KAWASAKI STEEL TECHNICAL REPORT
No.7 (March 1983)

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1 Introduction

The inner face of casting mold generally made of copper or copper alloy is plated to prevent steel casting's surface and to extend the mold life, with efforts made to improve the quality of the plating.

Chrome plating first used at Kawasaki Steel Corporation turned out unsuccessful as the difference of thermal expansion was large enough to cause the peeling off of plating and the flaking from copper plate after repeated thermal stress imposition of several tens of charges. Even a partial peeling and flaking of plating layer tends to cause copper to diffuse into the casting steel, inviting intercrystalline embrittlement and cracking of casting's surface. This suggested a need of a stable plating in casting high-grade steels.

Against such background, the authors adopted Ni plating and Ni multiplating (hereinafter called "MC") as shown in **Fig. 1** to reduce the mold's unit production cost. Both, however, were found unsatisfactory; Ni plating in terms of wear resistance, and MC in plating cost. A series of studies were made to develop a lower-cost longer-life plating material for copper plate, jointly with Nomura Plating Co. until a new plating method was applied for mold, and a single layer Ni-Fe plating was developed.

This paper introduces details of development of the plating method, together with the physical and mechanical properies of Ni-Fe plating layer and the application results thereof.

2 Details of Development of Ni-Fe Plating Method

2.1 Evolution of Plating Process in Mizushima Works

Plating techniques have made rapid development in the past several year[1-5] as an important role in preventing surface defects on continuously cast steels as well as in extending the service life of the mold. Since around 1977, Ni plating and MC which have excellent adhesiveness, have been replacing their predecessor Cr plating which had such disadvantages as its large difference from copper plate in thermal expansion coefficient and such defects as peeling and flaking[6]. Ni plating and MC are, however, also characterized by the following demerits. First, thickness of Ni plating must be made greater to compensate for insufficient wear resistance. In consequence, plated surface suffers uneven wear, which makes difficult an accurate control of the inner dimensions of the mold. Moreover, mold surface requires machining after use in each campaign, entailing complicated and troublesome maintenance work.

* Originally published in *Kawasaki Steel Giho*, **14** (1982) 4, pp. 12–19
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*** Tubarao Project Division

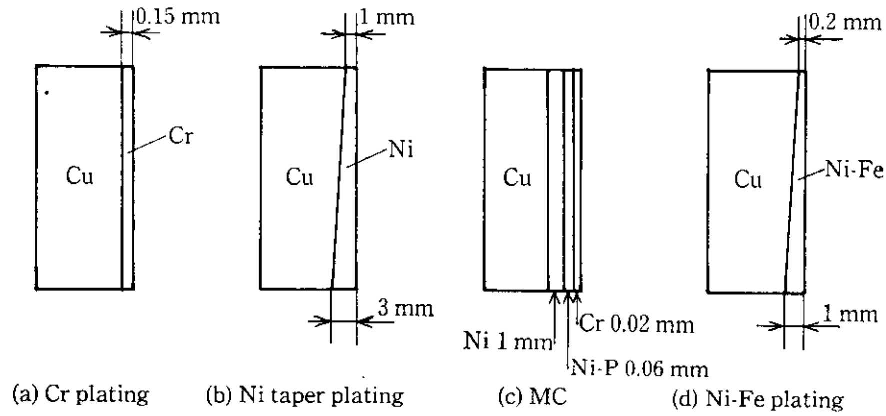


Fig. 1 Several types of plating on Cu mold plate

On the other hand, MC is composed of multilayer deposits of Ni, Ni-P and Cr. Ni-P layer, which comes second, is excellent in wear resistance, but difficult to thick-plate. Further, this layer brings about sticking of molten steel. Cr plating to be applied thereon is intended to make it easier to peel off the molten steel adhered. Multilayer deposits of MC thus have the drawback of relatively high cost.

In order to correct such demerits of existing plating methods, the authors studied anew the three methods of metal spraying, overlays (welding) and plating.

Metal spraying method is difficult to apply, because peeling strength of the material sprayed is 3–5 kgf/mm^2, or only 1/5–1/8 of that in plating. Welding method was not adopted, for it remains large strain in copper plate by welding heat, and deposited metal is embrittled by dissolved copper from base metal, thereby easily causing hot shortness.

