Control of Uneven Shell Formation of Stainless in Early Stages of Solidification

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Abstract

The surface cracks that are originated by an uneven solidified shell formation in mold tend to occur frequently in continuously cast slab of austenitic stainless steels. "Soft" cooling mold is one of advantageous methods to decrease these defects, however there is not enough.An investigation has been carried out into the mechanism of uneven solidified shell formation at the initial stage of solidification by dipping of water cooled chill plates in the molten stainless steel. Steel grade employed for the dip tests is AISI304, 316 and 430. The chill plates have been employed with Ni plating on the entire Cu surface and with Ni latticed plating (2,10,15mm pitch).

The experimental results indicated that, (1) the shell of austenitic stainless steel has a irregular roughness and these roughness form air gap between the shell and the chill plate and results in the uneven solidified shell formation. (2) the chill plate with Ni latticed plating (10mm pitch) was most effective to prevent the uneven solidified shell formation. This effect can be explained in terms of the dispersion of contraction force into the solidified shell. Nextly, the casting tests using a small continuous casting machine with this mold controlled uneven heat extraction were performed to investigate the measures for prevention of the uneven solidified shell formation.

Riassunto

Le cricche superficiali generate dalla formazione irregolare del guscio solidificato frequentemente si manifestano nelle lastre d'acciaio austenitico ottenute per colata continua.

L'utilizzo di uno stampo "tenero" per il raffreddamento porta ad una riduzione dell'incidenza di tali difetti, ma non alla eliminazione totale degli stessi. Questo lavoro esamina l'effetto sul meccanismo della formazione irregolare del guscio solidificato all'inizio della solidificazione provocato dall'immersione nell'acciaio inossidabile fuso (AISI 304,316 e 430) di due tipi di lastra di rame raffreddata ad acqua: una completamente rivestita di Ni; l'altra rivestita a reticolo (passo 2, 10 o 15 mm). I risultati hanno dimostrato che: (1) le rugosità irregolari che vengono a formarsi sulla superficie del guscio dell'acciaio in oggetto creano uno spazio riempito d'aria tra il guscio stesso e la lastra che porta alla formazione irregolare del guscio allo stato solidificato; (2) tra le lastre sperimentate, quella rivestita a reticolo (passo 10 mm) era la più efficace nel prevenire tale formazione. Si ritiene che questo effetto sia dovuto alla dispersione delle forze di contrazione dentro il guscio solidificato. Sono state inoltre eseguite delle prove di colata continua su una piccola colatrice con l'impiego del metodo descritto per il controllo della estrazione non uniforme nello stampo allo scopo di esaminare gli interventi necessari per prevenire la formazione irregolare del guscio solidificato.

Key Words:

Continuous casting, Stainless steel, Surface crack, Uneven solidification, Depression, Dip tests

Introduction

During continuous casting of hypo-peritectic carbon steel and austenitic stainless steels, surface defects such as surface cracks$^{2)}$ and depression$^{3)}$ often occur from uneven solidification $^{1)}$ in the mold. Many studies of uneven solidification phenomena that accompany this kind of peritectic reaction in steels have been reported. Grill et al.$^{4)}$ and Sugitani et al.$^{5)}$ maintained that contraction of the solidifying shell during δ/γ transformation recurves the shell and then floats it from the mold surface, causing an uneven transfer of heat that results in uneven growth of the shell. On the other hand, many researchers have also worked on methods for reducing surface defects such as surface cracks. Sugitani et al.$^{6)}$ reported that "soft" cooling of molds is effective for reducing the contraction volume gap between the mold and molten steel sides of the shell during the early stages of solidification and also for reducing the shell strength. Consequently, bending of the shell toward the molten steel can be prevented, allowing the shell to grow without separating itself from the mold. Therefore, approaches have been attempted to prevent surface cracks, such as reducing the volume of mold cooling water$^{7)}$ and lattice grooving on the mold surface$^{7)8)}$. To develop a cooling plate capable of controlling uneven solidification during the casting of stainless steel, the influence of the cooling plate on uneven solidification was examined in this study using a dip test of cooling plates into molten steel and a casting test using a small continuous casting (CC) machine.

