

博士学位论文

热力耦合作用下高温合金复杂铸件变形预测
及尺寸精度控制研究

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A Dissertation for the Degree of Doctor

**DEFORMATION PREDICTION AND DIMENSIONAL
ACCURACY CONTROL OF SUPERALLOY
COMPLEX CASTINGS UNDER THERMO-
MECHANICAL COUPLING**

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摘 要

高端精密制造对复杂构件一体化成形与尺寸精度提出了严苛要求,熔模铸造技术凭借其尺寸精度高与表面质量优异等优势,在航空发动机和生物医用器械等领域获得了广泛应用。然而,在复杂构件的熔模铸造工艺流程中,尺寸变形仍然难以定量精准预测与补偿。由此引发的尺寸超差难题,导致关键零部件时常陷入“有件难用”的困境。鉴于此,本论文从热学接触换热行为及高温合金力学本构关系的共性基础难题出发开展研究,将其应用于复杂铸件在热力耦合作用下的变形预测及补偿,最终实现了铸件尺寸精度控制的研究闭环。本论文工作的主要研究成果如下:

(1) 设计了陶瓷型壳-合金铸件界面温度的多通道测定实验方法,建立了瞬态界面换热系数反求方法,揭示了由裂纹诱导产生多层间隙的界面换热机理。通过设计多通道测温铸件结构与可控变厚度型壳涂层工艺,实现了单次浇注过程中对不同型壳-合金厚度组合界面两侧温度的多通道同步获取。基于反问题求解,揭示了界面换热系数随合金温度、型壳及合金厚度的演化规律。发现反求的界面换热系数在降温过程中下降趋势明显,且数值低于传统“间隙”模型的预测下限,在真空条件下该差异尤为显著。研究表明,陶瓷型壳内部裂纹引入的多重热阻被等效为界面总热阻,因而其数值显著高于仅由合金铸件-陶瓷型壳间隙引起的热阻;型壳及合金厚度通过影响合金-型壳脱离以及型壳内部损伤的进程,进而影响界面换热系数变化规律。将反求结果应用于最大径向尺寸为 274 mm 的典型环状铸件进行验证,试验表明:相较于基于文献中界面换热系数反算值所预测的温度,型壳温度预测误差由 41 °C 降低至 9 °C。

(2) 开发了耦合 γ' 相演变效应的高温合金本构模型,揭示了高温合金在极高温区间间的变形行为转变规律。针对现有本构模型多基于服役或锻造温度区间开发,不完全适用于描述极高温区间($0.8 T_m \sim 1.0 T_m$)内 γ' 相演变效应的问题,通过恒定应变速率及应变速率阶跃试验方法,获得了 K439B 型高温合金在 1220 °C 至 950 °C 温度区间、 10^{-5} 至 10^{-2} s^{-1} 应变速率范围内的稳态应力数据,并构建了一种关联 γ' 相演变与应力敏感性的本构模型,并在测试范围内具有极高的精度($R^2 = 0.9998$)。研究发现:在 γ' 固溶线以下,应力指数 N 与 γ' 析出相分数 f 呈线性关系($N = 29.09f + 4.76$), N 值介于 4.76 至 11.43 之间,在整个测试温度与应变速率范围内均未出现阈值应力,且应力敏感性的变化仅受 γ' 相分数控制,分析了位错在极高温区间中的攀移机制以及通过攀移机

制跨越障碍物的力学行为。

(3) 构建了铸件凝固过程尺寸变形的热力耦合数值模型, 阐明了蠕变行为是影响铸件尺寸变形计算模拟准确性的决定性因素。针对合金凝固过程中尺寸变形难以精准定量预测的问题, 集成了前述热学与力学模型, 通过耦合温度场与位移场的相互作用, 对 K439B 型高温合金典型薄壁铸件凝固过程进行数值模拟, 并结合工业实验验证热力耦合模型的预测精度。结果表明: 在初始 1000 秒的冷却阶段, 尽管熔模铸造型壳较薄(约 1 cm), 力学性能较低(模量 < 5 GPa, 强度 < 10 MPa), 却由于极高温下蠕变行为显著而导致铸件最大径向尺寸收缩率较合金材料的热收缩率低 13%(对应总收缩率为 2.48×10^{-2}), 产生了平均幅度为 0.1~0.2 mm 正弦形态的几何变形。统计表明, 塑性变形主要发生于 γ' 相未析出区域。其中, 厚壁区域的变形行为遵循由位错攀移机制主导的五幂次蠕变规律; 而在薄壁区域, 则观察到具有部分低应变速率敏感性的黏塑性变形特征。部分热应变转化为蠕变应变, 蠕变应变范围为 6.1×10^{-4} 至 3.1×10^{-2} , 引发永久变形与尺寸变化。通过工业级实验验证, 计算机断层扫描与蓝光扫描结果显示, 在最大径向尺寸为 274 mm 的典型环状铸件上, 最大预测偏差仅为 0.1 mm。

