2001年上海大学博士学位论文 18

圆坯连铸结晶器电磁搅拌过程数学模拟与实验研究

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Shanghai University Doctoral Dissertation (2001)

Numerical Simulation and Experiment Study on Electromagnetic Stirring Process in Continuous Casting Mold of Round Billets

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Major : Ferroous metallurgy
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Shanghai University Press
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上 海 大 学

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答辩委员会对论文的评语

连铸电磁搅拌在结晶器内所引起的复杂物理现象是国内外研究的热点和难点问题。论文从理论解析、数学模型、计算机模拟、实验测定和现场运行数据的优化等方面对圆坯连铸结晶器电磁搅拌过程进行了全面而系统的研究。选题紧密结合实际生产急需解决的重要技术问题，具有重要的理论意义和很高的工程应用价值。论文作者查阅了大量的研究文献，把握了该领域国内外研究动态和发展趋势，对存在的难点有深入的理解和恰当的评价。在此基础上，作者开展了以下几方面的创新工作：

(1) 分析了连铸电磁搅拌过程的无量纲参数，推导了连铸结晶器内磁准静态方程。以数学解析方法研究了连铸结晶器内的磁场与电磁力解析模型。

(2) 建立了连铸结晶器内流动和传热数学模型，以矢量磁位和标量电位组合方法表述了连铸电磁搅拌过程的电磁场模型。此外，分析了结晶器内弯月面形状的数学模型，提出了在低频情况下弯月面形状受电磁力旋转分量影响的见解。

(3) 建立了连铸电磁搅拌过程电磁场、流动、传热及其耦合场的有限元计算模型。并将 ANSYS 软件应用于连铸冶金过程二维和三维电磁场、流场和温度场的仿真计算，分析了不同电磁搅拌与浇注工艺参数条件对铸坯质量的影响。

(4) 研制了测量金属熔体内搅拌力的装置，提出了测量磁感应强度的新方法——分量法，简化了操作难度与避免了测量的不稳定性。并测量和分析了连铸结晶器内磁场分布、电磁力和弯月

面形状。

(5) 利用模式识别方法直观地分析了电磁搅拌参数和浇注工艺参数对铸坯质量影响规律，探明了拉速、过热度的合理区域和电流强度、频率的较佳范围。

论文具有跨学科性、涉及面广、难度很大、工作量大，具有较强的系统性。所做的工作对生产实际有较好的参考价值和一定的指导意义。论文结构严谨，行文流畅，层次分明，研究方法正确，内容丰富，数据真实可靠，文献量大且引用规范，结论中肯合理。答辩过程中，论述清楚，思路清晰，逻辑性强，回答问题正确。这表明论文作者具有扎实的理论基础知识、较高的计算机水平和独立从事科研工作的能力。

答辩委员会表决结果

答辩委员会一致认为吴扣根同学的论文与答辩已达到博士学位要求，经过投票，一致通过博士学位论文答辩，建议授予其博士学位，并推荐为优秀博士论文。

答辩委员会主席：**陈念贻**

2001 年 11 月 28 日

摘　要

连铸技术经历了 60 年的发展历程，以高产量、高质量和产品多样性为目标，在中间包、结晶器和二冷区开发了一系列的相关技术，目前朝着高拉速、高质量的高效连铸和近终形连铸技术的方向发展。连铸结晶器具有净化、凝固、换热和化学反应等多种功能，是控制铸坯质量的重要环节，也是影响钢液流动和凝固传热的关键部位。电磁搅拌技术具有高能量密度、非接触性和易于自动控制等优点，在连铸生产中得到了广泛的应用。结晶器电磁搅拌改善铸坯质量的机理是借助感应产生的电磁力强化钢液流动、传热等过程，因此电磁搅拌磁场和电磁力分布是分析流体流动和传热过程的基础。现在虽开展了一些连铸电磁搅拌过程物理实验与数学模拟的研究工作，但由于电磁搅拌作用机理和凝固过程非常复杂，连铸电磁搅拌理论研究和磁场分布特征的定量分析还很欠缺。这是连铸电磁搅拌过程研究的难点，制约着电磁搅拌技术的发展与应用。