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Method of Dip Test

Dip Test Equipment

To examine the properties of the solidifying shell, an internally water-cooled copper plate was dipped into molten steel. Fig. 1 shows the test equipment, which consists of an air cylinder for moving the dip piece up and down, a platform and the dip piece. The dip piece consists of a watercooled copper plate, a cooling jacket and castable sections. All face plates of the cooling jacket except the water-cooled plate are covered with Al2O3 castable so that the cooling jacket does not contact the molten steel directly.
After preparing the molten steel to the specified composition and temperature in a 100 kg induction furnace, the dip piece was immersed into molten steel using the air cylinder.
The piece was then lifted up immediately after the given time period to permit examination of solidified shell formed on the water-cooled plate surface.

Dip Test Condition

The condition for the dip test are listed in Table 1. Three steel types were used, i.e., AISI 304 and AISI 316, which are typical austenitic stainless steels, and AISI 430, which is a typical ferritic stainless steel. The molten steel temperature during the dip test was kept constant at the liquidus temperature of each steel +50° C. A 10 mm thick Cu plate was used as the cooling plate material for the dip pieces, and approximately 90 l/min of water was used for cooling.
To confirm the "soft" cooling effect of the cooling plates, the cooling plate surfaces were manufactured in two ways. First, the entire surface of the cooling plates was Ni-plated in two thickness of 0.2 mm and 0.5 mm. As an alternative, the cooling plate surfaces shown in Fig. 2 were Ni plated to form a lattice. Three different cooling plates were used, and the surfaces were Ni plated to have 1mm thick and Smm wide strips at intervals of 2mm,10mm and 15mm.
Three dip periods of 5 sec, 10 sec and 15 sec were used, and the dip speed was set at approximately 400 mm/sec. The method shown in Fig. 3 was used to evaluate the unevenness of solidified shells formed on the cooling plates. The top and bottom ends of the shells formed on the cooling plate surface were cropped and the remaining approximately 200mm was cut longitudinally to measure the thickness of the solidified shells at intervals of 5mm.
The unevenness parameter of the solidified shells (σ/X) was derived from X, the average thickness, and σ, the standard deviation.

TABLE 1 - Experimental condition for dip test

Molten Steel	Grade	SUS304, SUS316, SUS430
	Temperature	$\Delta T = 5\,0 \pm 5$ °C
Water cooled plate	Material	Cu
	Thickness	10 mm
	Water	90 l/min
	Surface	Ni plating on the over-all - Cu surface (Ni thickness 0, 0.2, 0.5 mm) Ni latticod plating on the Cu surface (lattice spacing 2, 10, 15, mm)
Dipping time		5, 10, 15 sec.

Test Results and Considerations

Dip·Test Results

Photo. 1 shows the influence of the Ni plated thickness on the unevenness of solidified shells forrned on the cooling plate surface. For the austenitic AISI304 and AISI316 steels, the shells that solidified on the original unplated Cu plates are characterized by a high level of unevenness, as shown in this Photo. However, the unevenness decreases with increasing Ni plating thickness. These solidified shells are concave on the cooling side, as opposed to also being concave on the molten steel side. This suggests that in the early stages of solidification, the solidifying shell is concave on the molten steel side as s result of a thermal shrinkage gap. This gap is caused by an uneven temperature distribution beneath the shell surface, which in turn suppresses heat transfer to the cooling plates, delaying subsequent solidification.
In the case of ferritic AISI430, on the other hand, evenly solidified shells were formed under all conditions, suggesting that the smaller the peritectic reaction in stainless steels, the lower the probability of uneven solidification, as is the case with carbon steel.
Fig. 4 summarizes the influence of the Ni plated thickness on unevenness (σ/X) of the solidified shells. For the Cu plate that was not Ni plated, unevenness of the solidifying shell increased with the dip time. On the other hand, the unevenness parameter decreased with increasing Ni plating thickness. In particular, for the sample Ni plated to a thickness of 0.5mm, the unevenness parameter of the solidified shell decreased with increasing dip time.
Fig. 5 shows the differences due to different steel types. As is seen from Photo.1, AISI316 was the most uneven and AISI430 the most uniform. It is also shown that regardless of steel type, with a Ni plated thickness of 0.5mm, uniformity improved as the dip time was extended.
Photo. 2 shows cross sections of the solidified shells formed on plates that were Ni plated to form a lattice. Solidified shells formed on Ni plated lattices at intervals of 2mm or 10mm featured sufficient evenness and few thickness fluctuations, as with the cooling plates Ni plated to a thickness of 0.5mm over the entire surface. When the pitch was widened to 15mm, however, the unevenness increased.
Fig. 6 shows the influence of lattice pitch on the unevenness of solidified shells for AISI316, which had the greatest unevenness of the samples that were entirely Ni plated. Under the conditions of this test, 10mm was the most effective lattice pitch capable of improving unevenness.
It was shown that extension of the dip time did not affect unevenness. On the other hand, Ni plating at intervals of 15mm produced similar results in the initial stage of dipping to that of the 2mm pitch, but unevenness increased as the dip time was extended, ultimately producing a result similar to that with the surface entirely Ni plated to a thickness of 0.5mm.

