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Effect of low frequency electromagnetic field on microstructures and macrosegregation of horizontal direct chill casting aluminum alloy①

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Abstract: The influences of low frequency electromagnetic field on cast surface, microstructures and macrosegregation in horizontal direct chill(HDC) casting process were investigated experimentally. The cast surfaces, microstructures and macrosegregation of the ingots manufactured by conventional HDC and low frequency electromagnetic HDC casting were compared. The results show that low frequency electromagnetic field significantly improves the surface quality, refines the microstructures and reduces macrosegregation. Further more, increasing electromagnetic intensity or decreasing frequency is beneficial to the improvement. In the range of ampere-turns and frequency employed in the experiments, the optimum ampere-turns is found to be 10 000 A·turn and the frequency to be 30 Hz.

Key words: horizontal direct chill casting; low frequency electromagnetic field; microstructure; macrosegregation
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1 INTRODUCTION

The DC(direct chill) casting process is a well-established production route for aluminum alloy and has been classified into VDC(vertical direct chill) casting and HDC (horizontal direct chill) casting process. As compared with VDC process, HDC process has many advantages such as lower investment cost, higher flexibility, longer casting times[1-3]. However, HDC process has some characteristic technical problems due to gravity difference between top surface and bottom surface at horizontal portion, which, in turn, results in inhomogeneous microstructures and serious macrosegregation in the ingot. Therefore, how to find an effective way to get homogeneous microstructures and reduce macrosegregation is an inevitable problem for the HDC process development.

The application of electromagnetic casting technique for improving production quality has attracted a great deal of attention in recent years, and considerable development has been achieved[4-8]. However, the traditional electromagnetic casting methods always require elaborate processing and/or special expensive devices. A simple and efficient way, low frequency electromagnetic casting[9-11] (LFEC) was developed in our laboratory with the frequencies lower than that in casting, refining and electromagnetic process (CREM), which was put forward by Vivès[12, 13] to refine structures and improve the surface quality of DC ingots.

Based on the LFEC process, we have applied low frequency electromagnetic field in the HDC casting process to improve production quality. In the present paper, the effect of low electromagnetic field on surface quality, microstructure and macrosegregation of HDC casting process has been systematically studied.

2 EXPERIMENTAL

The experimental equipment is illustrated schematically in Fig. 1. The inner diameter of the mold is 60 mm and a 50-turn coil is arranged outside the mold. A casting speed of 200 mm/min and a casting temperature of 725 ℃ were held constant throughout the process of experiment to guarantee that the influence of electromagnetic field on microstructure was considered exclusively. Moreover, as there were two main parameters of electromagnetic field, the experimental procedures were divided into two groups: first, under a frequency of 30 Hz, the magnitude of ampere-turns increased from 0 to 10 000 A·turn, so that the effect of magnetic field intensity on the microstructure and distribution of alloying elements can be

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evaluated; second, the magnitude of ampere-turns was maintained at 10 000 A·turn, the frequency of alternating current was modulated in the range of 10 to 100 Hz, by which the effect of electromagnetic frequency was revealed.

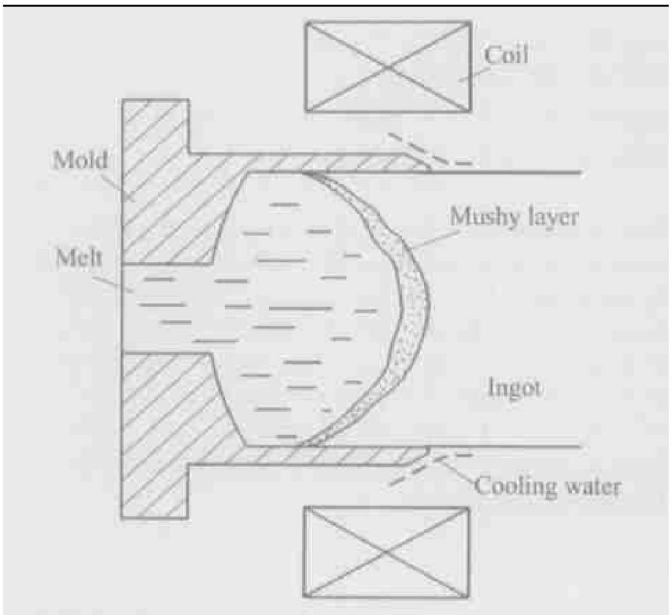

Fig. 1 Schematic illustration of electromagnetic HDC process

The materials used for this investigation were 6061, 2024 and 7075 alloys. The primarily discussed material in the present paper is 7075 aluminum alloy. The chemical composition of the alloy is shown in Table 1. The specimens were taken along the diameter in cross-section of ingot, and observed by an optical microscope, Leica DMR. The macro concentration of the elements such as Zn in the different areas was measured by chemical analysis.

