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连铸坯表面振痕形成机理及其电磁控制技术

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Shanghai University Doctoral Dissertation (2004)

Formation Mechanism of Oscillation Marks in Continuous Casting of Billets and Its Control with Electromagnetic Field

Candidate: LEI Zuosheng
Major: Ferro-metallurgy
Supervisor: Prof. REN Zhongming

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答辩委员会对论文的评语

雷作胜同学的博士学位论文《连铸坯表面振痕形成机理及其电磁控制技术》在广泛阅读相关文献、对比相关研究的基础上，紧紧围绕连铸过程铸坯表面振痕形成的两个本质问题，即"力"和"热"的作用进行研究，在理论上提出了一个新的振痕形成机理，引入"调幅磁场"并提出了两项新的控制振痕形成的电磁连铸技术. 论文把握了该领域国内外研究动态和发展趋势，选题起点高，处于国际前沿. 论文所得结果不仅具有较高的学术意义，而且具有良好的应用前景.

该论文的主要贡献和创新如下：

（1）采用小型连铸实验、初始凝固物理模拟实验和数学模拟相结合的方法，系统深入地研究了连铸过程结晶器振动导致的铸坯初始凝固点温度波动的现象，认为这一现象是导致铸坯表面振痕形成的一个重要原因，在此基础上提出了一个新的连铸坯表面振痕形成机理.

（2）从连铸坯表面振痕形成"力"的作用出发，将一种特殊的幅值随时间变化的"调幅磁场"引入电磁连铸领域，并研制开发了可实现方波、三角波和正弦波的高频调幅磁场发生器. 这为电磁连铸技术进一步的研究提供了新的思路.

（3）提出了与结晶器振动相耦合的调幅磁场电磁连铸技术。基于结晶器振动导致保护渣道动态压力变化行为给出了一个调幅磁场优化设计模型，通过连铸实验进行了初步的验证.

（4）对多种波形调幅磁场下无结晶器振动电磁连铸技术进

行了实验探索，认为正弦波调幅磁场要优于方波和三角波.

雷作胜同学的博士论文研究内容新颖，研究手段丰富，工作量大，系统性强，有理论深度，结论正确。论文写作条理清晰，层次分明，文笔流畅、学风严谨. 在答辩过程中论述清楚，思路清晰，逻辑性强，回答问题正确. 表明雷作胜同学掌握了本门学科坚实的理论基础知识和系统的专业知识，具有较强的独立从事科研工作的能力.

答辩委员会表决结果

经答辩委员会投票表决，一致认为雷作胜同学的博士论文已经达到博士学位要求，同意通过该同学的博士学位论文答辩. 建议授予雷作胜同学博士学位，并推荐参加全国优秀博士论文评选.

答辩委员会主席：徐楚韶

2004 年 9 月 14 日

摘 要

随着连铸技术朝着近终形、高速度、高质量方向发展，对连铸坯的质量提出了更高的要求. 作为表面裂纹和偏析形成的主要原因，连铸坯表面振痕缺陷也越来越受到关注. 因此，弄清铸坯表面振痕形成的机理，进而减轻甚至消除铸坯表面振痕，具有重要的理论意义和现实意义.

本文的研究基于这样的学术思想：振痕是空间位置的波动，其形成与弯月面处力和热的波动相关，探究这些波动行为，将深刻揭示振痕的形成机理，控制这些波动，将有效抑制振痕.

本文的第一部分，提出了一种新的振痕形成机理，认为连铸过程中结晶器振动导致初始凝固坯壳的"温度波动"是铸坯表面振痕形成的一个重要原因.

通过小型连铸实验，在金属 Sn 的连铸过程中采用"热电偶序列依次通过初始凝固点"的方法，测量了结晶器振动对初始凝固点温度变化的影响. 实验结果发现初始凝固点的温度存在着与结晶器振动相对应的周期性变化，多次实验表明在 Sn 的连铸中这一温度变化大致在 4~11℃之间. 基于这一实验现象，分析了这一温度变化形成的原因和它对连铸初始凝固过程的可能影响.

设计了连铸初始凝固点温度波动研究物理模拟实验装置，测量了在结晶器振动情况下连铸坯弯月面处温度. 实验结果表明：结晶器振动频率越大，振动幅值越小，结晶器冷却强度越小，结晶器与铸坯间的接触压力越小，因结晶器振动而产生的初始凝固点的温度波动越小.