Heat Transfer Behavior

The method of assessing uneven solidification from the shape of the solidified shell was mentioned above. Change in the thermal transfer coefficient between the cooling plate and solidified shell that shows the conditions of contact between the cooling plate and solidified shell is important. Accordingly, the influence of Ni plating on the thermal transfer coefficient between the cooling plate and solidified shell was studied using the one-dimensional,transient-state thermal transfer calculation model shown in Fig. 7. The thermal transfer coefficient on the cooling water side, hw, was derived from the formula shown in the Figure by using TA, the measured temperature of the Cu plate interior at the point of time when heat flux to the cooling water was nearly stabilized. The term hs is the thermal transfer coefficient between cooling plate and solidified shell.
The hs at which the calculated temperature and the measured temperature, TA, coincided was determined by varying hs within a set range. Fig. 8 shows how this hs changed from the start of dipping. When an unplated Cu plate alone was used, the thermal transfer coefficient was observed to fall sharply within a very short

time after the start of dipping. This suggests the development of thermal resistance such as an air gap between the cooling plate and solidified shell. On the other hand, the thicker the Ni plating, the larger the thermal transfer coefficient becomes. This is the same tendency as the influence of Ni plating thickness on the unevenness of the solidified shell as seen from its shape. What deserves special attention is that the thermal transfer coefficient increased for about 2 seconds after immersion for both the AISI304 sample Ni plated to a thickness of 0.5mm and the AISI430 sample plated to 0.2mm. This suggests that for the first two seconds of solidification, the conditions of contact between the solidified shell and the cooling plate improve, eliminating unevenness of the solidified shell. The interaction between the rate of heat transfer from the cooling plate, the corresponding thickness of the solified shell and the hydrostatic pressure of the molten steel are considered to be determining factors although the details remain for future investigations.

Casting Test with Small CC Machine

Unlike actual casting, dip test results were obtained under conditions in which mold powder was not a factor. It was anticipated that if this method was applied to actual casting, the effect of the lattice-formed Ni plating would be offset by the effect of "soft" cooling by the mold powder.
Therefore, reconfirmation was made by using a small CC testing machine to provide conditions similar to that of an actual casting machine.

Test Method

Fig. 9 shows the test equipment and method of mold manufacturing. This is a small CC machine capable of casting a 300kg slab that is 310mm wide and 80mm thick. The test casting was made after a wide face of mold was Ni plated to make a 1Omm pitch lattice. Based on the dip test results, this configuration was thought to improve uneven shell solidification. As shown in the Figure, the lattice Ni plating extended down 300mm from the mold top. Table 2 shows the casting conditions. A low viscosity / melting point powder was used for casting. Fe-S was added during casting to define the shell in the casting process. Fig. 10 shows the method of measuring the unevenness parameter of the solidified shell. The solidified shell was located by using sulfur prints at 1/4 of the billet width in the longitudinal section of the casting direction.
The solidified shell thickness was measured at intervals of 2mm. An approximate curve was determined from the measured thickness of the solidified shell by using the rule of root ($d=A+B\sqrt{t}$). The deviation of the approximate curve and solidified shell thickness (area S) was defined as the unevenness parameter.

TABLE 2 - Casting conditions for small sized test caster

Molten steel	300 kg
Machine type	Vertical
Casting speed	0,6 , 0,45 m/min
Oscillation	± 5 mm 90, 67 cpm Non sinusoidal ($\alpha = 20\%$)
Steel grade	AISI 304
ΔT in ladle	45 ± 5K

Test Results

Results obtained under various conditions are summarized in Fig. 11. The unevenness is reduced by using latticed Ni plating under all conditions. Based on the shell's coefficient of solidification, the overall growth of the solidified shell is similar between the cases, as Fig. 12 shows. The actual casting tests using powder also confirmed that the Ni plated lattice mold could improve uneven shell solidification.

