非平衡条件下熔覆层转向枝晶生长的宏微观耦合研究

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摘要：激光再制造技术由于其高效便捷的修复过程，修复件组织致密、力学性能较好，工艺过程易实现自动化，因此在航空航天、海洋工程等设备的零部件修复中得到广泛应用。激光熔覆技术作为激光再制造技术的基础，通过将粉末和基体共同熔化凝固，形成与基体呈冶金结合的组织，从而提高基体表面的耐磨性、耐腐蚀性、耐高温性等性能，其熔覆层的凝固组织晶体取向对其性能优劣有较大影响。研究激光熔覆过程中的枝晶生长过程，对于预测和控制熔覆层的凝固组织、力学性能是至关重要的。数值模拟技术的发展，为研究激光熔覆过程中的急热急冷、熔池内复杂流动等现象提供了有效手段。本文基于体积平均法及元胞自动机方法，耦合激光熔覆过程中的宏微观物理现象，建立宏观凝固模型以及微观组织生长模型，模拟了激光熔覆过程中温度场、流场、溶质场分布的演变过程。本文探究了非平衡凝固过程中的动态溶质再分配系数对温度场、流场、溶质场分布的影响机理，并结合实验数据，分析了微观组织凝固过程中的转向生长机理。通过本文的研究有助于定量预测、定性控制单道熔覆层转向枝晶区域，为实际修复提供理论支撑。

关键词：激光熔覆，数值模拟，动态溶质再分配系数，枝晶生长，转向枝晶区域

Abstract：Laser remanufacturing technology has been widely used in the repair of aerospace, marine engineering and other equipment parts due to its efficient and convenient repair process, dense tissue, good mechanical properties, and easy automation of the process. As the basis of laser remanufacturing technology, by melting and solidifying the powder and the substrate together, a metallurgical bond with the substrate is formed, thereby improving the wear resistance, corrosion resistance, high-temperature resistance, and other properties of the substrate surface. the solidification organization and crystal orientation of the clad layer have a great influence on its performance. The study of the dendrite growth process during laser cladding is essential to predict and control the solidification organization and mechanical properties of the clad layer. The development of numerical simulation technology provides an effective means to study the phenomena such as rapid heat and cold, and complex flow in the melt pool during the laser cladding process. In this paper, the macroscopic solidification model and the microscopic tissue growth model are established based on the volume averaging method and the cellular automata method to couple the macro and microscopic physical phenomena in the laser melting process, and the evolution of the temperature field, flow field, and solute field distribution in the laser melting process is simulated. In this paper, we investigate the mechanism of dynamic solute redistribution coefficient on the distribution of temperature, flow, and solute fields during nonequilibrium solidification, and analyze the mechanism of steering growth during microstructure solidification with experimental data. The research in this paper helps to quantitatively predict and qualitatively control the steering dendritic region of the single-pass molten cladding layer and provides theoretical support for practical repair.

Keywords: laser cladding, numerical simulation, dynamic solute redistribution coefficient, dendrite growth, turning to dendrite region

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