发展一个具有周期性边界条件的初始凝固区域一维传热模型，

来定量分析钢连铸过程中温度波动的规律. 数学模拟的结果显示，在结晶器内侧存在温度波动的情况下，无论有无保护渣，在钢水内部每一点都存在着与表面温度波动频率一致的温度波动，但其幅值随深度的增加而下降；在无保护渣的情况下，表面温度波动在钢水中的渗透深度约为 1~2 mm；保护渣的存在对温度波动有很大的衰减作用，因而能提高铸坯表面的质量；另外，采用高频率小振幅的振动，降低保护渣导热率，增加保护渣道宽度，都能有效地减小温度波动对初始凝固坯壳的影响. 结果与上述实验现象基本一致.

基于此"温度波动"现象，分析了包括结晶器高频小振幅振动、非正弦振动，热顶结晶器，软接触结晶器电磁连铸等诸多技术改善铸坯表面质量的机理. 这些技术的共同之处在于减小了连铸坯初始凝固点的温度波动幅值，从而改善了铸坯的质量.

论文的第二部分，基于铸坯表面振痕形成的保护渣作用机理，提出了一项新的电磁连铸技术——调幅磁场耦合结晶器振动电磁连铸技术.

首先通过模型实验，测量了在不同强度高频电磁场作用下液态金属弯月面形状和保护渣道宽度，从而计算了在结晶器振动一个周期内保护渣道动态压力变化情况. 计算表明电磁连铸中高频电磁场能够显著减小保护渣道内动态压力的变化，并且结晶器外的磁感应强度越大，保护渣道动态压力的变化越小，这可能是软接触结晶器电磁连铸技术改善铸坯表面质量的一个可能机理. 但同时也发现，磁感应强度的增加并不能无限制地减小保护渣道内动态压力，考虑到连铸弯月面稳定性等因素，为了获得最佳的铸坯表面质量，磁感应强度存在一个合适的值.

推导并计算了连续交变磁场和调幅交变磁场作用下，圆柱形金属液中电磁力密度在半径方向上的分布及其随时间的变化情况. 计算发现，在连续及调幅磁场情况下，电磁力均以原输入电磁场载波

频率的两倍频率变化. 在调幅磁场的情况下，平均电磁力的变化规律与输入的磁场的幅值变化频率相同，但在调幅磁场幅值的一次上升段和下降段，电磁力幅值的变化为二次抛物线形，在调幅磁场的恒值段则与连续施加时一样. 在计算结晶器振动下保护渣道动态压力变化基础之上，提出了一个与结晶器振动相耦合的调幅磁场计算模型，得到了不同情况下调幅磁场波形.

以Sn和硅油为模拟体系进行了方波调幅磁场耦合结晶器振动的电磁连铸实验. 实验结果表明，在结晶器振动处于正滑脱期间施加电磁场，能有效地减小拉坯阻力，改善铸坯表面质量. 同时，在这一技术中，如何选择调幅磁场的波形，兼顾保护渣润滑效果和弯月面波动产生的影响，获得最佳连铸效果，是一个有待深入研究的问题.

论文的第三部分，基于以上的一些研究，提出了又一项新的技术——调幅磁场下无结晶器振动电磁连铸技术，以期用结晶器外调幅磁场电磁力的振动来取代庞大的机械振动系统.

研制成功包括方波、正弦波、三角波在内的三种波形高频调幅磁场发生器，并对其在结晶器内产生的磁场进行了测量. 进行了三种波形高频调幅磁场下的无结晶器振动电磁连铸初步实验研究，实验结果表明：在方波、三角波和正弦波调幅磁场作用下的无结晶器振动电磁连铸过程中，当调制波频率略低于系统固有频率时，弯月面与结晶器壁间断接触距离最大，保护渣润滑效果最好，连铸过程拉坯阻力最小，连铸坯表面质量相对较好. 在方波、三角波和正弦波三种高频调幅磁场中，从减小拉坯阻力和改善铸坯表面质量的角度讲，正弦波在整体上要稍优于三角波和方波.

关键词 连铸，振痕，结晶器振动，初始凝固，温度波动，电磁连铸，电磁场，调幅磁场

Abstract

The surface of continuously cast billets is characterized by the oscillation marks that form periodically at the meniscus zone due to mould reciprocation. The oscillation marks have an important influence on the surface quality of the billets because they are often the sites of transverse cracks and segregation happened, which is a disadvantage of the development of continuous casting toward near-net shape, high speed and high quality. Therefore, it is of significance to study how the oscillation marks form and how to decrease and eliminate the oscillation marks during continuous casing. This is what the paper concerned on.

The paper is composed of three main parts. In the first part, a new oscillation marks formation mechanism was proposed, in which it is considered that the temperature fluctuation of early solidified shell caused by mould reciprocation is a key factor for the oscillation marks formation during continuous casting.