Conclusion

Dip tests were performed to study uneven shell solidification, which is a problem for casting stainless and other steels. These tests provided a method for forcibly and unevenly cooling the surface on which the solidified shell is formed. It was found that uneven solidification could be improved by the use of lattice-formed Ni plating at an optimum spacing. A casting test using a small CC machine subsequently confirmed that uneven solidification could be improved even if powder was used. A future study is scheduled to confirm this effect by using an actual CC machine and to clarify the relationship between uneven solidification and slab surface defects.

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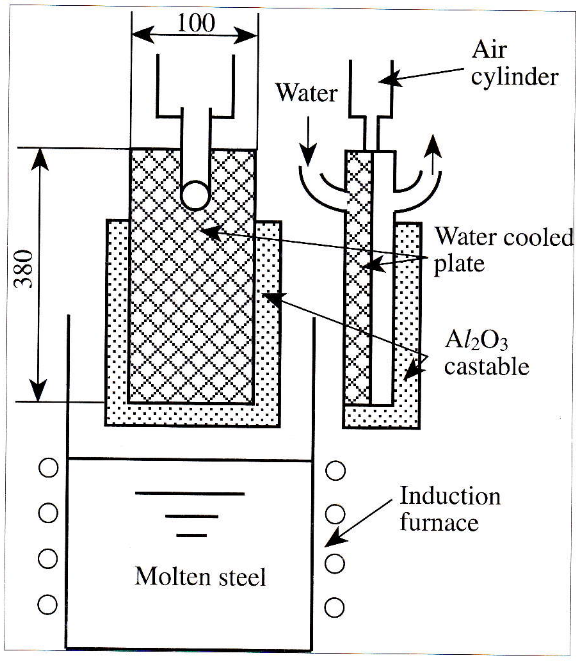


Fig. 1:
Schematic view of experimental apparatus for dip test

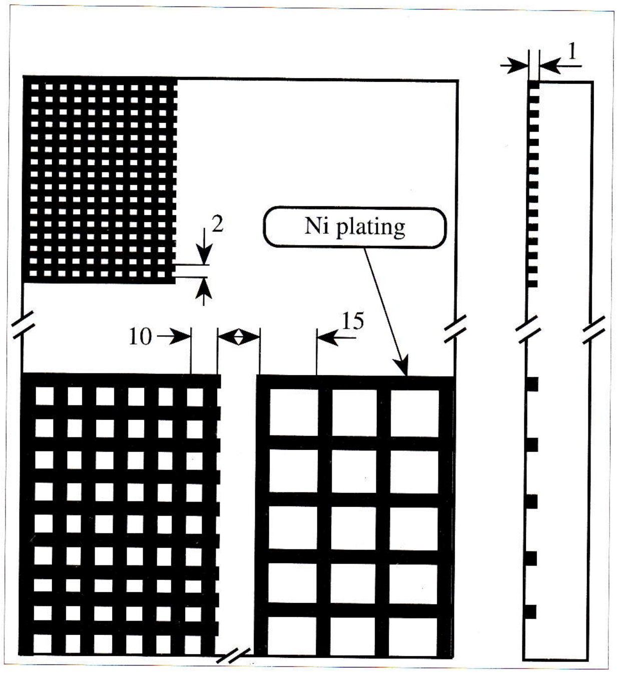


Fig. 2:
The method of Ni latticed plating

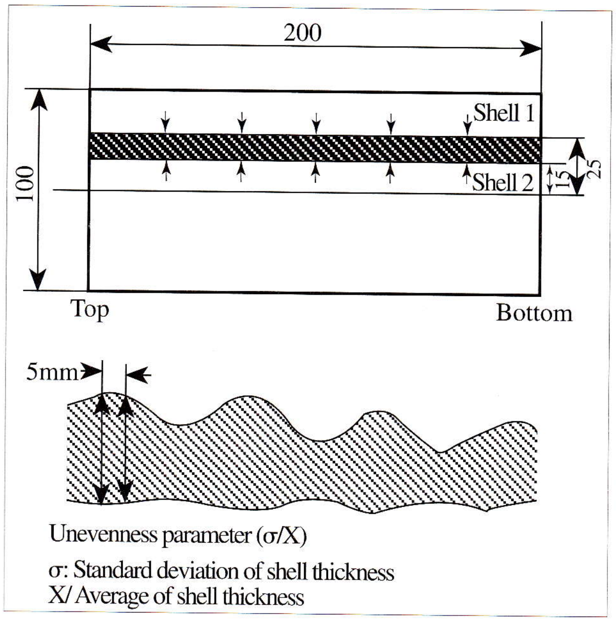


Fig. 3:
Evaluation method of unevenness parameter of shell (σ/X)