Table 1 Chemical composition of experimental 7075 alloy (mass fraction, %)

Zn	Mg	Cu	Cr	Al
6.0	2.8	1.2	0.23	Bal.

3 RESULTS AND DISCUSSION

Similar to VDC hot top process, molten metal in the HDC process is surrounded by refractory and the edge of casting mould at the initiating point of solidification. Moreover, quite different from VDC hot top process, as the metal is pulled out in the horizontal direction, non-uniform tensions are liable to occur on a shell being solidified. Besides, in the vicinity of a mould, the extraction of heat tends to vary between upper and bottom portions due to the unbalanced cooling and gravity difference. If this adversary conditions occur simultaneously, the microstructure of ingot tends to deteriorate and create thick segregation layer, which results in a great damage of ingot quality[14, 15]. However, in ingots taken up in this report, the inhomogeneous microstructures and macrosegregation rarely occur due to the application of low frequency electromagnetic field in HDC process.

3.1 Effect of low frequency electromagnetic field on surface quality

Under the effect of periodic current, the inductor generates an alternating magnetic field in the melt, which gives rise to an induced current. Thus, the melt is subjected to electromagnetic body forces caused by the interaction of the eddy currents J and the magnetic field B. Another characteristic of electromagnetic field is the presence of a fringe effect consisting of a pronounced inclination of the magnetic field lines toward the axis of symmetry of the ingot. Therefore, the Lorentz force density consists of two parts expressed as follows:

$$\boldsymbol{F}=\frac{1}{\mu}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}-\frac{1}{2\mu}\nabla\boldsymbol{B}^2 \tag{1}$$

The first part of Eqn. (1) is a rotational component which results in a forced convection in the melt, therefore, the ideal flow pattern in the melt will be achieved when the overheated melt can be driven from center region of the melt to the periphery, and the depth of sump decreases; the second part is a potential force balanced by static pressure of the melt, resulting in the decrease of the primary cooling intensity and the friction between ingot and mold. All these effects can effectively improve the surface quality, refine the microstructures and induce the macrosegregation[16].

Fig. 2 presents the typical cast surface of conventional HDC and electromagnetic HDC ingots. It shows that in the absence of electromagnetic field, the cast surface always suffer from slight nicks and segregation knots; contrarily, in the presence

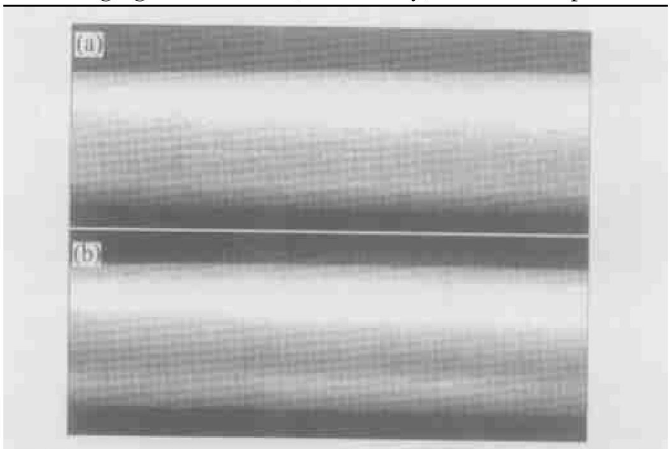

Fig. 2 Surface aspects of d60 mm ingots
(a) —In the absence of electromagnetic field;
(b) —10 000 A·turn, 30 Hz

of low frequency electromagnetic field, the cast surface is improved obviously.