本课题来自宝钢委托研究项目《高拉速无缺陷圆坯连铸制造技术》。该项目要求，以圆坯连铸结晶器电磁搅拌为对象，探明铸坯的质量缺陷的影响因素。为此，本文从理论解析、数学模型、计算机模拟、实验测定和现场运行数据的优化等方面对电磁搅拌过程进行了研究。

在圆坯连铸电磁搅拌过程的理论解析方面，作者分析了雷诺数(Re)、磁雷诺数(Re_m)、哈特曼数(Ha)和磁相互作用参数(N)等

无量纲参数及其对连铸电磁搅拌过程的影响。依据电磁流体力学的控制方程，推导了直角和圆柱坐标系下的连铸结晶器内磁准静态方程及其电磁力的表达式。本文指出：在低频磁场的电磁搅拌过程中，可以忽略钢液流动对电磁场的影响，简化电磁搅拌过程的分析与计算。作者以数学解析方法，建立了任意形状线圈的磁场分布模型。并在此基础上，推导了连铸结晶器内的磁场与电磁力解析模型。该模型表明了磁场和电磁力与电流强度、频率、搅拌器极对数、空间位置及媒介性质等参数有关，可为分析连铸电磁场分布与电磁力的特征提供了理论依据。

根据流动和传热的通用方程，作者在直角和柱坐标系下分别建立了有、无电磁搅拌两种情况下的连铸结晶器内二维和三维流动和传热数学模型，并以矢量磁位和标量电位组合方法表述了连铸电磁搅拌过程的电磁场模型。此外，本文针对有、无电磁场作用情况，分析了结晶器内弯月面形状的数学模型，认为在低频电磁搅拌条件下，弯月面形状计算方程中增加了电磁力项，电磁力的有旋分量驱使钢液运动，从而影响了弯月面形状。这些模型为推导电磁搅拌过程有限元模型和进行数值分析提供了基础。

作者选用兼有传热、流动和电磁场功能的 ANSYS 有限元软件作为电磁搅拌过程模拟计算的工具。利用有限元理论，建立了连铸电磁搅拌过程凝固传热、流体流动、电磁场和耦合场的有限元计算模型。应用 ANSYS 程序设计语言，编制了连铸结晶器电磁搅拌过程的二维和三维电磁场、流场和温度场计算程序，探索性地计算了不同工艺参数条件下的电磁场、流场和温度场分布，分析了电磁搅拌与浇注工艺参数的影响效果。计算结果表明：在低频条件下，钢液对磁场的分布影响较小，因而可以用空载时测量的结果作为有钢液时的近似估计，对实际应用具有指导意义。

为了给数值分析提供实验基础和验证模拟结果，根据相似原理和应力应变理论，作者自制了一套能测试熔体电磁搅拌力的装置，提出了一种测量磁感应强度的新方法一分量法。从实验室模拟角度对连铸结晶器内磁场分布、电磁力和弯月面形状进行了测试。之后，为探索搅拌器的结构与磁场分布特征的关系，寻求最佳电磁搅拌参数，在现场对圆坯和方坯结晶器内旋转磁场分布进行了测量。实验结果表明，磁场的空间分布受到电流强度、频率、电磁搅拌器的极对数、空间位置和结晶器断面等影响。磁感应强度随电流强度增大而增大、随频率增大而减小。在结晶器同一高度位置的断面上，从中心到结晶器壁面磁感应强度逐渐增加,在中心与壁面处的磁感应强度幅值相差不大。在中心轴线方向上磁感应强度在搅拌器中心位置处有最大值，呈现了“中间大、两端小”的分布规律。为分析电磁搅拌对连铸圆坯质量的影响，在工厂进行了生产试验，采集了试验数据。利用模式识别方法分析了电磁搅拌参数(电流强度和频率)和其它浇注工艺参数(拉速、过热度、二冷比水量)对铸坯质量影响规律，寻求了较为合理的拉速、过热度的区域和较佳的电磁搅拌的电流强度、频率范围，利用该分析结果有效地控制了铸坯质量。此外通过对比性试验，证明了这些工艺参数对改善铸坯质量的不同作用效果。