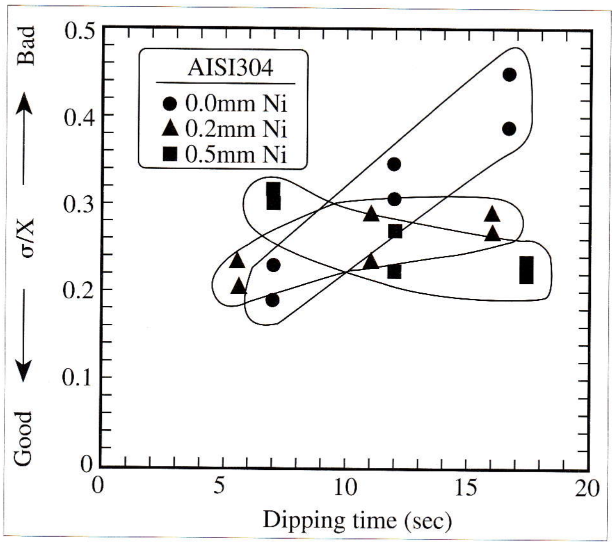


Fig. 4:
Influence of Ni thickness on the unevennes parameter of shell

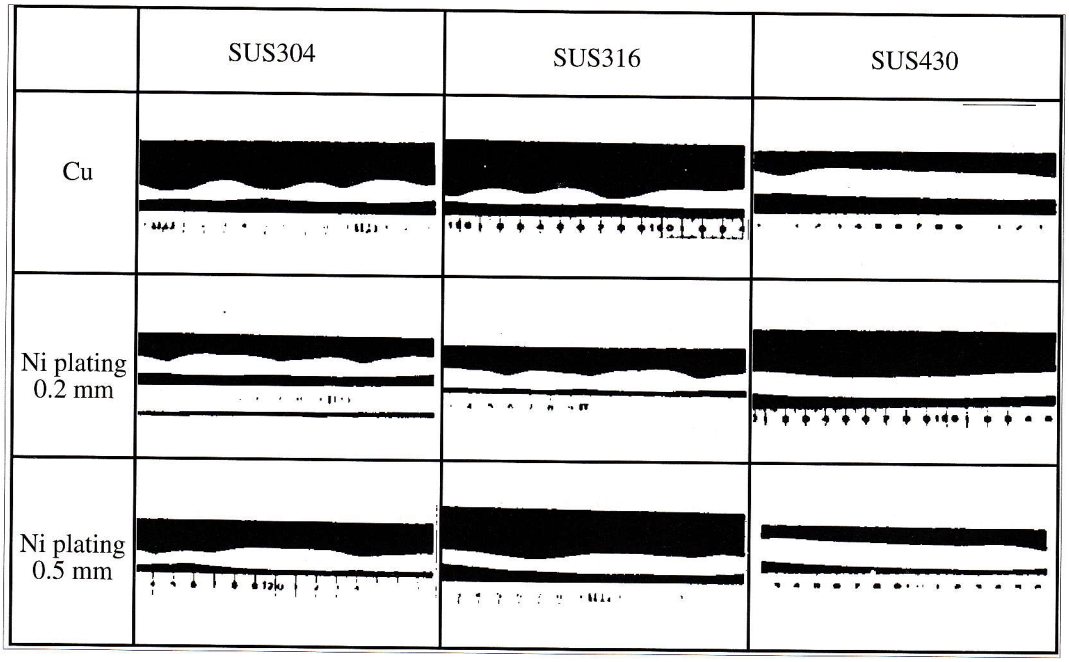


Photo. 1:
Influence of Ni thickness and steel grade on shell formation

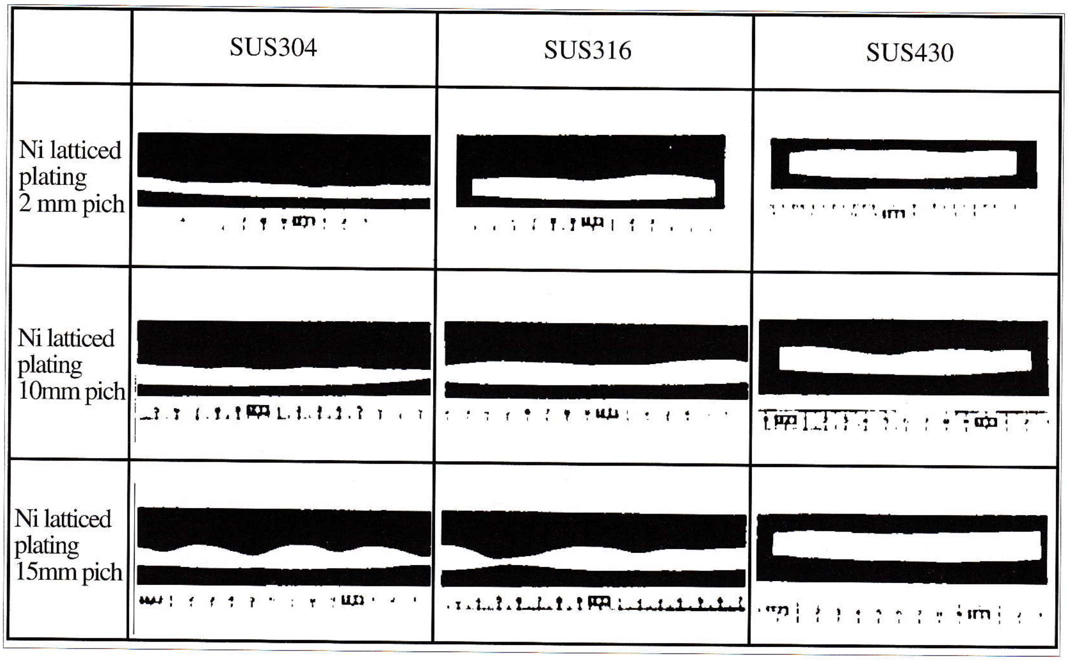