3.2 Effect of low frequency electromagnetic field on microstructures

In the low frequency electromagnetic HDC process, as discussed above, the harmful effects of unbalanced cooling and gravity difference are greatly weakened by the electromagnetic forced convection, by which more uniform microstructures are obtained. Fig. 3 shows the microstructures of HDC ingots, from which specimens are taken in the center of cross-section. Fig. 3(a) shows that the microstructure is inhomogeneous and coarse without electromagnetic field. Figs. 3(b), (c) and (d) show that the microstructures are accordingly improved with different electromagnetic fields.

With the increase of current intensity, the forced convection and confined effect of Lorentz force are intensified accordingly, and the effects are enhanced. The effect of the electromagnetic intensity on the microstructures is shown in Figs. 3(b) and (d). The cast conditions of the ingots, from which the samples are taken, are different only in the electromagnetic intensities while the frequency was kept the same, i. e. 30 Hz. Increasing the number of ampere-turns from 5 000 A·turn to 10 000 A·turn, the dendritic grains change from coarser to finer and more uniform.

As a principal parameter, frequency greatly influences the distribution of magnetic flux density in conductive media. In the process of electromagnetic casting, flow pattern and temperature field of the melt can be modified by means of frequency modulation, and the optimized conditions of solidification can be obtained. The characteristic length, which specifies how the magnitude of magnetic field decrease as a function of distance into the liquid metal is the skin depth:

$$\delta = \sqrt{\frac{1}{\sigma\mu\pi f}} \qquad (2)$$

where σ and μ are the conductivity and permeability, respectively, of the liquid metal, and f is the frequency. When the operating frequency is relatively high(50 Hz or more), the skin depth is extremely small and the force density significantly concentrates near the surface of the metal, the rapid change in magnetic flux density across a small skin depth means a high gradient of force density, which forms a stronger confined pressure. But on the other hand, stirring effect is also weakened. With the decrease of frequency, the magnetic field, the induced currents, and hence Lorentz force densities are increased throughout the bulk of the liquid metal, the rotational part becomes dominant and the forced convection will be enhanced. With further decrease of frequency(less than 10 Hz), although the magnetic flux density is still increased, the distribution of magnetic flux density is relatively uniform throughout the melt; the rotational force is weakened again. Therefore, under a fixed

