2004年上海大学博士学位论文 ⑱

冶金熔体中夹杂物一般动力学的理论研究及其应用

作　者：张邦文
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导　师：任忠鸣

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Shanghai University Doctoral Dissertation (2004)

Theoretical Study and Its Application on the General Dynamics of Inclusion Particle in Metallurgical Melts

Candidate: Zhang Bangwen
Magpr: Ferrp-metallurgy
Supervisor: Prof. Ren Zhongming

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上 海 大 学

本论文经答辩委员会全体委员审查，确认符合上海大学博士学位论文质量要求.

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答辩委员会对论文的评语

张邦文同学的博士论文“冶金熔体中夹杂物一般动力学的理论研究及其应用”，对金属熔体中夹杂物动力学的若干方面进行了深入的理论和实验研究，并应用到中间包去除夹杂物和电磁分离夹杂物等实际工程问题中，对于纯净钢生产、提高冶金企业的技术水平具有重要的理论指导意义和参考价值. 论文立题正确，视野开阔，内容丰富，处于该领域的前沿.

该论文的研究成果在以下几点上有所创新:

(1) 进行了不规则夹杂物运动阻力的水模型实验，获得的形状修正系数较有参考价值.

(2) 获得了夹杂物在冶金容器壁面的吸附效率，基于对 Engh 结果的修正，给出了更有物理意义的壁面传质系数.

(3) 提出了夹杂物单颗粒生长的动力学理论，对夹杂物碰撞聚合的微观形态进行了 Monte-Carlo 模拟，结果得到实验验证. 引入分形理论解释夹杂物的凝聚结构，发现夹杂物的分形维数约等于 2.25.

(4) 把夹杂物的形核、生长和传递等基本物理过程耦合，建立了一个有普适性的通用动力学模型，为深入研究冶金反应器中夹杂物的动力学行为奠定了基础.

(5) 在 Lagrange 框架下，提出了一个夹杂物运动、聚合和去除耦合的统计模型，为研究冶金熔体中夹杂物的传递和聚合，提供了一种新的方法. 验证了中间包中夹杂物的碰撞长大并不显著的结论.

(6) 利用工频电流，进行了单电流电磁分离铝熔体夹杂物的实验，取得了显著成效，对今后夹杂物的去除提供了新的方法.

(7) 提出了合金凝固过程中晶粒磁取向的动力学模型，获得了取向时间的一个分析解. 理论上解释了铁磁性的 BiMn 织构的形成机制，得到实验结果的支持.

论文反映出作者已较全面地掌握了与本课题相关的国内外发展动态，且具有扎实的数理基础及系统深入的专门知识，显示了该生已具有相当强的独立科研能力. 论文逻辑严谨，层次分明，文笔流畅，论据充分，实验数据可靠. 在答辩过程中，回答问题思路清晰，能予以正确回答.

答辩委员会表决结果

经答辩委员会表决，全票同意通过张邦文的博士学位论文答辩，建议授予工学博士学位.

答辩委员会主席：翟春泉

2003 年 10 月 10 日

摘 要

夹杂物的动力学一直是一个引起广泛兴趣的研究课题，涉及的内容很广，基本的物理过程大致包括：形核、生长、聚合、传递等，夹杂物去除可以视为传递过程的结果. 弄清冶金熔体中夹杂物动力学的一般规律，开展夹杂物去除技术的基础和应用研究，对于纯净钢生产、提高冶金企业的技术水平和市场竞争力具有重要的现实意义.

本文第一部分，对夹杂物动力学的若干方面进行了理论和实验研究.

采用聚苯乙烯颗粒，对夹杂物颗粒运动阻力的形状修正系数进行了水模型实验. 发现，在相同体积下，不同颗粒的形状修正系数的大小满足如下规律：棒状颗粒沿长轴方向<球形颗粒<十字形颗粒沿平面方向<簇状颗粒 <十字形颗粒沿平面的法向< 棒状颗粒沿横向；一般地，夹杂物的形状修正系数，可取 1.5~2.8.

对夹杂物在冶金容器壁面上吸附的稳定性进行了力学分析，结合已有的实验结果，提出了夹杂物吸附效率的一个预测关系，进而给出了夹杂物的壁面传质系数. 结果表明，传质系数是流体壁面剪力的函数，随着壁面剪力的增大，传质系数呈现先增后减的规律，在某个临界剪力出现极大值，该值大约是使夹杂物颗粒在壁面发生滚动的临界剪力的 5 倍.