Photo. 2:
Effect of Ni latticed plating on shell formation

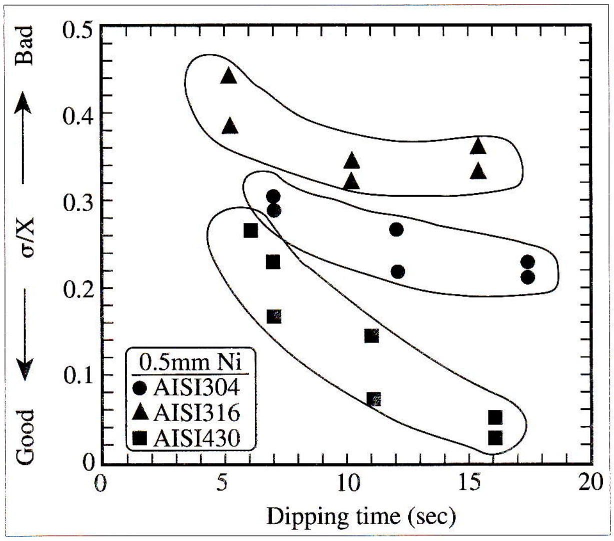


Fig. 5:
Influence of steel grade on the unevennes parameter of shell.

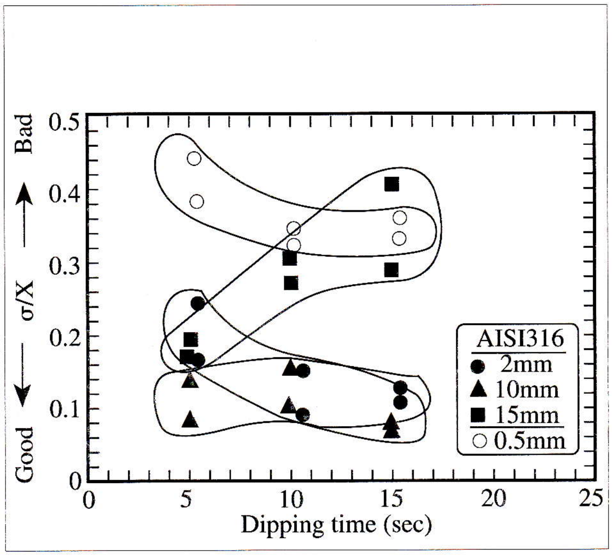
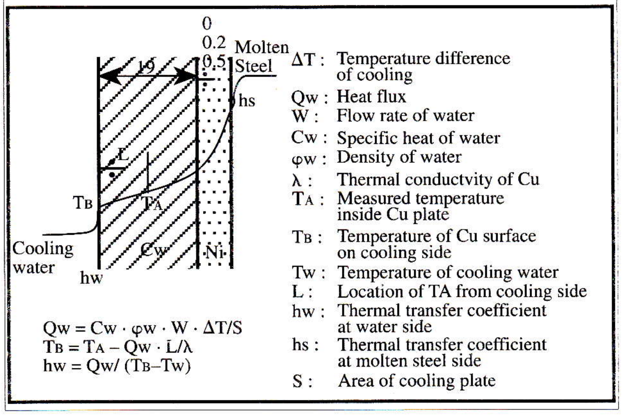