The plating method, which has been adopted for most continuous casters in steelworks, has little adverse effect on base material of copper, is easy to perform, with its stable quality. Consequently, studies were focused in this report on the plating method.

As plating material, nickel was mainly emplayed because of its excellent adhesiveness to base material of copper. The studies were started in 1978 in cooperation with Nomura Plating, Co. As a result, it was found that wear resistance of Ni plating could be improved by adding Fe, thus, taking full advantage of the merits of Ni plating.

2.2 Study on Composition of Ni-Fe Deposits

Functions required of mold plating is considerably different between its upper and lower parts. In the upper part, thermal fatigue crack (heat crack) tends to be caused by frequent thermal cycle (rapid heating and cooling) owing to the variation of meniscus level in the mold. This requires, therefore, a high resistance to

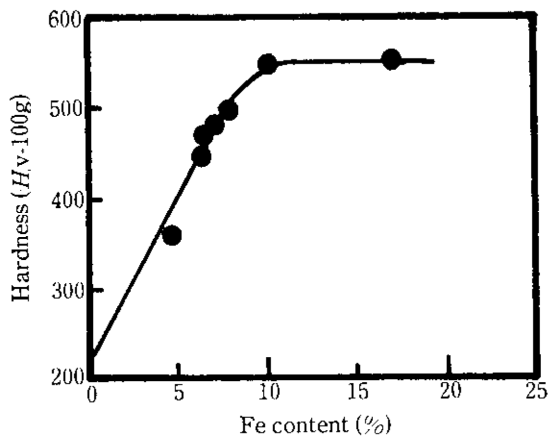


Fig. 2 Effect of Fe content on hardness of Ni-Fe deposit

thermal fatigue. On the other hand, in the lower part where frequency of the thermal cycle is low, the solidified castings should be guided while being cooled, and therefore wear resistance of mold must be emphasized.

(1) Study on improvement of wear resistance

Fig. 2 shows influence of Fe content on hardness on Ni-Fe deposit. As is clear from this diagram, the hardness improves as the Fe content increases. But, the limit of hardness (H_V 550 which is about 2.5 times[7] that of Ni plating) is attained when Fe content is on the order of 10%. As a result, wear resistance shows a great improvement approximately in proportion to the hardness.

(2) Study on resistance to thermal fatigue

To prevent thermal fatigue crack in plating primary stress in electrodeposits produced in the plating process should be reduced. To this end, a plating bath[7] was used based on sulfaminide nickel characterized by low stress level, to which

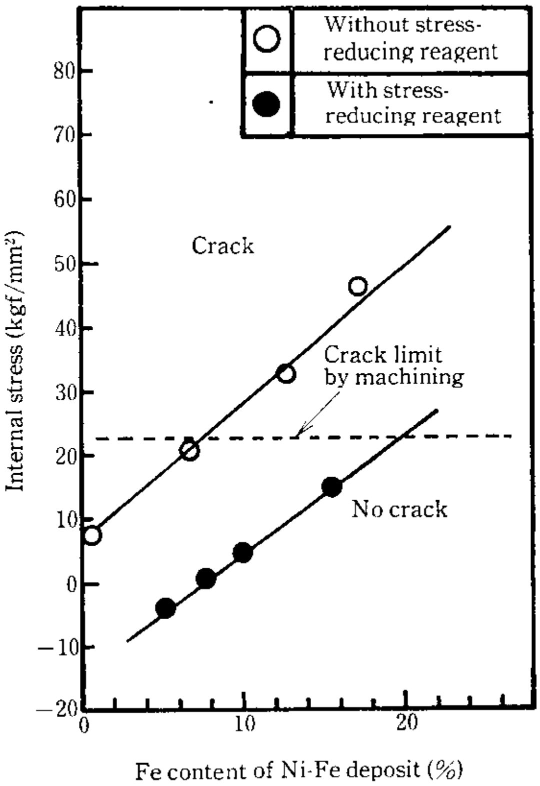


Fig. 3 Effect of stress-reducing reagent on susceptibility of Ni-Fe plated layer to cıack formation at machining