对夹杂物生长的两种主要形式“扩散长大”和“碰撞聚合”，进行适当的物理简化和数学建模，推导了夹杂物生长速率的解析关系，建立了夹杂物生长的动力学理论. 本文获得的扩散长大率，

得到前人实验结果的检验. 理论分析显示，夹杂物的早期生长依赖于扩散长大和布朗运动碰撞，前者作用是主要的，后期生长依赖于湍流碰撞和Stokes碰撞，湍流碰撞占主导地位. 在冶炼过程，碰撞聚合比较迅速，而在连铸过程，碰撞聚合作用并不明显，精炼过程则处于一个过渡状况. 对夹杂物碰撞聚合的微观形态进行了 Monte-Carlo 模拟，结果与文献报道的实验观察一致. 引入分形理论解释夹杂物的凝聚结构，发现夹杂物的分形维数约等于 2.25.

基于上述研究，把形核、生长、聚合和传递等基本物理过程耦合在一起，建立了一个有普适性的夹杂物通用动力学模型，为深入研究冶金反应器中夹杂物的动力学行为奠定了基础.

论文第二部分，基于前面的研究，在 Euler (流场)-Lagrange (颗粒运动) 框架下，提出了一个夹杂物运动、聚合和去除耦合的统计模型. 应用这个模型，对某工业中间包中夹杂物的传递和去除进行了数学模拟. 结果发现，通过浮力上浮，是中间包中夹杂物去除的主要方式，壁面吸附、碰撞聚合增进了夹杂物的去除效果. 半径 10 、20 、30 μm 夹杂物的总去除效率接近 20%、42% 和 75%，其中壁面吸附的贡献占 1/6~1/4. 碰撞长大对夹杂物去除的贡献<5%，表明中间包中夹杂物的碰撞长大并不显著，这个结论与传统的观点明显不同.

论文第三部分，基于前面的研究，对新型金属液纯净技术——单电流电磁分离夹杂物技术进行了系统的理论和实验研究，以期提供了一种经济、实用的钢液净化手段.

解析了直流和交流激励下，金属液在圆管、扁平管中的磁场分布，提出了相对电磁浮力、净化效率、净化时间的概念和理论关系，建立了单电流电磁分离夹杂物技术的基本框架. 理论分析

和数值计算表明，工频交流电产生的电磁力分布逼近直流电，使用直流电看上去没有必要；夹杂物的电磁净化效率是电流密度、颗粒半径及其在分离管中停留时间的函数，圆管和扁管的净化效率接近；矩形管会在截面诱发二次流，扰乱夹杂物的正常迁移，对夹杂物的去除不利，净化效率低于圆管.

利用 Al-22%Si 和 Al-5%Mg-2%SiC 合金，采用工频电流进行了电磁分离夹杂物的静态实验. 结果发现，通电 30 s、电流密度保持 $4\times10^6 A/m^2$，初晶 Si 在各种管道中都能完全偏聚，而半径大于 50 μm 的 SiC 颗粒，完全偏聚只要不到 10 s 的时间，SiC 颗粒的偏聚比初晶 Si 快. 电磁分离技术可望移植到表面增强梯度功能材料具的制备，从而提供一种经济、实用的新方法.

利用 Al-8%Mg-2%Al_2O_3 合金，采用工频电流进行了电磁分离夹杂物的连续实验. 结果发现，在铝液流速 2.3~2.9 cm/s，电流密度 0.8×10^7~1.4×10^7 A/m^2 的条件下，出口温度比入口温度提高了 15~25℃，加热效果可以满足对金属液加热的需要. 通电密度 1.4×10^7 A/m^2，金属液在管道中的停留时间保持 10 s，Al_2O_3 颗粒的去除效率可达 95%. 实验结果与理论预测基本吻合.

论文最后部分，研究了合金凝固过程中，晶粒磁取向的微观机制，提出了晶粒取向的一个动力学模型，获得了取向时间的一个分析解. 对 Bi-3%Mn 合金，在 300℃下和 0.3T 的磁场中进行了淬火实验，得到了有取向的 BiMn 织构. 发现铁磁性的 BiMn 晶粒的磁取向时间小于 1 s，与理论预测吻合. 在 BiMn 织构的形成过程中，取向不是控制性环节.

关键词 夹杂物，去除，生长，聚合，动力学，Monte-Carlo，流场，电磁场

Abstract

With the increasing demands for the quality of steel product, much attention has been drawn to the production of pure steel in metallurgical enterprises throughout the world. It is key to how to control the level of impurity, especially the inclusion, which mainly responsible for the defect of most steel products. Therefore, it is of significance to investigate the law of dynamics, such as growth, transfer and removal of inclusions in molten melts, and further improve the conventional process or develop new techniques regarding pure steel.

