Structure and performance characteristics of mold flux films for continuous casting of special alloy steels

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Flux films and liquid slags for low-expansion alloy Fe-36Ni, austenitic stainless steel 304 and martensitic stainless steel 420J2 were taken from casting mold. Chemical compositions were measured by chemical analysis; apparent morphologies of flux films were photographed; cross-section structure, thickness, crystalline fraction and crystalline phases of flux films were examined by SEM, EDS and XRD; viscosity and break temperature were calculated by models. The results showed flux films and liquid slags have similar chemical compositions, but there is a certain difference from the original powders. Flux films for the three steel grades have obvious layered structure and main crystalline phase cuspidine, viscosity and break temperature keep steady during casting. Heat transfer across flux films characterized by morphology, thickness, viscosity, break temperature and crystalline fraction of flux films showed flux film for austenitic stainless steel 304, martensitic stainless steel 420J2 and low-expansion alloy steel Fe-36Ni have the best, moderate and the lowest ability to control heat transfer. Heat transfer across flux films agrees with solidification characteristic of steel grades generally. Low-expansion alloy Fe-36Ni has good surface quality and there is no occurrence of hot-rolling cracking. Stainless steels 304 and 420J2 have no surface cracking but local depressions.

Keywords: Special Alloy Steels, Mold Fluxes, Flux Films, Crystallization, Heat Transfer

INTRODUCTION

Mold fluxes play significant roles in continuous casting, the most one of them is to control horizontal heat transfer across flux film from the strand to the mold. The mold powders which are fed onto liquid steel melt and infiltrate into the gap between the mold and the strand, and then quench to form solidified slag films due to high temperature gradient [1]. Some researchers [2-7] have reported that structure and property characteristics of flux films have an important effect on heat transfer from the strand to the mold, furthermore, on slab quality and stability of continuous casting.

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More studies on flux films for middle carbon (MC) and low carbon (LC) steels were carried out by field sampling or laboratory simulation [5,8-11]. However, study on flux films for special alloy steels is still little. Low-expansion alloy steel Fe-36Ni, austenitic stainless steel 304 and martensitic stainless steel 420J2 are all high alloy steel grades, different solidification characteristics require different flux films according to control of heat transfer across flux films. There is no obvious shrinkage from phase transformation because Fe-36Ni is single-phase austenitic steel, and it has low strength, so high heat transfer across flux film is necessary to form thick initial shell to increase strength. The release of large thermal stress arisen from large shrinkage due to peritectic reaction during solidification of austenitic stainless steel 304 causes cracking of cast slabs, the cracking can be alleviated by mild cooling during initial solidification. A certain amount of solidification shrinkage and sticking breakout occur easily during continuous casting of martensitic stainless steel 420J2 because of its relatively high carbon content, and hence mold fluxes with characteristics of both controlling heat transfer and ensuring lubrication are required. In the present work, liquid slags and flux films were taken from mold, the chemical compositions, structures, viscosities and break temperature also crystallization properties were studied in detail. The objective of this work is to study and reveal the relationship between solidification characteristic of special alloy steels, structures and properties of flux films, and heat transfer across flux films, furthermore, to provide references for design or improvement of mold fluxes for special alloy steels.

EXPERIMENT

Liquid slags and flux films samples were taken from cast mold. Liquid slags for low-expansion alloy steel Fe-36Ni, stainless steels 304 and 420J2 were taken by wood scoop and cast iron scoop respectively after the start of casting 30min since the first heat. The flux films were taken in range of 10~20cm below the meniscus after tailout. All liquid slags and flux films samples were cooled in air to room temperature. The casting conditions are shown in Table 1, the chemical compositions of the original mold powders for the three steel grades are shown in Table 2.

Flux	Steel	Caster type	Mold size/ mm	Casting speed m/ min
a	Fe-36Ni	vertical	1150×200	~0.7
b	304	arc	160×160	1.3~1.5
c	420J2	arc	160×160	1.2~1.4

Table 1 - Continuous casting parameters

Tabella 1 - Parametri di colata continua

Chemical analysis of liquid slags and flux films were carried out, apparent morphologies of flux films were observed by photograph, cross-section morphology, structure and thickness were analyzed by scanning electron microscope (SEM), crystalline phases of flux films were analyzed by energy dispersive X-ray Spectroscopy (EDS) together with X-ray diffraction (XRD). In addition, the ratio of the thickness of crystalline layer to the overall thickness of flux film is defined to be the crystalline fraction of flux film.