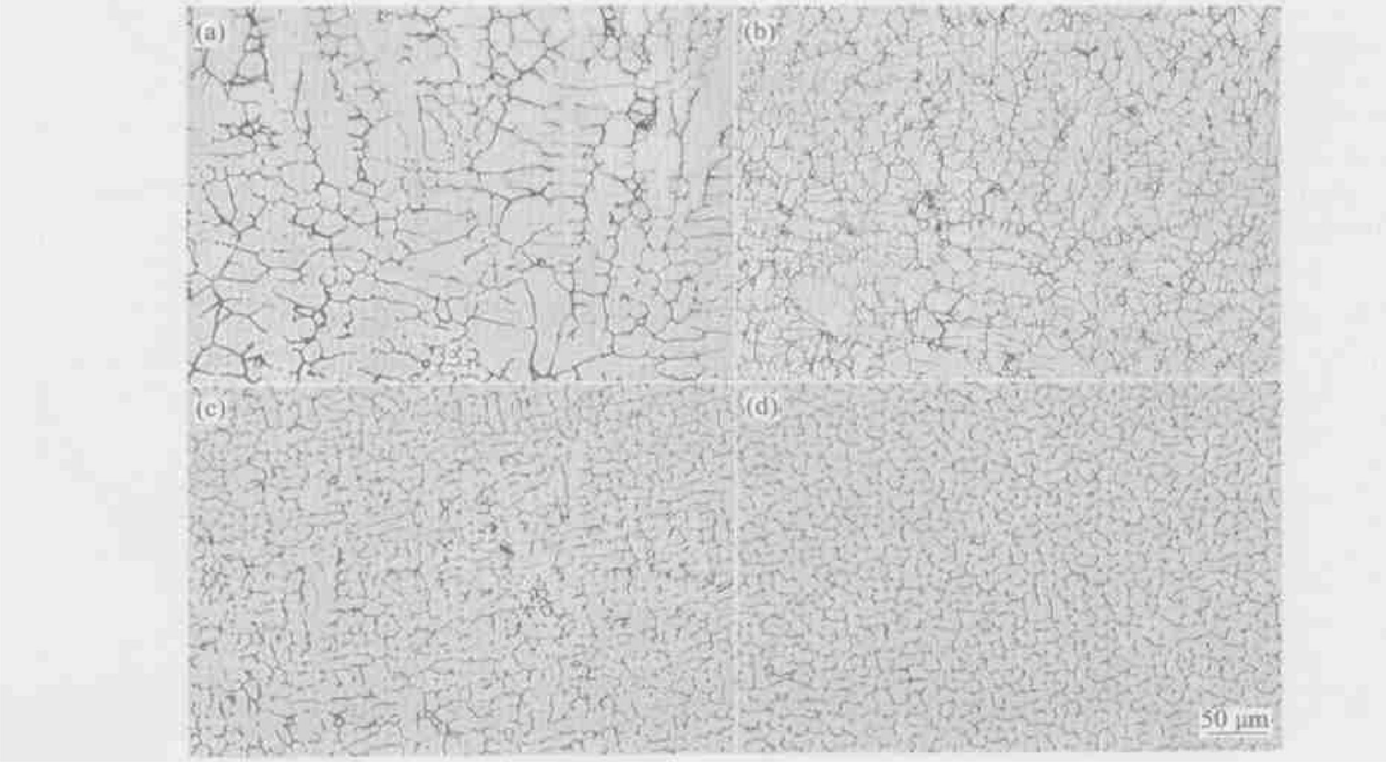

Fig. 3 Optical morphologies of as-cast microstructures in HDC
(a) —In absence of electromagnetic field; (b) —5 000 A·turn, 30 Hz; (c) —10 000 A·turn, 100 Hz; (d) —10 000 A·turn, 30 Hz

magnetic intensity, the ideal flow pattern and temperature field can be obtained by application of a proper frequency of electromagnetic field, which improves the microstructure to the best effect[16].

Figs. 3(c) and (d) show the effect of frequency of magnetic field on the microstructures. Fig. 3(c) shows that the structure is still dendritic with the frequency of 100 Hz, though the grain size is not too coarse; Fig. 3(d) shows that the structure is finer and more uniform with frequency of 30 Hz.

3.3 Effect of low frequency electromagnetic field on macrosegregation

The macrosegregation in horizontal direct chill casting process is composed of two types. One is inverse segregation and the other is gravity segregation. These two types of segregation do not singly but synthetically occur in ingot during solidification.

As a familiar defect in VDC casting process, inverse segregation occurs in HDC casting process also. Inverse segregation is caused by solidification shrinkage-induced flow. In the process of DC casting of aluminum alloys, solidification shrinkage-induced flow drives the solute-rich liquid to the ingot surface, which leads to macroscopic level compositional nonuniformity over the cross-section of the ingot. Solution concentration at the ingot surface is pronounced higher than the average value[11, 14]. Besides inverse segregation, gravity segregation can be obviously observed over the cross-section of the ingot cast by HDC process. Different to VDC process, as the metal is pulled out in the horizontal direction, gravity segregation is liable to occur in the HDC process. The average solution concentration in lower half of the cross-section of the ingot is higher than the average value in upper half by the effect of gravity-induced flow.

Fig. 4 shows the distribution of the Zn element along the diameter of the ingot in the absence of electromagnetic field. Alloying element is highly enriched at the ingot surface and greatly reduces surface quality. Moreover, the average solution concentration is different between upper and bottom portions due to gravity.

