电子束熔炼用水冷铜坩埚研制

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摘　　要：电子束熔炼作为一种优异的真空冶炼技术，其核心部件水冷坩埚的结构设计尤为重要，坩埚的冷却性能将直接影响电子束熔炼的效果及安全。通过理论分析、数值模拟、试验考核，研究了坩埚水道结构、熔池形貌对坩埚冷却能力的影响。通过坩埚选材、熔池利用率分析、能量损耗分析和冷却计算确定了坩埚结构，建立了数值仿真模型，采用模拟计算方式对比了两种熔池形貌的坩埚在不同装料量下的冷却性能，并针对性能优异的坩埚开展了试验考核。结果表明：模拟不同锭厚条件下，坩埚 B 的冷却水温度和坩埚表面温度较坩埚 A 均偏低，坩埚 B 的熔池形状和水道结构匹配更合理，散热效果更好。试验考核过程中坩埚 B 状态稳定，满足设计要求。

关 键 词：水冷坩埚；水道设计；熔池形貌；数值模拟；电子束熔炼

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Development of Water-cooled Copper Crucible for Electron Beam Melting

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Abstract: As an excellent vacuum smelting technology, the structural design of the water-cooled crucible, the core component of electron beam melting, is particularly important. The crucible cooling performance directly affects the performance and safety of electron beam melting. The influences of crucible water channel structure and melt pool morphology on the cooling capacity of crucibles were investigated through theoretical analysis, numerical simulation, and an experimental assessment. The crucible structure was determined through crucible material selection, melt pool utilization rate analysis, energy loss analysis and cooling calculation. A numerical simulation model was established and used to compare the cooling performance of two types of molten pool crucibles under different loading conditions, and experimental assessment was conducted on crucible with excellent performance. The results show that under different ingot thicknesses, the cooling water temperature and surface temperature of crucible B are lower than those of crucible A in numerical simulation, indicating that the shape of the molten pool and the structure of the water channel in crucible B are more reasonable and have better heat dissipation effects. The experimental assessment shows that the state of crucible B is stable and meets the design requirements.

Key words: water-cooled crucible; waterway design; molten pool morphology; simulation; electron beam melting

电子束熔炼技术是利用高能电子束轰击材料表面，使电子的动能转变为热能从而熔化并熔炼材料的工艺过程[1-13]。电子束作用使得金属锭熔化形成熔池，当温度继续升高，液态金属表面蒸气压力大于其饱和蒸气压时，液态金属开始蒸发[14]。由于表面张力和浮力的作用，液态金属内部产生强烈的对流，把热量传导给水冷铜坩埚。为了不使铜坩埚与液态金属发生化学反应，坩埚需要具有强大的冷却效率，使其表面保持很低的温度[15]。坩埚熔池结构和水道布局直接决定其冷却效率。目前的水冷铜坩埚设计，主要依靠以往的设计经验和实物考核，该方法迭代升级周期长、投入高。

本文提出了一种新型坩埚设计方法，主要包

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