Fig. 6:
Influence of lattice spacing on unevennes parameter of shell



$$Q_w = C_w \cdot \varphi_w \cdot W \cdot \Delta T/S$$
$$T_B = T_A - Q_w \cdot L/\lambda$$
$$h_w = Q_w/(T_B - T_w)$$

ΔT : Temperature difference of cooling
Q_w : Heat flux
W : Flow rate of water
C_w : Specific heat of water
φ_w : Density of water
λ : Thermal conductvity of Cu
T_A : Measured temperature inside Cu plate
T_B : Temperature of Cu surface on cooling side
T_w : Temperature of cooling water
L : Location of TA from cooling side
h_w : Thermal transfer coefficient at water side
h_s : Thermal transfer coefficient at molten steel side
S : Area of cooling plate

Fig. 7:
Calculation model of heat transfer at non-steady state to estimate the thermal transfer coefficient between cooling plate and shell.

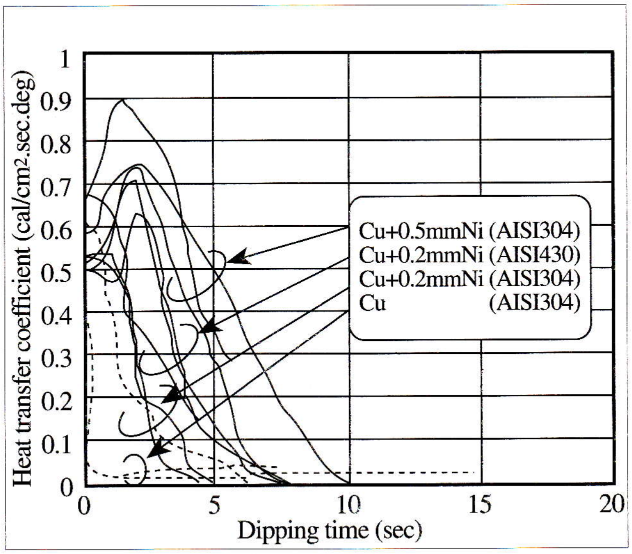


Fig. 8:
The change of thermal transfer coefficient between cooling plate and shell.

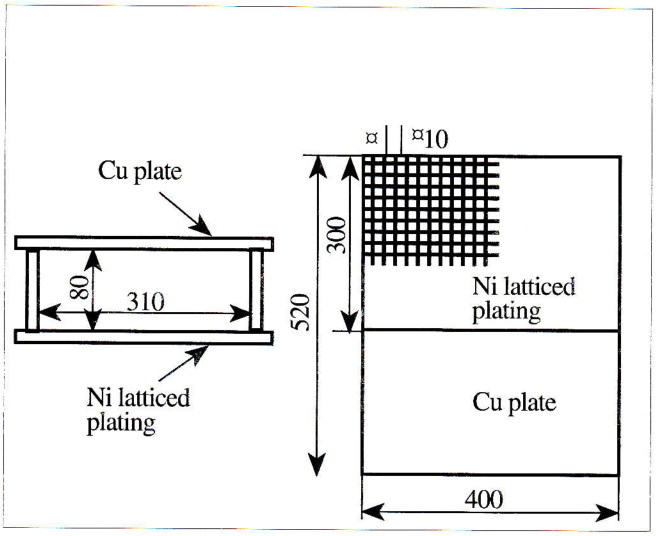


Fig. 9:
Schematic of small-sized test caster and Ni latticed plating method on mold surface.