The paper is divided into four parts. In the first part, the experimental and theoretical studies are carried out from several aspects involving the dynamics of inclusions as follows:

The modification coefficients of motion resistance, C_s, of inclusion particles of different shape to the ideal spherical particle are measured by model experiments using polystyrene particle of radius 1~2.6 mm. It is found that the order of increasing C_s is the rod-like particle oriented its long axis, the spherical particle, the flake-like particle oriented its plane, the cluster-type particle, the flake-like particle oriented the normal to its plane, and the rod-like particles oriented its radial axis. Commonly, C_s=1.5~2.8 for real inclusion particles.

The mechanical condition that an inclusion adheres stably to

the rough wall of vessel exposed to a shear flow is analyzed theoretically, then a relationship of the adhesion efficiency is formulated, and the mass transfer coefficient, β, of inclusion to the wall due to turbulence fluctuation and field force effect is obtained which is the function of wall friction force of fluid. It indicates that there exists a peak for the mass transfer coefficient over the wall friction force, and in most cases, the turbulence promotes the transfer of inclusion to wall.

A theory on inclusion growth of single particle in molten melts is developed. Two main growth modes, diffusion -reaction-precipitation and collision-coalescence, of inclusion are simplified physically and modeled mathematically, and some analytic solutions or relationships for the growth rate of inclusion are derived, which give an general physical picture of inclusion growth. The theoretical growth rate of diffusion is supported by the experimental results early reported by Japanese scholar. This theory shows that the early growth of inclusion depends on diffusion-reaction-precipitation and Braunian motion collision, and the former is decisive, while the latter growth depends on turbulence shear collision and Stokes' collision, and the former is dominant; The collision and coalescence proceeds quickly during smelting process, and is negligible in continuous casting process, moreover, a transition state exists in the refining process. Further, the micro- structure of inclusion aggregate is simulated by methods of Monte-Carlo, the resultant aggregates agree with the cluster inclusions reported in literatures. The Fractal theory is introduced to interpret the structure of the aggregate, the simulation shows that the cluster inclusion has a Fractal dimension of 2.25.

Based on above studies, a general dynamic model of inclusion coupling the nucleation, growth, coalescence and transfer has been developed firstly, which is expected to lay a foundation to further investigate widely and profoundly the basic behavior of inclusion in metallurgical vessels.

In the second part, foregoing theory has been utilized to build a comprehensive mathematical model within the Lagrangian framework to study the transport of inclusion in some continuous casting tundish. The results demonstrate that the floatout by buoyancy is the main path of removal of inclusion, and the coalescence and adhesion to wall provide a secondary aid. In present tundish, a removal efficiency of 20%~75% can be obtained for inclusion of radius from 10 μm to 30μm. The coalescence helps the removal of inclusion, but seems not notable, restricted by the practical condition of tundish.

In the third part, as another application, the only-by-current electromagnetic separation of inclusion from molten melt, a novel technique oriented to pure steel, is studied theoretically and experimentally. The magnetic field in the melt conducted by a direct and alternative current respectively through a round- or flat- pipe, which acts as the separator, is solved, then some parameters including the relative electromagnetic buoyancy, purification efficiency and purification time are defined and formulated, giving a basic outline of this technique.

The theoretical analysis and numerical solution show that the electromagnetic force produced by industrial-frequency alternative current is similar with that by direct current, so it seems not necessary to exploit the direct current for electromagnetic separation. The electromagnetic purification efficiency depends on applied current density, the radius of inclusion and the residence duration of melt in the separator. As far as the separator type is concerned, the efficiency obtained using round pipe is close to that using flat pipe. A secondary flow will be induced in the cross section of rectangular pipe separator, which plays an adverse effect on the removal of inclusion for it disturbs the migration trajectories of particle and prolong the real residence time of inclusion.

The experiments of static electromagnetic purification for Al-22%Si alloy and Al-5%Mg-2%SiC alloy have been conducted respectively by use of the separator with diverse cross-section under industrial-frequency alternative current. It is found that most of primary Si phase can migrate to the side wall of separation pipe within 30 s by imposing a current density of $4\times10^6 A/m^2$, and the SiC particles of radius 100 μm migrate faster, with less than 10 s. It is promising that this technique is transplanted to produce the FGMs (Functional Gradient Materials) with surface reinforced phase.