RESULTS

Chemical compositions of liquid slags and flux films

The chemical compositions of liquid slags and flux films for Fe-36Ni, 304 and 420J2 are shown in Table 3. The main chemical composition changes of the original mold powders, liquid slags and flux films are as follows.

i. Al_2O_3. Al_2O_3 contents of liquid slags and flux films for stainless steels 304 and 420J2 except for Fe-36Ni only have a slight increase of about 0.3%.

ii. MnO. In comparison with the original mold powders, the MnO contents of liquid slags and flux films have a different increase, especially for the flux films for stainless steels 304 and 420J2, have an increase of 1.02% and 1.33% respectively.

iii. Cr_2O_3. Stainless steels 304 and 420J2 have high Cr content, Cr is oxidized and absorbed into molten slags which increases Cr_2O_3 content in liquid slags. Cr_2O_3 contents of

	Flux	Steel	CaO	SiO_2	Al_2O_3	MgO	MnO	Na_2O	F	Cr_2O_3	C_{total}	LOI*
Including C and LOI	a	Fe-36Ni	33.09	29.81	6.91	1.21	-	11.69	4.9	-	3.9	9.32
	b	304	30.52	33.78	6.06	1.01	0.08	11.56	6.17	-	3.8	9.86
	c	420J2	30.60	33.76	6.15	0.94	0.07	10.68	6.44	-	5.1	10.74
Removing C and LOI	a	Fe-36Ni	37.77	34.03	7.89	1.38	-	13.34	5.59	-	-	-
	b	304	34.22	37.88	6.80	1.13	0.09	12.96	6.92	-	-	-
	c	420J2	34.52	38.09	6.94	1.06	0.08	12.05	7.27	-	-	-

Table 2 - Chemical compositions of the original mold powders (in mass percent)

Tabella 2 - Composizioni chimiche delle polveri originali per lingottiere (massa in percentuale)

Steel	Samples	CaO	SiO_2	Al_2O_3	MgO	MnO	Na_2O	F	Cr_2O_3
Fe-36Ni	film a	37.56	34.19	8.11	1.43	0.26	12.02	6.43	-
	28min liquid slags	37.05	34.14	8.09	1.47	0.19	12.53	6.52	-
304	film b	33.06	36.65	6.87	1.19	1.11	12.14	7.78	1.21
	30min liquid slags	33.04	36.57	7.02	1.22	1.43	12.18	7.61	0.92
420J2	film c	34.06	35.16	6.58	1.07	1.41	12.20	8.61	0.91
	26min liquid slags	32.88	36.74	7.23	1.21	1.36	11.79	7.88	0.91

Table 3 - Chemical compositions of liquid slags and slag films (in mass percent)

Tabella 3 - Composizione chimica delle scorie liquide e del film di scorie (massa in percentuale)

Film	Steel	Apparent morphology	Cross-section morphology	Cross-section structure (mold⟶strand)	Thickness range/ mm
a	Fe-36Ni	coarse, cracks	more pores cracks	mixed layer of coarse and fine crystals⟶glassy layer	1.43~1.77
b	304	very coarse, no crack	pores no crack	mixed layer of glass and fine crystals⟶mixed layer of coarse and fine crystals⟶glassy layer	1.58~1.69
c	420J2	coarse, cracks	few pores cracks	mixed layer of glass and fine crystals⟶mixed layer of coarse and fine crystals⟶glassy layer	0.61~0.86