(4) 提出了基于物理信息的变形追踪与非线性几何补偿方法, 实现了符合 ISO 8062-3:2023 标准 DCTG2 级公差要求精度的铸件尺寸控制。针对熔模铸造全流程尺寸精度控制的需求, 在各工艺环节中, 以变形后的实测点云描述当前形状, 以工艺变形前的网格作为模板网格, 在三维体网格变形能量约束下, 最小化控制面与实测面(欧拉坐标系下描述)之间的点云距离; 基于前几章节所述非线性蠕变行为, 在时间增量步内等效线性化为应力-应变关系的原理, 求解满足连续介质力学最小势能原理的位移场(拉格朗日坐标系下描述), 再现了蠕变累积导致的应变及位移。而后, 推导并建立了补偿场与偏差场之间受变形场影响的非线性关系模型。通过单次试制实验, 采集模具型腔、蜡模及铸件的三维点云数据, 追踪了从模具型腔到蜡模、蜡模到铸件的位移场, 及铸件相对于设计模型的偏差场; 随后, 基于非线性补偿方法, 结合各子流程位移场及铸件偏差场计算出模具型面的补偿场, 并依据此对模具型面进行了补偿修正。在不改变其他工艺参数的情况下, 采用修模后的模具重复熔模制造流程, 成功制备出符合 DCTG2 级别公差要求的合格铸件。

关键词: 尺寸精度控制, 高温合金, 本构模型, 复杂铸件, 热力耦合, 非线性补偿

Abstract

High-end precision manufacturing imposes stringent requirements on the integrated forming and dimensional accuracy of complex components. Owing to its advantages of high-dimensional precision and superior surface quality, investment casting technology has been widely adopted in areas such as aero-engine manufacturing and biomedical devices. Nevertheless, the quantitative prediction and compensation of dimensional distortions in the investment-cast complex components remains a significant challenge. The resulting dimensional deviations often lead to issues wherein critical components become "unusable despite being produced." To address this problem, this dissertation first investigates the fundamental challenges associated with thermal contact behavior and the mechanical constitutive relationship of superalloys. Building on these findings, the study further predicts and compensates for the coupled thermomechanical distortions in complex castings, realizing a closed-loop study on dimensional accuracy control in investment castings. The main research achievements of this dissertation are as follows:

(1) A multi-channel measurement experimental method for the interface temperature between ceramic shells and alloy castings was designed, and a transient interface heat transfer coefficient inverse solution method was established, revealing the heat transfer mechanism induced by multi-layer gaps due to cracking. By designing a multi-channel temperature measurement casting structure and a controllable variable-thickness shell coating process, synchronous multi-channel acquisition of temperatures on both sides of the interface for different shell-alloy thickness combinations during a single pouring process was achieved. Based on inverse problem solving, the evolution of the interface heat transfer coefficient with respect to alloy temperature, shell thickness, and alloy thickness was revealed. The inverse-calculated interface heat transfer coefficient exhibited a significant decline during cooling, with values lower than the predicted lower limit of the traditional "gap" model, particularly under vacuum conditions. The study demonstrated that the multiple thermal resistances introduced by cracks in the ceramic shell were equivalent to the total interfacial thermal resistance, resulting in values significantly higher than those

caused solely by the gap between the alloy casting and ceramic shell. The thickness of the shell and alloy influenced the interfacial heat transfer coefficient by affecting the detachment of the alloy from the shell and the progression of internal shell damage. The inverse solution results were validated on a typical ring-shaped casting with a maximum radial dimension of 274 mm, demonstrating that compared to temperatures predicted using literature-based interface heat transfer coefficients, the prediction error for shell temperature was reduced from 41 °C to 9 °C.