结合理论分析，作者比较了电磁搅拌过程仿真计算与实验结果，讨论了连铸结晶器电磁搅拌过程中的电磁搅拌强度、电磁搅拌器安装位置、凝固坯壳厚度和设备结构参数等问题。仿真计算得到的电流强度、频率、结晶器出口处凝壳厚度优化值与实验测量结果吻合的较好。计算与测量得到的磁感应强度分布规律一致，但计算较测量的磁感应强度峰值要向上偏移，而不在搅拌器的中心位置。这证明了电磁搅拌器安装位置的合理性，为连铸电

磁搅拌生产的参数优化提供了理论依据。

根据理论模型、仿真计算、模拟实验和现场生产试验的研究结果，为保证在高拉速条件下的铸坯质量，作者认为在宝钢圆坯生产过程中控制以下几个参数：拉速与过热度应分别控制在 2.30~2.50m/min 和 15~30℃范围内；浇注水口采用侧孔浸入式水口；水口倾角可控制在向下 15° 左右；插入深度建议在弯月面下 100mm 附近；电源频率选择较佳值 5Hz；电流强度合理范围为 200A 左右；搅拌器安装位置应靠近结晶器下方。

最后归纳了本研究的主要工作与结果，指出以后工作的方向。认为在计算技术进一步发展的基础上，最终需要将电磁场、流场、温度场和浓度场等多种物理场完全耦合模拟，以求得对连铸结晶器电磁搅拌机理更深入透彻的了解。

关键词 圆坯，连铸结晶器，电磁搅拌，数值模拟，**ANSYS** 软件，模式识别，铸坯质量

Abstract

With sixty years progress, continuous casting technology is now developing to the orientation of high withdrawal velocity and near net shape of few-defect products, accompanied by a series of relative technologies concerning tundish, mold and second cooling zone aiming at high efficiency, high quality and diversity products.

Having functions of purification, solidification, heat exchange and chemical reaction, continuous casting mold is the important chain of strand quality control and the key part influencing on molten steel flow, heat transfer and solidification.

Electromagnetic stirring (EMS) has been widely applied in continuous casting process for its advantages of high energy density, non-contact and easy control. The mechanism that mold EMS improves strand quality is intensive fluid flow and heat/mass transfer of solidification process by means of electromagnetic force. The distribution of magnetic field and electromagnetic force is the foundation of analysis fluid flow and heat transfer. Although some physical experiments and mathematical modeling of EMS have been reported, the researches on theoretic analytic modeling of EMS and the distribution character of electromagnetic field used in continuous casting are still imperfect for its complication. These problems are just the difficult points of EMS investigation and the obstacles of EMS developing.

The present subject is part of a research project submitted by Baoshan Iron and Steel Corporation named Study on Manufacture

Technology of Round Billet with High Withdrawal Velocity and Non-Defection. The project demanded to prove up factors that influenced strand quality with mold EMS in round billet continuous casting. With this purpose, electromagnetic stirring was investigated in aspects of theoretic analysis, mathematical modeling, computer simulation, experimental measure and process optimization.

During the theoretical analysis of electromagnetic stirring process of continuous casting of round billet, the effect of several elementary dimensionless numbers including Reynolds number (*Re*), magnetic Reynolds number (Re_m), Hartmann number (*Ha*) and magnetic interaction parameter (*N*) on electromagnetic stirring procedure were analyzed. The quasi-static magnetic field equations of EMS in continuous casting mold and electromagnetic force equations were deduced at right angle and column coordinate system based on magneto-hydrodynamics equations. According to the physical meaning of dimensionless numbers, the influence of liquid steel flow on electromagnetic field could be neglected during the analysis of EMS process in continuous casting so that its analysis and calculation could be simplified. Moreover, the models of magnetic field and electromagnetic force of arbitrary empty loaded windings were illustrated by mathematical analytic method. Based on above work, the distribution modeling of 2-D and/or 3-D electromagnetic field, electromagnetic force for traveling wave and rotating magnetic field in continuous casting mold were obtained respectively, which provided theoretic foundation for the analysis of EMS process. It shows that the distribution of magnetic field and electromagnetic force are related to current strength, frequency, the pole pair number of the

stirrer, spatial position and media parameters.