Table 4 - Morphology and structure of flux films

Tabella 4 - Morfologia e struttura dei film

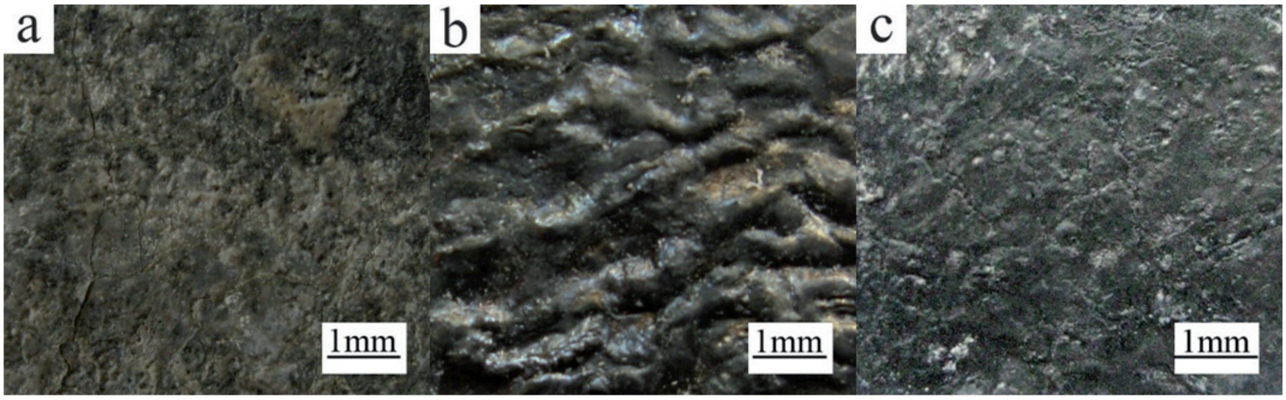

Fig. 1 Apparent morphology of flux films near the mold (a) Fe-36Ni, (b) 304, (c) 420J2

Fig . 1 - Morfologia apparente del film di flusso in prossimità della lingottiera (a) Fe - 36Ni , (b) 304 , (c) 420J2

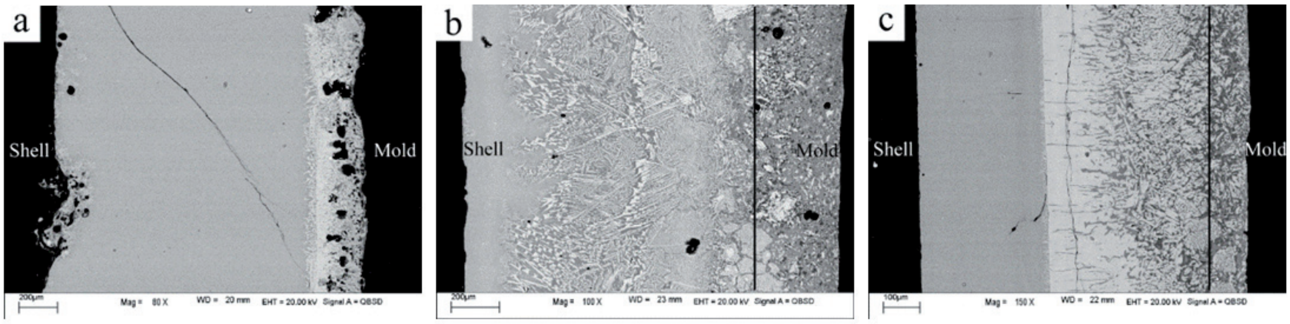

Fig. 2 - Section morphology of flux films (a) Fe-36Ni, (b) 304, (c) 420J2

Fig . 2 - Morfologia dei film in sezione (a) Fe - 36Ni , (b) 304 , (c) 420J2

liquid slags and flux films for stainless steels increase by about 1%.

iv. Na_2O. Decrease of Na_2O is due to the evaporation pressure of Na_2O at higher temperatures. Na_2O of flux films for low-expansion alloy Fe-36Ni has the largest decrease of 1.32%, Na_2O of flux films for 304 steels has mid decrease of 0.82%, Na_2O of flux films for 420J2 steels has the least decrease of 0.15%, but Na_2O of liquid slags for 420J2 steels has an obvious decrease.

It can be seen that the chemical compositions changes of flux films for Fe-36Ni, 304 and 420J2 are expressed mainly by changes of Al_2O_3, MnO, Cr_2O_3 and Na_2O (there is an analysis error for F, F should decrease due to volatilization from the experience). There are similar chemical compositions between liquid slags and flux films but relatively big difference from that of the original mold powders. This indicates flux films consume all the time with oscillation of mold and slab withdrawing during continuous casting.

MORPHOLOGY AND STRUCTURE OF FLUX FILMS

The apparent morphology and cross-section morphology of flux films are shown in Fig. 1 and Fig. 2. It can be seen that from Fig. 1 flux films in connection with mold have different roughness. Gutters distribute all over the flux films in connection with the mold for stainless steel 304, it has the highest roughness. Flux films in connection with the