(2) A superalloy constitutive model considering the γ' phase evolution effect was developed, revealing the deformation behavior transition of superalloys in the extremely high-temperature range. Addressing the issue that existing constitutive models are mostly developed for service or forging temperature ranges and are not fully applicable to describing the γ' phase evolution effect in the extremely high-temperature range ($0.8 T_m \sim 1.0 T_m$), steady-state stress data for K439B superalloy were obtained through constant strain rate and strain rate jump tests within the temperature range of 1220 °C to 950 °C and strain rate range of 10^{-5} to 10^{-2} s^{-1} . A constitutive model linking γ' phase evolution and stress sensitivity was constructed, exhibiting extremely high accuracy ($R^2 = 0.9998$) within the tested range. The study found that below the γ' solvus line, the stress exponent N and γ' precipitate fraction f exhibited a linear relationship ($N = 29.09f + 4.76$), with N values ranging from 4.76 to 11.43. No threshold stress was observed across the entire tested temperature and strain rate range, and the γ' phase fraction solely controlled the variation in stress sensitivity. The dislocation climb mechanism and the mechanical behavior of overcoming obstacles through climb in the extremely high-temperature range were analyzed.

(3) A thermomechanical coupling numerical model for dimensional deformation prediction during alloy solidification was constructed, clarifying that creep behavior is the decisive factor affecting the accuracy of deformation simulation. To address the challenge of precise quantitative prediction of dimensional deformation during alloy solidification, the aforementioned thermal and mechanical models were integrated. By coupling the interaction between the temperature field and displacement field, numerical simulations of the solidification process of a typical thin-walled K439B superalloy casting were performed, and the prediction accuracy of the thermomechanical coupling model was validated through industrial experiments. The results showed that during the initial 1000-

second cooling phase, despite the thin ceramic shell mold (~ 1 cm) and its low mechanical properties (modulus < 5 GPa, strength < 10 MPa), the maximum radial shrinkage rate of the alloy casting was 13% lower than the thermal shrinkage rate of the alloy material (corresponding to a total shrinkage rate of 2.48×10^{-2}) due to significant creep behavior at extremely high temperatures, resulting in geometric deformation with an average sinusoidal amplitude of 0.1~0.2 mm. Statistical analysis revealed that plastic deformation primarily occurred in regions where the γ' phase had not precipitated. In thick-walled regions, the deformation behavior followed a fifth-power creep law dominated by dislocation climb, while in thin-walled regions, viscoplastic deformation characteristics with lower strain rate sensitivity were observed. A portion of thermal strain was converted into creep strain, with creep strain rates ranging from 6.1×10^{-4} to 3.1×10^{-2} , leading to permanent deformation and dimensional changes. Industrial-scale validation through computed tomography and blue-light scanning showed that for a typical ring-shaped casting with a maximum radial dimension of 274 mm, the maximum prediction deviation was only 0.1 mm.

(4) A physics-informed deformation tracking and nonlinear geometric compensation method was proposed, achieving dimensional control of castings that meet the ISO 8062-3:2023 standard DCTG2-level tolerance requirements. To address the need for whole-process dimensional accuracy control for the investment casting process, the measured point cloud was used to characterize the current deformed shape after each process stage, with the initial mesh serving as the template mesh. Under the constraint of 3D volumetric mesh deformation energy, the point cloud distance between the control surface and the measured surface (described in Eulerian coordinates) was minimized. Based on the nonlinear creep behavior discussed in previous chapters, the stress-strain relationship was equivalently linearized within time increments, and the displacement field (described in Lagrangian coordinates) satisfying the minimum potential energy principle of continuum mechanics was solved, reproducing the strain and displacement caused by creep accumulation. Subsequently, a nonlinear relationship model between the compensation field and deviation field influenced by the deformation field was derived and established. Through a single trial production, 3D point cloud data of the pattern die cavity, wax pattern, and casting were collected, tracking the displacement fields from the pattern die cavity to the wax pattern and from the wax pattern to the casting, as well as the deviation field of the

casting relative to the design model. The nonlinear compensation method was then applied to calculate the compensation field for the pattern die surface based on the sub-process displacement fields and casting deviation field, and the pattern die surface was compensated and corrected accordingly. Without altering other process parameters, the modified pattern die was used to repeat the investment casting process, successfully producing qualified castings that met the DCTG2-level tolerance requirements.

Keywords: dimensional accuracy control, superalloy, constitutive model, complex casting, thermomechanical coupling, nonlinear compensation