The initial solidified point(ISP)t emperature fluctuation caused by mold reciprocation was measured by a method named as thermocouples column passed ISP one by one during experimental scale Tin continuous casting. The repeated experiments results show that the ISP temperature varied periodically along with mold oscillation, the fluctuation amplitudes are between 4 and 11℃. Based on the phenomenon, the reason caused the temperature

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fluctuation and its possible influence on early solidification is analyzed.

Then a model experiment device, as a simulation of continuous casting early solidified process, was designed in order to measure the temperature fluctuation accurately. According to the experiments, the temperature fluctuation amplitudes of ISP decrease with the increasing of mold oscillation frequency, the decreasing of mold oscillation amplitude, cooling density, contact pressure between mold and solidified shell.

A one-dimension heat transfer mathematic model on continuous casting early solidification process with a periodical boundary condition was developed to quantitatively study the temperature fluctuation. The mathematic model results show that when there was a temperature fluctuation in the inner mould wall, there were corresponding temperature fluctuations at every point in the molten steel, whose frequency is the same as the boundary condition and amplitude decreased along with the increasing depth whether there was mould flux between mould and steel or not. The influence depth of surface temperature fluctuation in molten steel is about 1~2 mm when there was no mould flux. The surface temperature fluctuation attenuated rapidly when there was mould flux. Therefore mould flux was helpful to improve the billets surface quality. In addition, high frequency and low amplitude mould oscillation, decrease the thermal conductivity of mould flux and increase the mould flux channel width are all helpful to decrease the influence on early solidified shell caused by surface temperature fluctuation. The mathematic model results were well consistent with the experimental results.

Based on the phenomenon, the mechanism of how some technologies, including high frequency and low amplitude mold oscillation, soft-contact mold electromagnetic continuous casting, hot top mold and so on, improve surface quality of continuous casting billets is analyzed. Their common mechanism was the decreasing of the temperature fluctuation of early solidification shell.

In the second part of the paper, by using a kind of special amplitude-modulated magnetic field (AMMF), *i.e.* a high frequency magnetic field (carrier wave) modulated by a low frequency periodic wave (modulate wave), a new electromagnetic continuous casting (EMCC) technology, named as mold oscillation coupled with AMMF EMCC, was proposed based on the oscillation marks formation mechanism in which the dynamic pressure of mould flux channel playes an important roll.

Molten metal meniscus profile and mold flux channel width are measured under high frequency magnetic field with different intensities by model experiments, then the dynamic pressure in mold flux channel is calculated during one mold oscillation period. It is found that the high frequency magnetic field can decrease the dynamic pressure greatly, which may be one possible mechanism of improving the billets surface quality by soft-contact mold electromagnetic continuous casting. According to the calculation, the mold flux channel dynamic pressure can not be decreased unlimitedly by increasing magnetic flux density, there must be a most appropriate magnetic flux density in order to get best billet surface quality.

The distribution of electromagnetic force along with radius and time in cylinder shape liquid metal under continuous and amplitude modulated alternating magnetic field are deduced and calculated based on Maxwell equation. It is found that the frequency of electromagnetic force was the twice of the magnetic field under both continuous and amplitude modulated condition, and the amplitude of it changed in a square parabola type while amplitude of magnetic field changed in a linear type. Based on the study of mold flux channel dynamic pressure, a model to optimize design AMMF was proposed.

Continuous casting experiments results show that in the mold oscillation coupled with AMMF EMCC, imposition of AMMF duty part during mold oscillation positive strip can deduce the withdraw resistance and improve the billets surface. On the other hand, in the mild O_3cidatim coupled with AMMF technology, how to select the wave of AMMF to balance the lubrication effect and meniscus fluctuation in order to gain the best billets surface is a problem to be intensely studied.

In the third part of the paper, another novel technology, named as mould oscillation-less electromagnetic continuous casting (MOLECC) under AMMF was proposed in order to replace the huge mechanical mould oscillation system by AMMF imposing outside the mould in continuous casting.

A high frequency AMMF power source that can produce rectangle, triangle and sine wave AMMF has been invented, and then the magnetic field inducted in the mould by the power source was measured. Experimental results of MOLECC under three kinds wave of AMMF show that: (1) During the MOLECC process under rectangle, triangle and sine wave AMMF, when the modulated wave frequency is a little less than the intrinsic frequency of the experimental system the intermittent contacting distance is the greatest, the mould flux lubrication is the best, the continuous casting withdraw resistance is the least and the surface quality of billets is better relatively. (2) Among the three kinds of AMMF, sine wave is better than rectangle and triangle wave AMMF in order to deduce the withdraw resistance and improve the billets surface quality.

Key words continuous casting, oscillation marks, mould oscillation, initial solidification, temperature fluctuation, electromagnetic continuous casting, high frequency amplitude-modulated magnetic field

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