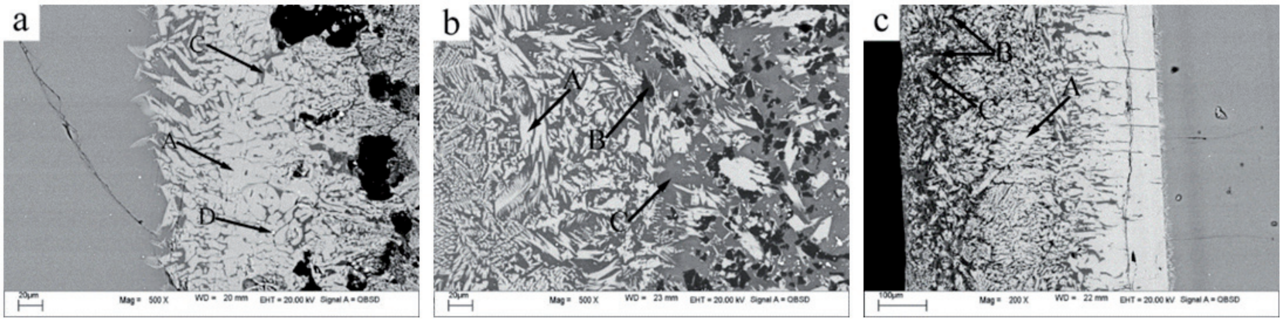

Fig. 3 - BSE images of flux films (a Fe-36Ni, b 304, c 420J2; A cuspidine, B nepheline, C matrix, D Fe)

Fig . 3 - Immagini BSE del film (a Fe - 36Ni , b 304 , c 420J2 ; A a cuspide , B nefelinica , C matrice , D Fe)

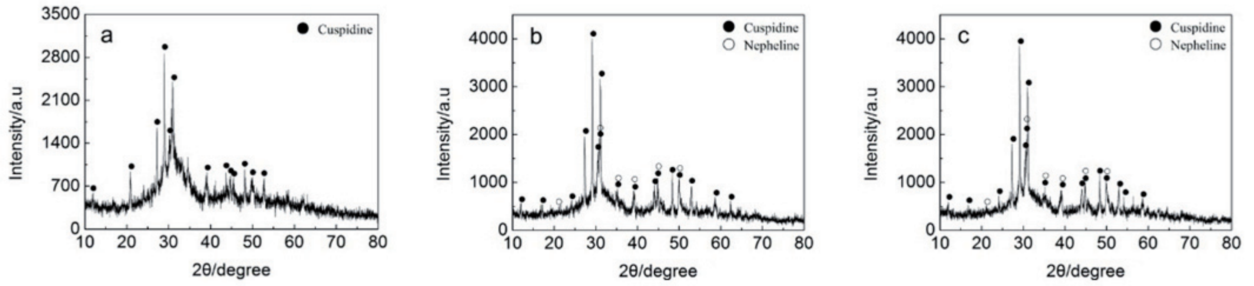

Fig. 4 - XRD patterns of flux films (a) Fe-36Ni, (b) 304, (c) 420J2

Fig . 4 - Schemi di XRD dei film (a) Fe - 36Ni , (b) 304 , (c) 420J2

mold for Fe-36Ni and 420J2 steels have similar roughness, but the roughness is far lower than that of flux film for 304 steel. Fig. 2 shows long cracks in cross-section of flux film for Fe-36Ni and 420J2 steels, but there is no crack in cross-section of flux film for 304 steel. In addition, more pores are found in both sides of flux film for Fe-36Ni, and the pores in flux film near the mold are more than that near the strand. There are a certain amount of pores in flux film for stainless steel 304, relatively, the less pores are in flux film for stainless steel 420J2. The contraction due to phase transformation from glass to crystallization is the main factor to cause rough surface and pores, moreover, entrainment of gas is also an important factor to cause pores during fast cooling of molten slags.

Meanwhile, as can be seen that from Fig. 2 there are similar and obvious layered structures in cross-section of flux films, namely, mixed layer of glass and fine crystals in connection with the mold(except for flux film for Fe-36Ni), dense mixed layer of coarse and fine crystals, and glassy layer near the strand.

The thickness of flux films is the average thickness of some pieces of flux films. Flux films for Fe-36Ni and 304 steels have the almost same thickness about 1.6mm, flux film for 420J2 has the least thickness 0.74mm.

CRYSTALLIZATION PROPERTIES OF FLUX FILMS

The crystallization properties of flux films can be expressed mainly by crystalline fraction and crystalline phases.

Film	Steel	Crystalline phase	Crystalline fraction/%
a	Fe-36Ni	cuspidine	21.4
b	304	cuspidine, nepheline	85.3
c	420J2	cuspidine, nepheline	49.8

Tab. 5 - Thickness and crystalline fraction of flux films

Tab. 5 - Spessore e frazione cristallina del film di flusso

The crystalline fraction of flux film is defined by the ratio of the thickness of crystalline layer to the overall thickness of flux film. The average crystalline fractions of flux films are shown in Table 5. It can be seen that from Table 5 flux film for stainless steel 304 has the highest crystalline fraction about 85% which is four times of crystalline fraction of flux film for Fe-36Ni. Flux film for 420J2 has the mid crystalline fraction about 50%.