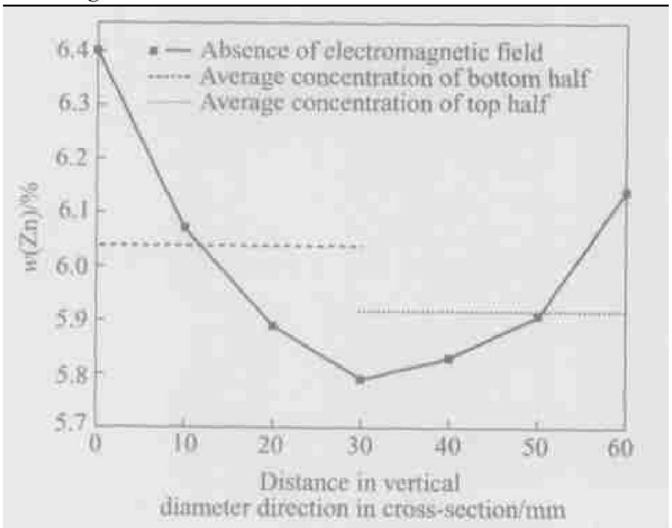

Fig. 4 Zn concentration profile in absence of electromagnetic field

The constrained effect of electromagnetic forces reduces the contact pressure between melt and mold, which reduces the primary cooling intensity. Electromagnetic forced convection broadens the mushy zone, decreases the height and depth of the sump, promotes heterogeneous nucleation, reduces temperature gradient and weakens the effect of gravity. All these effects result in a significant improvement of microstructures and solute redistribution of the ingot[12, 13]. Fig. 5 shows the distribution of the Zn element along the diameter of the ingot in the presence of different electromagnetic field. Fig. 5(a) shows the Zn element distribution along the diameter of the ingot under various intensities of electromagnetic field, while the frequency is held constant at 30 Hz. The intensity of electromagnetic field varies from 2 500

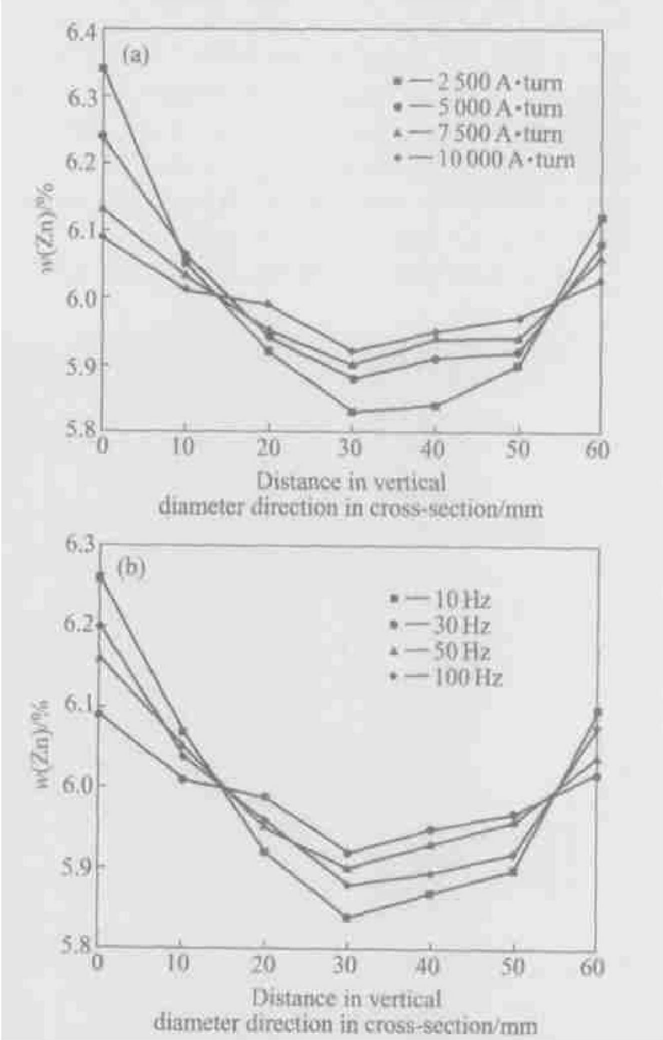

Fig. 5 Zn concentration profiles under different intensities of electromagnetic field (a) and different frequencies of electromagnetic field (b)

to 10 000 A·turn, large-scale inhomogeneous of alloying elements is alleviated significantly. Fig. 5(b) is the distribution of Zn element along the diameter under different frequencies of electromagnetic field, while the intensity is held constant at 10 000 A·turn. In the presence of electromagnetic field, the inverse segregation and gravity segregation are drastically reduced; especially, the best effect is gotten when frequency is approximately 30 Hz.

4 CONCLUSIONS

1) The application of low frequency electromagnetic field can effectively reduce surface defects in HDC casting process.

