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涡轮叶片气膜孔超快激光加工精确控形方法研究

Research on the Precise Shape-controlling Method of the Turbine Blade Film-cooling Hole Based on Ultrafast Laser

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摘　要

气膜冷却是一种通过在涡轮叶片表面设计大量线性排列的气膜孔，以形成薄层冷气膜隔离高温燃气的技术，可有效提高航空发动机热端部件的抗高温蠕变能力，其冷却效率与气膜孔的精度与质量息息相关。本文针对当前超快激光加工气膜孔存在的精度不高、质量不稳问题，修正了气膜孔的设计形位参数，建立了超快激光螺旋加工微小孔的工艺模型，分析了微小孔的时空演化过程。本论文的研究成果对提高气膜孔成形精度具有重要的理论意义与工程价值。

本文主要研究内容包括：

1.基于涡轮叶片定向凝固工艺，对叶片精铸过程进行了数值模拟，获得了叶片的铸件模型，结合叶片铸件的实测，建立了叶片精铸位移场模型。

2.采用变形特征补偿法，建立了叶片的扭转、弯曲与收缩变形表征模型，提出了基于叶片截面中弧线的气膜孔形位参数的修正方法。

3.基于五坐标超快激光叶片微孔加工机床，设计了飞秒激光在304不锈钢、5052铝合金以及DD6镍基合金试板上的微小孔螺旋加工实验，分析了激光重复频率、平均输出功率、激光旋转速度及重叠率对微小孔成形过程的影响；进行了激光能量参数正交实验，建立了能量参数与微小孔成形过程的映射模型。

4.结合超快激光金属烧蚀双温方程，求解了激光烧蚀过程的电子与晶格的温度变化曲线，分析了激光螺旋加工的工艺过程，建立了微小孔加工时空演化过程模型。

关键词：气膜孔；超快激光；螺旋加工；时空演化

Abstract

Film cooling can effectively improve the high-temperature creep ability of the aerial engine hot end parts by designing a large number of linearly arranged gas film holes on the turbine blade surface to form a thin layer of cold air to isolate high-temperature gas, whose cooling efficiency related closely to the accuracy and quality of the film holes. In this paper, the problems of low precision and unstable quality of gas film holes processed with ultrafast laser are discussed. The design parameters of the film holes are modified. The process model of drilling micro holes with ultrafast laser is established. The spatio-temporal evolution of drilling micro holes is analyzed.

The main contents are described as follows:

1.Based on the directional solidification process of turbine blades, the numerical simulation of blade casting process is carried out. The casting model of blade is obtained. Combined with the measurement of blade casting model, the displacement field model of blade casting is established.

2.The deformation model of the torsion, bending and shrinkage of the blade is established by using the deformation error compensation method. A correction method of the film hole position parameters is proposed, which is based on the camber line of the blade sections.

3.The micro hole drilling experiments on the 304 stainless steel, 5052 aluminum alloy and DD6 nickel base alloy with femtosecond laser using the five-axis ultrafast laser blade micro hole machining machine are completed. The effects of laser repetition rate, average output power, laser rotation speed and overlapping rate to the drilling process of micro holes are analyzed. The orthogonal experiments of laser energy parameters are carried out. The mapping model of energy parameters and micro hole drilling process is established.

4.Combined with the double-temperature equation which can describe ultrafast

laser ablation on metal surface, the temperature curves of electrons and lattices in the laser ablation process are solved. The process of laser helical processing is analyzed. The spatio-temporal evolution of drilling micro holes is established.

Keywords: Film Hole; Ultrafast Laser; Helical Processing; Spatio-temporal Evolution

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