According to Fig. 3 and Fig. 4, the analysis results of SEM have a good agreement with XRD analysis. The cuspidine phase is the main crystalline phase of flux films for Fe-36Ni, 304 and 420J2 steels; furthermore, a small quantity of nepheline phases exist in flux films for stainless steel 304 and 420J2, there is also a spot of metal particles in flux films for Fe-36Ni.

DISCUSSION

Relation between viscosities, break temperature and heat transfer

Changes of chemical compositions during continuous casting will affect viscosity, break temperature, crystallization and heat transfer properties of mold fluxes, and then affect slab quality and stability of continuous casting. Increase of viscosity will decrease lubrication and thicken flux films; increase of break temperature will increase thickness and crystallinity of flux films, and control heat transfer eventually.

Viscosity [12] and break temperature [13] of the original mold powders, liquid slags after casting 30min and flux films are calculated by models (1~4) as follows. The results as Fig. 5 show that viscosities and break temperature keep steady by and large during continuous casting.

$$\log\eta = \log A + B/T \tag{1}$$

$$\log A = -2.307 - 0.046(X_{SiO_2}) - 0.07(X_{CaO}) - 0.041(X_{MgO}) - 0.185(X_{Al_2O_3}) + 0.035(X_{CaF_2}) - 0.095(X_{B_2O_3}) \tag{2}$$

$$B = 6807.2 + 70.68(X_{SiO_2}) + 32.58(X_{CaO}) + 321.65(X_{Al_2O_3}) - 34.77(X_{Na_2O}) - 176.1(X_{CaF_2}) - 167.4(X_{Li_2O}) + 59.7(X_{B_2O_3}) \tag{3}$$

$$T_{break} - 1120\ ^{\circ}C = -8.43\%Al_2O_3 - 3.3\%SiO_2 + 8.65\%CaO - 13.86\%MgO - 18.4\%Fe_2O_3 - 3.2\%MnO + 22.86\%K_2O - 3.20\%Na_2O - 6.47\%F \tag{4}$$

Where η is viscosity at 1300 °C, Pa·s; T, Kelvin temperature, K; X_i is molar fraction of composition i; T_{break} is break temperature, °C; %i is weight percent of composition i.

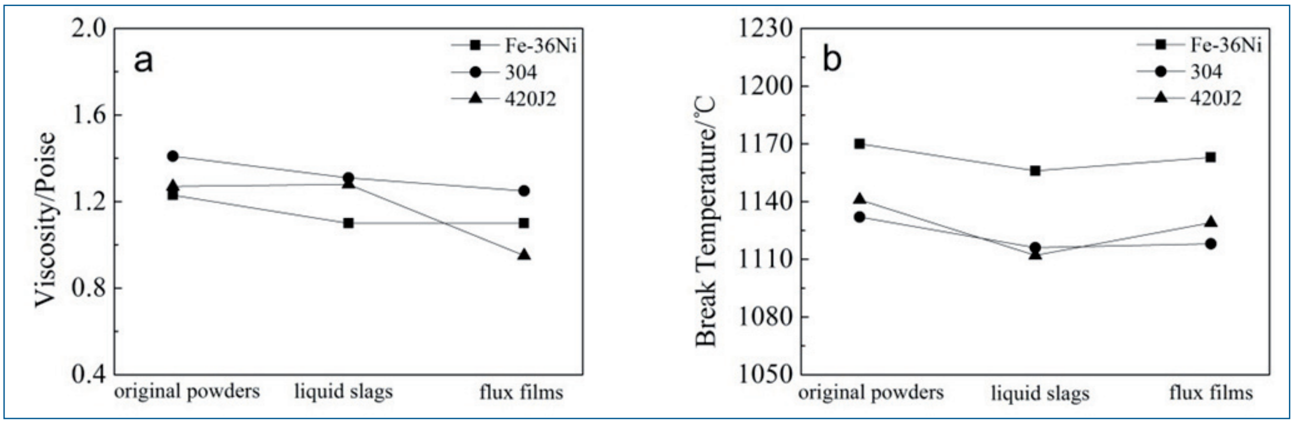

Fig. 5 - Effect of comprehensive changes of chemical compositions on properties of mold fluxes

