperature crystallization of glassy solid for LC2.

6. Conclusion

The thermal resistances to the heat transfer from solidifying steel shell to copper mold across mold flux film in continuous casting consist of radiative-, conductive- and interfacial-components. All of these thermal resistances for commercial mold fluxes have been evaluated with a model system under conditions similar to those in real continuous casting mold, and utilized in an analysis of heat transfer in mold. There are not much difference in radiative and conductive thermal resistance between the mold fluxes for medium carbon steels and low carbon steels. However, mold flux MC2 shows much higher interfacial thermal resistance, R_{INT}, than LC2. Observation with CSLM indicates that this difference arises mainly from greater crystallizing tendency, e.g., faster growth rate of crystalline layer, of the former mold flux. Slow cooling attainable with basic mold fluxes for casting peritectic medium carbon steels is caused by this greater R_{INT} as a consequence of faster crystallization in mold flux film. There are good possibilities to reduce the heat flux, and hence to raise the casting speed of steel slabs by controlling the thermophysical properties, especially interfacial thermal resistance, of mold flux film as a function of the composition of the mold flux.

審査結果の要旨

鉄鋼素材の生産性向上には、連続鋳造速度を上げることが不可欠であるが、高速化すると鋳型内の熱流束が大きくなり、鋼の凝固殻が不均一成長し、スラブの表面に縦割れが発生する原因となる。このような縦割れを防止するには、塩基性モールドフラックスを使用し、鋳型内の熱流束を低下させると効果的なことが経験的に知られているが、その機構は未だ明らかではない。本研究は、鋼の連続鋳造用モールドフラックスの伝導および輻射熱物性ならびにフラックス／銅鋳型の界面熱抵抗を測定し、それらの値を利用して数値計算を行い、連続鋳造プロセスにおける熱流束について検討したもので、全編6章よりなる。

第1章は序論であり、本研究の意義と目的について述べている。

第2章では、中炭素鋼および低炭素鋼で実用化されているモールドフラックスの吸収係数を測定し、その値を利用して輻射および伝導伝熱に関する数値計算を試み、フラックスの液相における輻射熱流束が小さいなどの知見を定量的に明らかにしている。

第3章では、独自に作製した実験装置を用いて実施した、モールドフラックスと銅鋳型間の界面熱抵抗に関する測定値と、その解析について述べており、界面熱抵抗は凝固殻と銅鋳型間の総熱抵抗の 50%以上であり、鋳型内の伝熱に最も影響すること、界面熱抵抗が高塩基度モールドフラックスの緩冷却機構の主役であることを明らかにしている。

第4章では、連続鋳造プロセス、メニスカス直下部におけるモールドフラックスを介して生ずる初期凝固殻から銅鋳型への熱伝達について実施した数値計算結果を示し、縦割れを防止するためには、中炭素鋼の場合はフラックスの厚さを 0.4mm,低炭素鋼の場合は 0.25mm 以下に維持する必要があることなどの定量的知見を得ている。

第5章では、共焦点走査型レーザー顕微鏡を用いて中炭素鋼および低炭素鋼用モールドフラックスの高温における結晶化挙動を直接観察し、界面熱抵抗の生成原因を検討するとともに、中炭素鋼用フラックスと低炭素鋼用フラックスとの間に認められる界面熱抵抗の差は、それぞれのフラックスの結晶化挙動の違いによることなどを明らかにしている。

第6章は総括である。

以上要するに、本論文は、モールドフラックスの熱物性ならびにフラックス／鋳型の界面熱抵抗の情報を基に、鋼の連続鋳造鋳型内の伝熱機構について詳細に検討し、熱流速の制御に関する基礎的な知見を得たもので、金属工学および材料加工プロセス学の発展に寄与するところが少なくない。よって本論文は博士（工学）の学位論文として合格と認める。