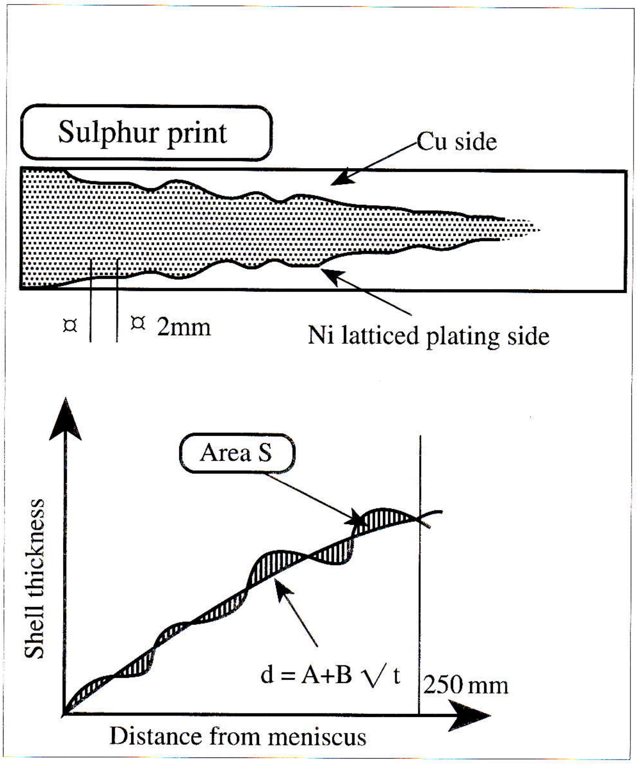


Fig. 10:
Evaluation method of unevennes parameter measured from sulphur print.

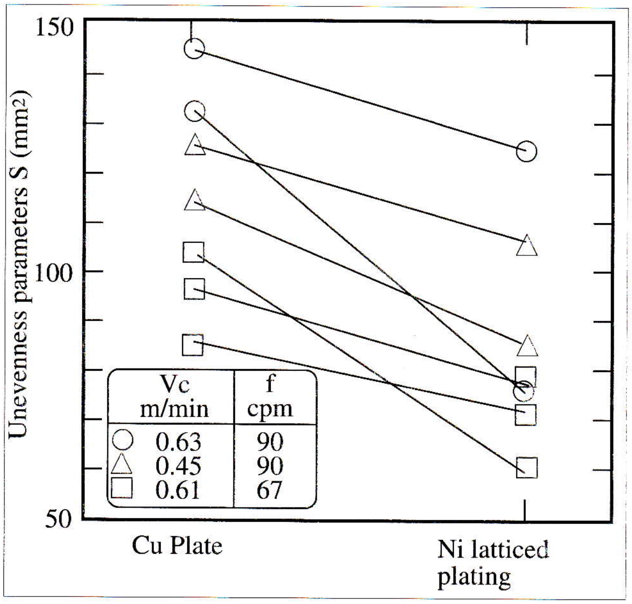


Fig. 11:
Effect of Ni latticed plating of unevenness parameter of shell.

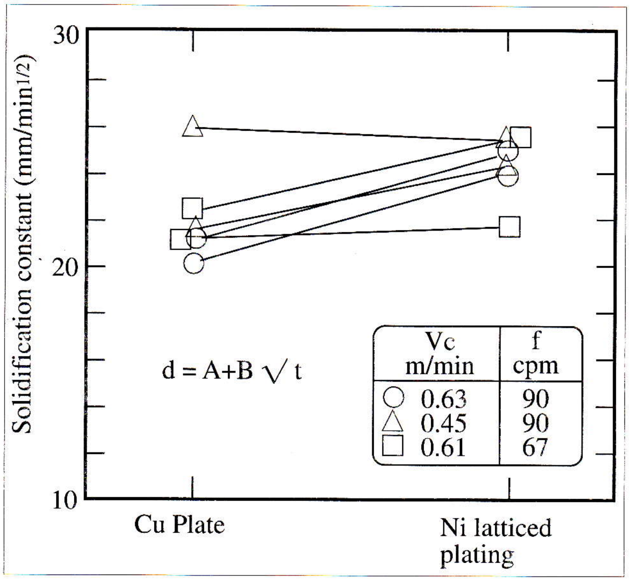


Fig. 12:
Effect of Ni latticed plating of the solidification constant.