2) Under the effects of low frequency electromagnetic field, the flow pattern of the melt and therefore, the temperature field in the sump can be effectively improved, the uniform microstructure is obtained and the macrosegregation is reduced.

3) As two main parameters of electromagnetic field, the intensity and frequency of electromagnetic field play significant roles in grain refinement and solute redistribution. In this study, the results show that high intensity and relatively low frequency are more effective. When the number of ampere-turns is 10 000 A·turn and frequency is 30 Hz, the product quality is improved to the best effect.

REFERENCES

[1] Dawood A A. Improving horizontal direct chill casting [A]. Seventh Australian Asian Pacific Conference on Aluminum Cast House Technology [C]. Warrendale: Minerals, Metals & Materials Soc(TEMS), 2001. 275－283.

[2] Hertwich G, Loh L T. Hertwich horizontal DC casting [A]. Proceedings of the 4th Australasian Asian Pacific Conference on Aluminum Cast House Technology [C]. Warrendale: Minerals Metals & Materials Soc(TMS), 1995. 335－343.

[3] Wertli T P. Horizontal continuous casting technology in the eighties [J]. Metallurgia, 1986, 53(5): 192, 194.

[4] Birat J P, Chone J. Electromagnetic stirring on billet, bloom, and slab continuous casters: state of art in 1982 [J]. Ironmaking and Steelmaking, 1983, 110(6): 269－281.

[5] Vivès C, Ricou R. Experimental study of continuous electromagnetic casting of aluminum alloys [J]. Metall Trans B, 1985, 16B(6): 377－384.

[6] Meyer J L, Szekely J, Elkaddah N, et al. Comprehensive study of the induced current, the electromagnetic force field, and the velocity field in a complex electromagnetically driven flow system [J]. Metall Trans B, 1987, 18B(3): 529－538.

[7] Beitelman L. Effect of mold EMS design on billet casting productivity and product quality [J]. Canadian Metallurgical Quarterly, 1999, 38(5): 301－309.

[8] Spitzer K H, Reiter G, Schwerdtfeger K. Multi-frequency electromagnetic stirring of liquid metals [J]. ISIJ International, 1996, 36(5): 487－492.

[9] ZHANG Bei-jiang, CUI Jian-zhong, LU Gui-min, et al. Effects of electromagnetic field on macrosegregation of continuous casting 7075 alloy [J]. Trans Nonferrous Met Soc China, 2003, 13(1): 158－161.

[10] DONG Jie, CUI Jian-zhong, LIU Xiao-tao, et al. Super-high strength 7A60 Al alloy by low frequency electromagnetic cast (Ⅰ)—as-cast structures of billets with diameter of 0.2 m [J]. The Chinese Journal of Nonferrous Metals, 2003, 13(6): 1494－1499. (in Chinese)

[11] DONG Jie, CUI Jian-zhong, LIU Xiao-tao, et al. Super-high strength 7A60 Al alloy by low frequency electromagnetic cast (Ⅱ)—Intracrytalline solubility of alloy element and mechanical property of billets with diameter of 0.2 m [J]. The Chinese Journal of Nonferrous Metals, 2004, 14(1): 117－121. (in Chinese)

[12] Vivès C. Electromagnetic refining of aluminum alloys by the CREM process, part Ⅰ: working principle and metallurgical results [J]. Metall Trans B, 1989, 20B(8): 623－629.

[13] Vivès C. Electromagnetic refining of aluminum alloys by the CREM process, part Ⅱ: specific practical problems and their solutions [J]. Metall Trans B, 1989, 20B(8): 631－643.

[14] Reddy A V, Beckermann C. Modeling of macrosegregation due to thermosolute convection and contraction-driven flow in direct chill continuous casting of an Al-Cu round ingot [J]. Metall Mater Trans B, 1997, 28B(6): 479－489.

[15] Ishii Y. HDC process for small diameter ingot [A]. Proceedings of the Technical Sessions by the TMS Light Metals Committee at the 118 TMS Annual Meeting [C]. Las Vegas: Metallurgical Soc of AIME, 1989. 673－679.

[16] ZHANG Bei-jiang, LU Gui-min, CUI Jian-zhong. Effect of electromagnetic frequency on microstructures of continuous casting aluminum alloys [J]. J Mater Sci & Tech, 2002, 18(5): 401－403.

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