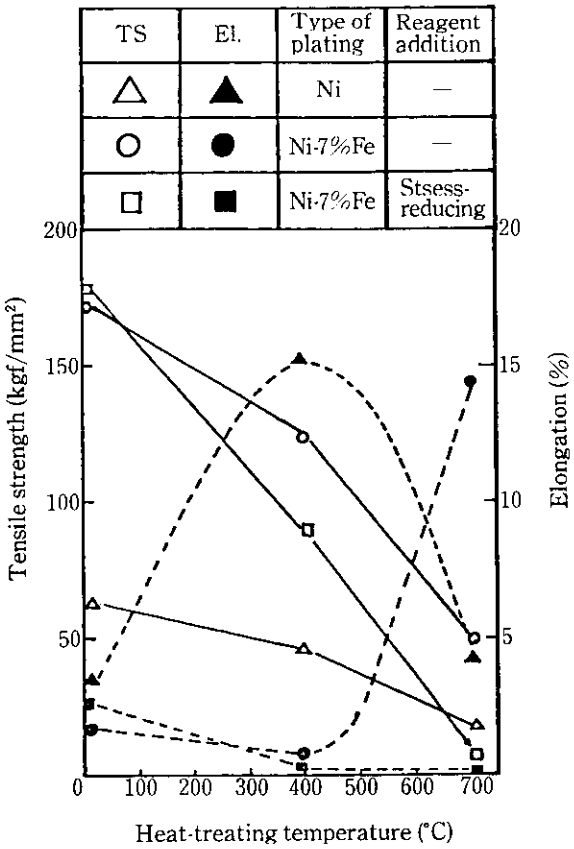


Fig. 4 Tensile properties of plating films heated at several temperatures for an hour and then air cooled

Fe ion was added. As is shown by the white circle in **Fig. 3**, however, with the increase of Fe content, stress in electrodeposits becomes higher, and thus hydrogen embrittlement and cracks by machining are more likely to be produced. In certain cases, cracks were not caused with 6% Fe, but were brought on with 7%. In limiting Fe content to these values, wear resistance remains at a rather low level. To overcome this difficulty, and thereby take maximum advantage of the characteristics of Ni-Fe plating, addition of stress-reducing reagent is made in the plating bath. Thus, plating with much Fe content under lower stress is rendered possible as shown by the black circle in **Fig. 3**. However, with this method, elongation after heating at 400°C for an hour is reduced as shown in **Fig. 4**. The reason for this reduction is that S which constitutes the stress-reducing reagent precipitates as NiS in the Ni during recrystallization of the plating layer, thereby forming an embrittled grain boundary[9].

(3) Plating conditions suited to the process
A constitution with 4 to 6% Fe content is adopted for the mold in medium-speed caster, though this constitution is a little inferior in wear resistance. And no stress-reducing reagent was employed. On the other hand, it was decided to adopt 8 to 10% Fe content and use the said reagent for plating in low-speed caster where the tendency to thermal crack is relatively small, underlining wear resistance of lower mold against solidified shell of slab.

(4) Application to process
The above-mentioned plating was put into practice in the process. No practical problem arose under any of the specifications, except for shallow radial thermal crack on the plating surface.

2.3 Improvement in Plating for Assembled Mold

In general, the assembled mold has been adopted for continuous bloom caster. The following techniques led to an improvement in the deposit efficiency and the machining cost saving.

2.3.1 Assembled mold plating by auxiliary anodes

Thick plating, which was liable to bear ununiform thickness, required a complicated process; disassembling the mold, followed by machining, plating,

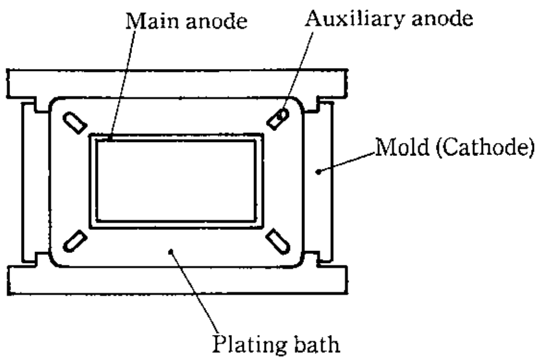


Fig. 5 Schematic arrangement of Ni-Fe plating on mold inside

machining and assembling. This process made plating thickness uniform but increased the plating cost. Mindful of the fact that the machining process may be omitted, if a uniform plating thickness can be obtained on the inner face of the mold, the authors conceived an improved control method[10] of current concentration uniformity by installing auxiliary anodes with separate power source into corners of the assembled mold taken as plating bath (see **Fig. 5**).