Fig . 5 - Effetto dei cambiamenti globali della composizione chimica sulle proprietà dei flussi nella lingottiera

Nakano's [14,15] study on continuous casting of MC steels showed that when the temperature difference between a certain portion of steel in the vicinity of the meniscus and the normal portions is about 10 °C, namely, corresponding $\eta\cdot V$ (V is casting speed) is in range of 1.0~3.5Poise·m/min, more even heat transfer and less occurrence of longitudinal cracking are achieved. In association with viscosity calculated above and casting parameters in Table 1, the $\eta\cdot V$ values of mold fluxes for Fe-36Ni, 304 and 420J2 steels are presented in Fig. 6. It can be seen that from Fig. 6 ηV values of mold fluxes and slag films for stainless steels 304 and 420J2 locate in the region where heat transfer is more even and longitudinal cracking is less. However, mold flux and slag film for Fe-

36Ni have the same η·V which locates in the bottom edge of the optimum region. This optimum region is obtained by statistical investigations on MC and high crack-sensitivity steels, therefore, this optimum region can be suitable for MC stainless steels 304 and 420J2 but should be widened for LC and low crack-sensitivity steel Fe-36Ni. In terms of casting effects, there are no cracks in casting billets of Fe-36Ni, 304 and 420J2. Consequently, from the perspective of relation between viscosity and heat transfer, liquid slags and flux films for three steel grades meet the requirement of continuous casting. Furthermore, the application range of viscosity is wide for continuous casting of billets; moderate increase of viscosity of mold fluxes for 304 and 420J2 steels can make η·V locate in intermediate position of the optimum region. Low-expansion alloy steel Fe-36Ni has small solidification shrinkage and low high temperature strength, mold fluxes with good fluidity and heat transfer are more practical for casting of Fe-36Ni.

Flux film for Fe-36Ni has high break temperature. According to the principles that crack sensitive steels require mold fluxes with high break temperature but sticking sensitive steels has the opposite requirement; it is recommendable to decrease break temperature of flux film for Fe-36Ni to facilitate heat transfer. Based on relation between viscosities, break temperature of mold fluxes and casting speed reported in reference [1], moderate decrease of break temperature of mold fluxes are beneficial for continuous casting Fe-36Ni. Moderate increase viscosity of mold fluxes for stainless steel 304 and 420J2 can meet comprehensive needs of surface quality and stable continuous casting. Analysis from this perspective is in accordance with that from Fig. 6.

EFFECT OF STRUCTURE AND CRYSTALLINITY OF FLUX FILMS ON HEAT TRANSFER

Structure and crystallinity (or crystalline fraction) of flux films determine their heat transfer capability which introduces a key effect on continuous casting and surface quality of casting slabs.

It can be seen that from Fig. 2 and Table 4 flux films for special alloy steels Fe-36Ni, 304 and 420J2 have similar layered structures, which are mixed layer of glassy and fine crystals in connection with the mold (except for flux film for Fe-36Ni), mid dense mixed layer of coarse and fine crystals, glassy layer near the strand. In general, sandwich structured "glassy layer-crystalline layer-glassy layer" forms after infiltration of molten slags into the gap between the mold and strand. However, more fine crystals in the region in connection with the mold are found during this study. The main cause may be the high crystallization trend of high melting temperature phase cuspidine at early stage of infiltration of molten slags into gap between the mold and the strand. In addition, longtime annealing of flux films because of their slow consumption also provides growth conditions for crystals. This kind of structure changes of flux films will cause important effects on horizontal heat transfer eventually.

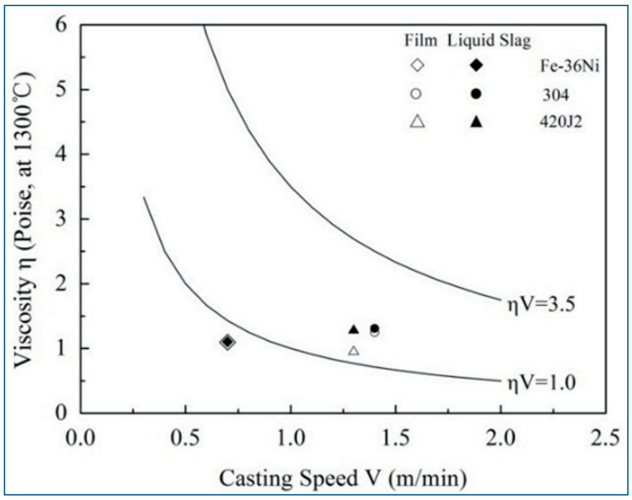

Fig. 6 - Relation between even heat transfer and viscosities of mold fluxes

Fig . 6 - Relazione tra il trasferimento del calore e viscosità dei flussi nella lingottiera