The experiment of continuous electromagnetic purification for Al-8%Mg-2%Al_2O_3 alloy have been carried utilizing the round pipe separator and rectangular pipe separator, and the heating effect for melt is measured. It is found that when the flow velocity of melt equal 2.3~2.9 cm/s, and the current density is $(0.8\sim1.4)\times10^7 A/m^2$, the temperature in the outlet of separator is higher by 15~25℃ than the inlet, enough for heating the melt. Under the condition that the current density is 1.4×10^7 A/m^2, and the residence of melt in the separator equal 10 s, a 95% removal efficiency is obtained, in good agreement with the theoretical prediction. And, most inclusions more than 20 μm can be successfully removed from the melt.

In the last part, the micro mechanism of magnetic alignment of grains in electromagnetic processing of materials attracts an additional interest of the paper beyond the title. A general dynamics model has been developed, and a theoretical relationship for the alignment time of grain was derived. An experiment was conducted for Bi-3%Mn, which melted below the Courier temperature and quenched under a 0.3*T* magnetic field. It is found that the texture comes into being within a second, which is in accord with the theoretical prediction. It means that the alignment is not the controlling step for texture formation of ferromagnetic BiMn phase during solidification.

Key words inclusion, removal, growth, coalescence, dynamics, Monte-Carlo, flow field, electromagnetic field

主要符号清单

$\boldsymbol{A}, A$ 磁位(矢量和标量), Wb/m

A_{12} Hammker 数, J

$\boldsymbol{B}, B$ 磁通密度, T

v_{st} 夹杂物的 Stokes 速度, m/s

c 夹杂物周围反应元素的浓度, mol/m^3

c_0 夹杂物周围元素的初始浓度, mol/m^3

c_e 夹杂物周围应元素的平衡浓度, mol/m^3

C_s 夹杂物运动阻力的形状修正系数

C_{em} 夹杂物电磁浮力的形状修正系数

D 分子扩散系数, m^2/s

D_t 夹杂物湍流扩散系数, m^2/s

f_{em} 电磁力密度, N/m^3

f_{ep} 电磁浮力密度, N/m^3

$\boldsymbol{H}, H$ 磁场强度, A/m

I 电流强度, A

j 质量通量, mol/m^2/s

$\boldsymbol{J}, J$ 电流密度, A/m^2

k 湍流动能, m^2/s^3

$K()$ 夹杂物颗粒碰撞核

M 夹杂物受到的相对电磁浮力

M_p 夹杂物摩尔质量, kg/mol

N 夹杂物颗粒的数密度, m^{-3}

$n(r)$ 夹杂物颗粒的分布密度函数, m^{-1}m^{-3}

u_{pi} 夹杂物颗粒的运动速度, m/s

u^* 壁面摩擦速度, m/s

v 夹杂物体积, m^3

v_p 夹杂物的迁移速度, m/s

v_{st} 夹杂物的 Stokes 速度, m/s

α 夹杂物碰撞效率

β 夹杂物的壁面传质系数, m/s

β_i 夹杂物表面的传质系数, m/s

γ 夹杂物与金属液的界面张力, N/m

δ 交变电磁场的集肤深度, m

ε 湍流耗散率, m^2/s^3

ζ 随机数

η 夹杂物壁面吸附效率

θ 晶粒转角, °

κ Boltzmann 常数

μ_f 液体分子动力学粘度, pa.s

μ_t 液体的湍流粘性系数, pa.s

μ_{eff} 湍流有效粘性系数, pa.s

μ_0 真空磁导率, H/m

γ 液体分子运动学粘度, m^2/s

v_t 液体湍流扩散系数, m^2/s

ρ_f 液体密度, kg/m^3

ρ_p 夹杂物密度, kg/m^3

P_a 夹杂物壁面吸附概率

P_c 夹杂物碰撞的聚合概率

Q 金属液体积流率, m^3/s

r, R 夹杂物半径, m

Re 金属液雷诺数

Re_p 夹杂物雷诺数

S 面积, m^2

t 时间, s

T_p 电磁净化时间, s

T_r 金属液平均停留时间, s

U_i 湍流金属液的时均速度, m/s

u_i 湍流金属液的瞬时速度, m/s

u_i' 湍流金属液的脉动速度, m/s

σ 金属液电导率, S/m

τ_p 颗粒的驰豫时间, s

τ_w 壁面剪力, pa

τ_1 夹杂物脱附的第一临界剪力, pa

τ_2 夹杂物脱附的第二临界剪力, pa

τ_3 夹杂物传质的第三临界剪力, pa

φ 金属液中颗粒占的体积分数

ψ 标量电位, V

χ, χ 磁化率

ω 角速度, rad/s

Γ 夹杂物去除效率

Δ 壁面粗糙度, m