Fig. 6 shows the comparison of the plating thickness between this method and the conventional one. In the conventional plating method, the thickness is greatly reduced in corners as compared with that in the plane part. Corner thickness can be improved by up to 78% of that in plane part with the use of auxiliary anodes.

2.3.2 Tapered plating

A tapered plating technique was thought to be much favorable, in which plating thickness is decreased to 0.2 mm to reduce as far as possible the thermal stress in plating layer of the upper part of mold, and is increased to 1 mm in the lower part taking wear into consideration. To realize this, the tapered plating process[11] was conceived whereby plating reaction time is controlled by gradually lowering the meniscus of plating bath in the assembled mold, as is shown in **Fig. 7**.

3 Physical and Chemical Properties of Ni-Fe Plating Layer

3.1 Structure of Plating Layer

In the single metallic plating, dendritic structure generally grows vertically to the surface in the plated metal. In the case of alloy platings, however, competitive discharge reaction between two or more metal ions occurs in the plating bath; first noble metal ion is discharged and the density decreases to the level in which electric potential is inverted, then base metal ion

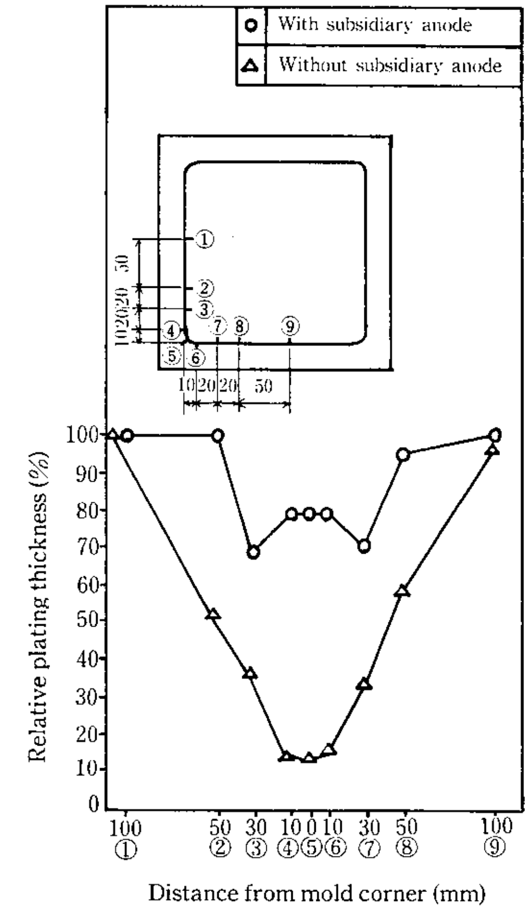


Fig. 6 Effect of auxiliary anode on the uniformity of Ni-Fe plating thickness

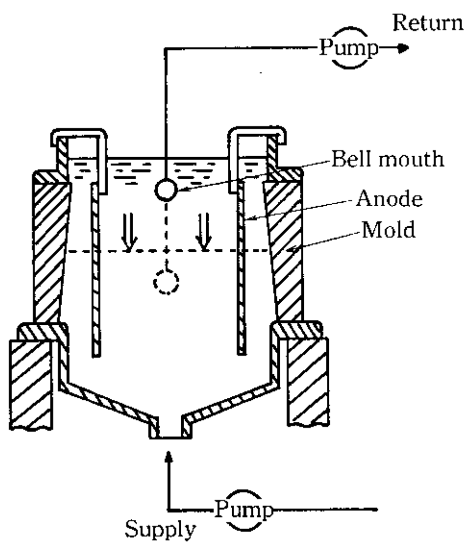
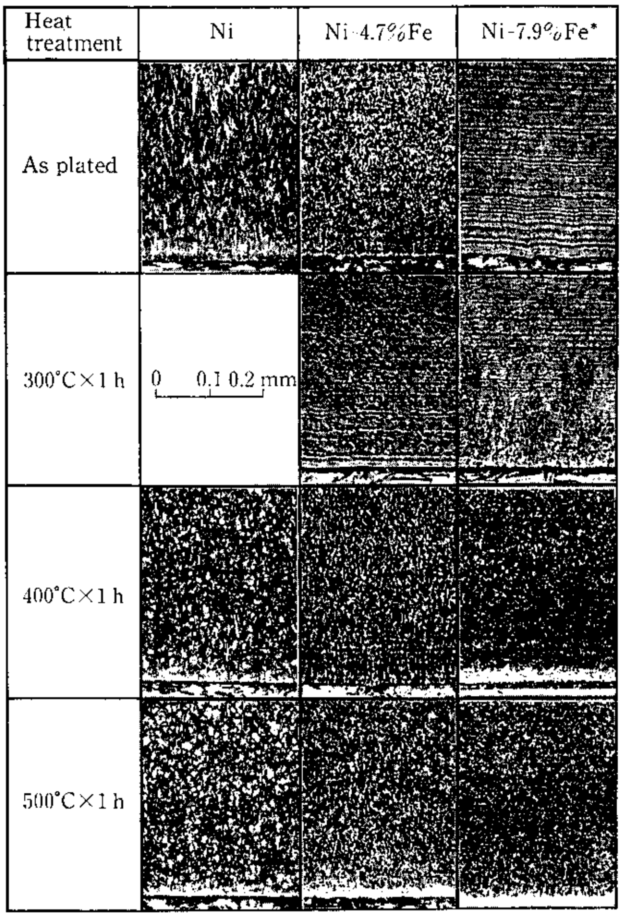


Fig. 7 Schema of taper plating of mold



* Stress reducing reagent was applied in the case of Ni-7.9%Fe

Photo 1 Microstructure of plated layer