Horizontal heat transfer across flux films involves phonon conductivity kc and radiation conductivity k_R, radiation conductivity is the dominant conduction mechanism in glassy materials. Crystals in flux films will enhance scattering, more radiation energies from the strand are reflected to the strand as a consequence of grain boundary scattering, as a result, k_R decreases to 10~30%k_c and hence heat transfer across flux films decreases [3,9,16,17].

As presented in Fig. 7, the total heat resistance between the mold and the strand can be expressed as Equation (5) as follows:

$$R_{total}=R_{Cu/sl}+(d/k)_{gl}+(d/k)_{cry}+(d/k)_{l} \quad (5)$$

Where $R_{Cu/sl}$ is interfacial heat resistance, d and k are thickness and thermal conductivity, subscripts gl, cry and l represent glassy, crystalline and liquid layers. Interfacial heat resistance $R_{Cu/sl}$ and thickness of solid layer have the largest influence on the total heat resistance R_{total}. Cho [5] and Watanabe [18] reported that $R_{Cu/sl}$ increases with an increase of thickness and crystallinity of flux films. That is to say, thickness and crystallinity of flux films cause the most important effect on the total heat resistance R_{total}.

In order to ensure stable continuous casting and casting slabs with good surface quality, it is particularly necessary to select mold fluxes whose properties match with solidification characteristics of special alloy steels.

i. Heat transfer across flux films for low-expansion alloy steel Fe-36Ni

Low-expansion high alloy steel Fe-36Ni has low strength and has no phase transformation during solidification. Mild heat transfer during solidification will promote linear and parallel growth of coarse columnar crystals in border of slabs, which may give rise to hot-rolling cracking. Moreover, in consideration of its low strength, thin shell will increase

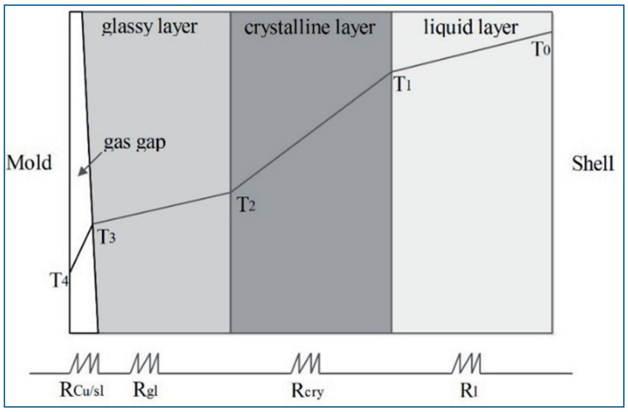

Fig. 7 - Schematic diagram of horizontal heat transfer across flux films

Fig . 7 - Schema del trasferimento di calore orizzontale attraverso i film

breakouts because of slow heat transfer. In association with solidification characteristic of Fe-36Ni, it is necessary to adopt mold fluxes with low crystallinity to promote heat transfer and ensure stable casting and surface quality of slabs. The crystalline fraction of flux films taken from the mold is only 21.4%, and the thickness is 1.6mm, the field production showed that the comprehensive characteristics of flux films meet the requirement of continuous casting of Fe-36Ni. Border solidification structures are fined; good surface quality are achieved, and there is no occurrence of hot-rolling cracking.

ii. Heat transfer across flux films for austenitic stainless steel 304

Austenitic stainless steel 304 has 0.08% C, which cause 4% phase transformation shrinkage due to peritectic reaction $L+\delta \rightarrow \gamma$. Meanwhile, it has high thermal expansion coefficient and low thermal conductivity; all these features lead to high crack sensitivity, longitudinal cracking and depressions are frequent. Thin and uniform shell due to mild cooling is beneficial to release thermal stress produced during solidification shrinkage and decrease the mentioned surface defects. This requires high crystallinity and thick flux film to achieve mild cooling. The flux film for 304 steel taken from the mold has high roughness, and some pores; it also has high crystalline fraction 85.3% and thickness 1.6mm, rough surface, high crystalline fraction and thickness, existence of pores will increase thermal resistance to control heat transfer. There are no cracks but local slight depressions in surface of casting billets, which can be removed by grinding.