According to general equation of fluid flow and heat transfer, 2-D and/or 3-D mathematical modeling of fluid flow and heat transfer with/without EMS in continuous casting mold were presented at right angle and column coordinate system. The mathematical modeling of electromagnetic field of EMS in continuous casting was described by means of the combination of magnetic vector potential and electric scalar potential. Furthermore, the mathematical modeling of meniscus shape of molten metal in continuous casting mold was deduced and analyzed under conditions of static state and electromagnetic field. Comparing their calculated modeling, the difference is that electromagnetic force changes liquid steel flow consequently to influence meniscus shape with EMS action. It provided the theoretic basis for establishing finite element modeling (FEM) and numerical simulation.

ANSYS finite element analysis software was chosen as simulation tool due to its analysis functions of heat transfer, fluid flow and electromagnetic field. The calculation modeling of temperature field, flow field and electromagnetic field and their coupled field were established base on the finite element theory. Corresponding programs of mold EMS process in continuous casting were written by ANSYS parameter design language (APDL). The distribution of electromagnetic field and the behavior of fluid flow, solidification and heat transfer of continuous casting process were simulated respectively. The measure data that mold is Empty load may be regarded as a good estimation of the mold filled with liquid steel. This result has direction meaning for

practical operation of continuous casting.

To verify the numerically simulated results, a set of experimental device was designed based on similarity theory. A new method for magnetic flux measurement was proposed. The magnetic flux distribution, electromagnetic force and meniscus shape were measured in the laboratory. For the further explore of the characteristic of electromagnetic stirrer configuration and magnetic flux distribution and to optimize EMS parameters, the magnetic flux of rotating magnetic field in square/round billet mold were measured in workshop.

The measured results indicated that the spatial distribution of magnetic flux was affected by EMS parameters, such as the electric current strength, frequency, the pole pairs number of electromagnetic stirrer and the cross section of mold. Magnetic flux increased with the enhancement of current strength, and decreased with reduce of frequency. On the same depth of mold, the magnetic flux gradually increased from the center to the wall of mold, however, its amplitude had little difference. The values of magnetic flux reached its maximum in the middle plane of the stirrer and became smaller towards the end plane of the mold. The industrial trials on the effect of EMS on the quality of round billet were carried out and the corresponding trial data have been collected and extracted. The influence of EMS parameters (such as electric current strength and frequency) and other casting parameters (such as casting speed, superheat and specific water quantity of second cooling section) on the quality of round billet was investigated with the pattern recognize method. Besides, the reasonable ranges of casting speed and superheat were found out, and the optimal values

of electric current strength and frequency were suggested. These results could be used to monitor the strand quality. From contrast experiments, the influence of these processing parameters on strand quality was certified.

On the basis of the comparison of the computation results and the measured ones, the several special questions of EMS, such as the installation position of the stirrer in mold, the thickness of the solidification shell and the equipment configuration parameters, were discussed combining theoretic analysis. The calculated results of current strength, frequency and the solidification shell thickness in mold exit were agreement with the experimental ones. The simulated magnetic flux and the measured one had same distribution rule, but the position of the magnetic flux amplitude by calculation moved a little upward. It is not in the middle of the stirrer height. That shows the installation position of the stirrer in mold is reasonable. The research results provide the theory basis for the parameter optimum of the EMS operation of continuous casting. Based on the results obtained from theory modeling, computer simulation, physical experiments and industrial trial, the following parameters range have been suggested in continuous casting of round billet in Baoshan Iron & Steel Co.. That is, the proposed range of the withdrawal velocity from 2.3 to 2.5m/min and the superheat from 15 to 30℃. The casting nozzle is suggested to adopt immersion entry nozzle of side-hole type with a inclination angle of 15° downward, the immersion depth of nozzle under the meniscus about 100mm, the optimized value of electric current strength and frequency about 200A and 5Hz respectively. The electromagnetic stirrer was proposed to arrange near the bottom of mold.

Finally, the research results of EMS process in continuous casting mold were summarized. Meanwhile, the research direction and object were also pointed out. With the development of calculation technique in the future, electromagnetic field, flow field, temperature field and concentration field should be completely coupled. So the EMS mechanism in continuous casting would be intensively comprehended.

Key words round billet, continuous casting mold, electromagnetic stirring, numerical simulation, ANSYS software, pattern recognize, strand quality