is discharged. It is said that the crystalline structure formed through such repeated electrolysis changes into lamellar structure which is parallel to the metal surface to be plated if the Fe content increases[12]. **Photo 1** represents a comparison of structures of Ni plating and Ni-Fe plating, under the conditions of as plated or heated at 300, 400 and 500°C for an hour and air-cooled thereafter. Partial recrystallization was recognized in dendritic structure of Ni plating after heating at 400°C or more. Ni-Fe plating with 4.7% of Fe content, as plated, finds itself in a state between

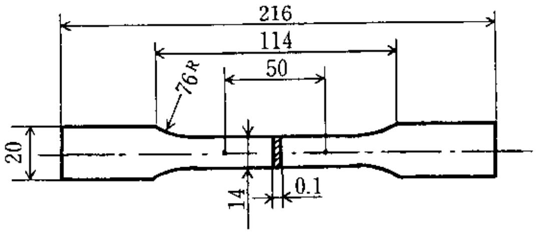


Fig. 8 Profile of tensile test piece of plating film

dendritic and lamellar structures, but if heated at 400°C or higher, partial recrystallization thereof can be recognized. Ni-Fe plating with 7.9% of Fe content presents a perfect lamellar structure, and recrystallizes partially at 300°C. Grain of Ni-Fe plating, as compared with that of Ni plating, is fine.

3.2 Resistance to High Temperature

Specimens for tension test of plating film were made as follows. Plating 0.1 mm-thick was applied onto a stainless steel plate with smooth polished surface. Then plating film was sampled by peeling and from this film tension test pieces were made as shown in **Fig. 8** referring to JIS Z 2241 (Tension test method for metallic materials) and to ASTM, Designation D774 46.

Fig. 4 represents the test results made on pieces of Ni and Ni-Fe platings, before and after heat treatment. Without heat treatment, and elongation of the former is 1/2 of the latter. As for stength after heating at 400°C, it declines both for Ni plated and Ni-Fe plated pieces, and elongation increases for Ni piece but decreases remarkably for Ni-Fe piece.

3.3 Adhesion

One of important factors in evaluating quality of plating for copper mold is adhesion. If plating layer is peeled off during continuous casting, formation of solidified shell becomes uneven, and in some cases seizure even occurs. Thus shell may be broken to cause breakout.