iii. Heat transfer across flux films for martensitic stainless steel 420J2

Martensitic stainless steel 420J2 has 0.26~0.35% C, in comparison with austenitic stainless steel 304, solidification shrinkage and strength of martensitic stainless steel 420J2 steel are less than that of austenitic stainless steel 304. As a consequence of relatively high C content, peritectic and the residual liquid phase still exist below the peritectic point. These characteristics make 420J2 have both crack sensitivity and sticking sensitivity, which can be avoided by both control of heat transfer and good lubrication of mold fluxes. In addition, billets have more even heat transfer than that of slabs, and 420J2 has less shrinkage than 304, so there is no cracking in the conditions of flux films for 420J2 with crystalline fraction 49.8%, thickness 0.74mm and basicity 0.97, but depressions are found. The occurrence of depressions may be concerned with more slag rims, which obstruct uniform infiltration of molten slags, accordingly, frequent rupture of flux films because of lack of supply of molten slags interrupts even heat transfer, depressions occur eventually. Consequently, avoidance of slag rims by adjustment of physicochemical properties of mold fluxes is the key to further improvement of mold fluxes for 420J2.

CONCLUSIONS

Conclusions following can be drawn by study on liquid slags and flux films taken from the field for special alloy steels Fe-36Ni, 304 and 420J2.

i. Similar chemical compositions of flux films and liquid slags indicate flux films are consumed during casting. Flux film for 304 steel grade has higher roughness and thickness. Flux films for the three steel grades have similar layered structure, namely, mixed layer of glass and fine crystals in connection with the mold (except for flux film for Fe-36Ni), dense mixed layer of coarse and fine crystals, glassy layer near the strand.

ii. Flux film for 304 has the largest crystalline fraction 85% which is four times of crystalline fraction of flux film for Fe-36Ni; flux film for 420J2 has mid crystalline fraction about 50%. Cuspidine is the main crystalline phase of flux films for Fe-36Ni, 304 and 420J2; nepheline is also examined in flux films for stainless steels 304 and 420J2.

iii. Flux films for special alloy steels Fe-36Ni, 304 and 420J2 meet requirement of continuous casting on the whole. Flux film for Fe-36Ni has the optimal properties, there is no surface defects and hot-rolling cracking in casting slabs; flux film for 304 has moderate performance, there are local slight depressions in surface of 304 billets; however, some depressions are found in stainless steel 420J2, which may be concerned with uneven heat transfer arisen from slag rims.

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Struttura e caratteristiche prestazionali di film da polveri per lingottiere di colata continua di acciai speciali

Parole chiave: Acciaio – Colata continua - Cristallizzazione

Campioni di film fluido e di scorie liquide, impiegati per una lega Fe - 36Ni a bassa di espansione, per un acciaio inossidabile austenitico 304 e per un acciaio inossidabile martensitico 420J2, sono state prelevate da una lingottiera di colata continua. Mediante analisi chimica è stata determinata la composizione dei campioni; sono state fotografate le morfologie apparenti dei film; inoltre mediante SEM, EDS e XRD sono stati esaminati la struttura della sezione trasversale, lo spessore, la frazione cristallina e le fasi cristalline dei film; infine sono state calcolate viscosità e temperatura di rottura del film, mediante modelli. I risultati hanno mostrato che i film fluidi e le scorie liquide hanno composizioni chimiche simili, ma con una certa differenza dalle polveri originali. I film per tutti e tre i tipi di acciaio hanno ovviamente una struttura a strati e la fase cristallina principale a cuspide; viscosità e temperatura di rottura del film si mantengono costanti durante la colata. Il trasferimento di calore attraverso i film, caratterizzato tramite morfologia, spessore, viscosità, temperatura di rottura e frazione cristallina dei film, ha evidenziato che la caratteristica di controllare il trasferimento di calore è migliore, intermedia e minima rispettivamente nel caso dell’acciaio inossidabile austenitico 304, in quello dell’acciaio inossidabile martensitico 420J2 e in quello della lega di acciaio Fe - 36Ni a bassa espansione. Il trasferimento di calore attraverso i film si è rivelato generalmente in accordo con le caratteristiche di solidificazione dei diversi tipi di acciaio. La lega di Fe – 36Ni a bassa espansione ha mostrato una buona qualità della superficie e non si sono riscontrate cricche di laminazione a caldo. Negli acciai inossidabili 304 e 420J2 non si sono formate cricche superficiali ma depressioni locali.