As quantitative evaluation method of adhesion, the Clad Steel Shearing Test was performed as prescribed in ASTM E-8-66. **Table 1**[7] indicates the results of shearing test of Ni or Ni-Fe plating before and after

Table 1 Test results of adhesion strength of plating

Heat treatment	Ni-7%Fe plating		Ni plating	
	Shearing strength (kgf/mm^2)	Sheared point	Shearing strength (kgf/mm^2)	Sheared point
As plated	21-25	Within copper	19-25	Within copper
400°C×1 h	21-25	〃	19-25	〃
700°C×1 h	10-13	〃	19-25	〃

heat treatment. Breaking was found on base material of copper for both platings, and therefore adhesion of plating layers is considered to be sufficient.

3.4 Heat Transfer Coefficient

Cooling of molten steel is made with heat transferred to cooling water at the back of copper plate, passing through plating material and copper plate, if mold powder film can be disregarded.

Under these conditions, general formula of heat transfer may be expressed as follows:

$$Q = K(\theta_S - \theta_W)$$

$$K = \left(\frac{1}{h_S} + \sum \frac{l_n}{\lambda_n} + \frac{1}{h_W}\right)^{-1}$$

Q: Total heat transfer rate per unit area and unit time
K: Total heat transfer coefficient
θ_S: Surface temperature of solidified shell
θ_W: Temperature of cooling water
h_S: Heat transfer coefficient between solidified shell and copper plate surface
h_W: Heat transfer coefficient between copper plate and cooling water
λ_n: Thermal conductivity of copper plate or each plating layer
l_n: Thickness of copper plate or each plating layer

Therefore, heat transfer rate depends on thickness of plating and on thermal conductivity of each layer. Thermal resistance of layers of Ni plating, MC and Ni-Fe plating in low speed slab caster were calculated, assuming that temperature in plating layers is 400°C. **Table 2** compares the results. It can be said that the thermal resistance, K^{-1}, of Ni-Fe plating layer is smaller than that of Ni plating and MC.

3.5 Comparison of Wear Resistance

Test pieces of each plating material were exposed to heating for one hour at several temperatures and air-cooled thereafter. Wear of these pieces was then measured by Tabor Wear Test, and **Fig. 9** represents the results. Thickness of plating material divided by value of this wear gives the wear resistance, which is considered as one of the indices for evaluating service life of plating layer. When calculating the wear resistance of plating layer at 400°C, using the wear quantity given in **Fig. 9**, we can obtain:

$$\text{Ni}\,(1\,000/0.86): \text{MC}\,(1\,000/0.86 + 60/0.25 + 20/0.14): \text{Ni-Fe}\,(1\,000/0.47) = 1 : 1.33 : 1.83.$$

Also, we get MC: Ni-Fe = 1: 1.38.

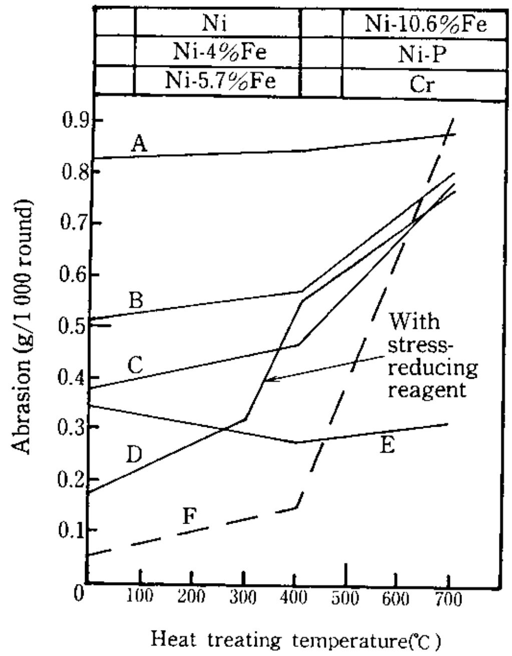


Fig. 9 Comparison of abrasion by Taber abrasion testing between different plating materials heated at several temperatures for an hour and air cooled

Table 2 Comparison of thermal conductivity at 400°C between different plating

Calculated heat resistance of plating layer (cm²·s·°C/cal)				Observed heat conductivity of plating at 400°C used for calculation (cal/cm ·s·°C)
Position	Type of plating			
	Ni	MC	Ni-5%Fe	
Meniscus	1.22	1.25	0.20	Ni/0.10*, Ni-P/0.025*,
Mold bottom	3.00	1.25	0.68	Ni-5%Fe/0.146, Cr/0.16**

* Data given by the courtesy of Satosen Co. Ltd.
** Metallic Cr at room temperature[13]

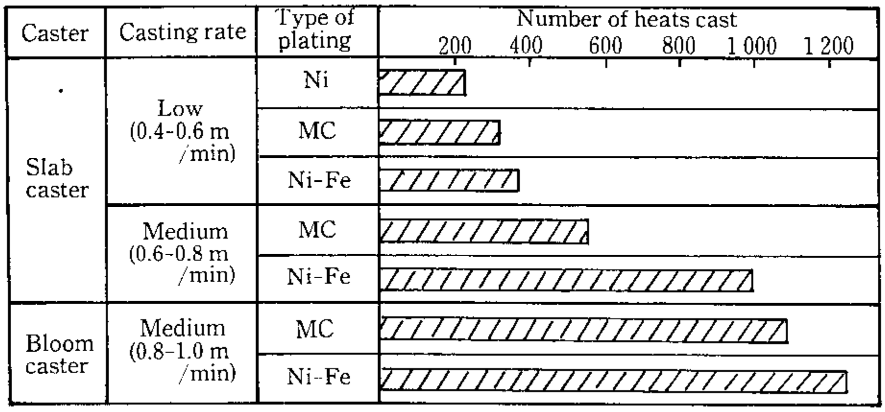


Fig. 10 Comparison of mold life between different types of mold plating

4 Service Life and Life Cycle Cost of Mold Copper Plate

Fig. 10 represents compared service life by plating material of Ni-Fe plating, etc. now used in the process in Mizushima Works. **Fig. 10** also shows the service life of mold for low-speed caster of slab. The ratio thereof almost coincides with that of wear resistance calculated above. As for the mold for medium-speed slab caster, its service life is 1.7 times that of MC plating.

Total cost of mold copper plate per ton of steel cast, consisting of copper plate cost and such working costs summed up to disposal as machining, plating, assembling, disassembling after casting several heats, remachining and so on, is hereafter defined as "mold life cycle cost". **Fig. 11** shows relative values of this cost in comparison of Ni-Fe plating those and other platings. In conclusion, use of Ni-Fe plated copper plate reduces the cost by a significant 25% in mold for continuous bloom caster, and by 43% in mold for medium-speed slab caster.

5 Conclusion

Kawasaki Steel's Mizushima Works has succeeded in establishing an original single layer tapered plating method of Ni-Fe alloy after having successively used Cr plating, Ni plating, MC, and in using this method in the production process. It has been proved that thermal resistance of Ni-Fe plating is smaller than that of any other plating. Mold life cycle, cost of copper plate has been significantly reduced by 25% for mold used in continuous bloom caster, and by 43% for mold in medium-speed slab caster. The authors intend to change in future MC used in mold for high-speed slab casting, into Ni-Fe plating, and incorporate this into the production process.

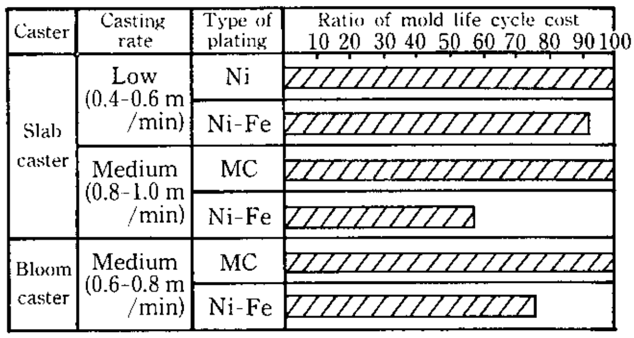


Fig. 11 Comparison of mold life cycle cost between different types of mold plating

Data on platings used in this paper were obtained from Nomura Plating, Co., and their contribution is highly appreciated.

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