

博士学位论文

装配界面接触热性能精准分析与调控方法研究

学位申请人：XX

指导教师：XX

合作导师：XXX

学科名称：机械工程

2025 年 09 月

**Precise Analysis and Regulation Methods for Thermal Contact
Performance at Assembly Interfaces**

A dissertation submitted to
XXXXXX
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

By
XX
Supervisor: XX
Associate Supervisor: XXX
Mechanical Engineering
September 2025

博士学位论文答辩委员会

装配界面接触热性能精准分析与调控方法研究

答辩人：XX

答辩委员会委员：

XXXXXXXXX 教授:_____（注：主席）

XXXXXXXXX 教授:_____

XXXXXXXXX 教授:_____

XXXXXXXXX 教授:_____

XXXXXXXXX 教授:_____

答辩时间：XXXXXX

答辩地点：XXXXXX

摘要

高端数控机床、电子芯片封装等复杂机械产品装配衍生的热性能不足的问题，已成为制约其服役性能及性能稳定性的关键瓶颈。装配界面作为传递零部件间热力载荷的介质和承托接触热性能的载体，其力学特性（刚度、硬度等）和热学特性（导热系数等）直接影响力学和温度等物理场的传递分布状态，是决定接触热性能和装配热性能的关键因素。本研究摒弃传统装配界面力学和热学特性“均一化”惯性设计思维，构建了装配界面接触热性能精准分析模型，提出了面向精准调控接触热性能的装配界面力学和热学特性“异质化”设计方法。本文开展了以下研究工作：

（1）针对装配界面接触热性能“算不准”的难题，开展了基于数值分析与实验测试的装配界面接触热性能分析研究。基于实测和模拟表面微观几何形貌，构建了装配界面接触热性能宏微观多尺度、机械-传热多场耦合数值分析模型，揭示了样品固有属性、载荷分布特征等对装配界面接触热性能的影响规律，构建了基于稳态法的装配界面接触热性能实验测试方法和测试平台，建立了基于 Levenberg-Marquardt 算法的接触热阻快速预测模型，为装配界面接触热性能的精准分析提供“计算工具”。

（2）面向非对称温度梯度引起的双向接触热性能，开展了考虑非对称温度梯度的双向接触热性能分析与实验测试研究。创建了考虑热膨胀、热软化等二次热效应的机械-传热双循环耦合分析模型，揭示了二次微观接触状态对正、反向接触热阻和热整流系数的影响规律，提出了非对称热应力诱导的热整流效应强化设计方法，实验测试了多种载荷工况下双向接触热性能，发现了接触热阻与热整流系数之间的内在联系。

（3）针对装配界面接触热性能“控不住”的难题，开展了接触热性能驱动的装配界面力学特性优化设计方法研究。基于装配界面刚度、硬度等力学特性与表面温度分布之间的内在联系，发现了装配界面力学特性调控接触热性能的作用机制，构建了接触热性能驱动的装配界面力学特性渐进演化优化设计方法，实现了装配界面接触热阻的大幅降低和温度分布均匀性的有效提升，开展了质子交换膜燃料电池应用验证。

（4）基于装配界面物理特性“异质化”设计理念，开展了接触热性能驱动的装配界面热学特性优化设计方法研究。从温度传递过程中“能量耗散机制”入手，发现了影响接触热性能的内因（导热系数分布）和外因（边界温度梯度分布），揭示了三类温度边界条件下均质与非均质材料的接触热性能变化规律，发现了装配界面热学特性（导热系数）调控界面温度梯度分布和有效热导率的作用机制，提出了基于最小热阻原理的热学特性渐进演化设计准则，构建了接触热性能驱动的装配界面热学特性优化设计方法，实现了接触热性能的有效提升，开展了高档数控机床应用验证。

（5）以工作性能对温度分布高敏感的倒装芯片封装为研究对象，应用上述构建的

装配界面接触热性能精准分析方法与调控方法，开展倒装芯片封装装配热性能分析与优化设计研究。构建了考虑双层热界面材料的倒装芯片封装装配热性能分析模型，揭示了影响接触热性能和装配热性能的关键因素及其影响规律，通过对比现有填充优质热界面材料的热设计方法与本研究提出的装配界面“异质化”创新热设计方法，充分验证了所提装配界面设计方法在保障热性能上的先进性和有效性。

本研究提出的装配界面接触热性能精准分析与调控方法，助力丰富“高性能装配理论”与“热设计理论”体系，为保障复杂机械产品装配热性能提供了一种新的解决方案，具有重要的理论价值与广阔的工程应用前景。

关键词：装配界面；装配应力；接触热阻；优化设计；表面形貌

论文类型：应用基础

ABSTRACT

The issue of inadequate thermal performance derived from the assembly of complex mechanical products such as high-end CNC machine tools and electronic chip packaging has become a key bottleneck restricting their service performance and performance stability. The assembly interface serves as a medium for transmitting internal loads among components and as a substrate for supporting thermal contact performance. Its mechanical properties (stiffness, hardness, etc.) and thermal properties (thermal conductivity, etc.) significantly influence the distribution of physical fields, such as stress and temperature, and are the key factors that determine thermal contact performance and assembly thermal performance. This research departs from the conventional approach of “homogenization” in the design of assembly interface. Instead, it develops a precise analysis model for the thermal contact performance at assembly interfaces and introduces a methodology for the “heterogenization” of mechanical and thermal properties of assembly interfaces, to precisely regulate thermal contact performance. This paper carries out the following research work:

1. Aiming at the problem of “inaccurate calculation” of the thermal contact performance at assembly interfaces, a study on the thermal contact performance at assembly interface based on numerical analysis and experimental testing was carried out. Based on the measured and simulated micromorphology to construct a macro-micro multi-scale, multi-field coupled numerical analysis model. We established a comprehensive evaluation standard and revealed how the inherent properties of the sample, load distribution characteristics, etc. affect thermal contact performance. Direct and indirect testing methods based on steady-state heat flow were proposed, along with an experimental platform and a prediction model for thermal contact resistance using the Levenberg-Marquardt algorithm, providing a “computational tool” for the precise analysis of thermal contact performance at assembly interfaces.

2. Aiming at the bidirectional thermal contact performance caused by asymmetric temperature gradients, a study on bidirectional thermal contact performance analysis and experimental test considering asymmetric temperature gradients was conducted. A numerical analysis method was developed to consider secondary thermal effects, revealing how microscopic contact states influence thermal resistance ratios and the thermal rectification coefficient. A design method for enhancing the thermal rectification effect induced by asymmetric thermal stress was proposed. The bidirectional thermal contact performance under different working conditions was experimentally tested, and the intrinsic relationship between thermal contact resistance and thermal rectification coefficient was found.

3. This study tackles the thermal contact performance at the assembly interface of complex mechanical products. We explored optimizing the mechanical properties of the assembly

interface to enhance thermal contact performance. By analyzing the relationship between properties like hardness and stiffness and surface temperature distribution, we identified their influence on contact deformation behavior. A progressive evolution optimization design method of mechanical properties driven by thermal contact performance was constructed, which achieved a significant reduction in thermal contact resistance and an effective improvement in temperature distribution uniformity. The application verification of proton exchange membrane fuel cells has been completed.

4. Based on the design concept of “heterogeneous” physical properties of the assembly interface, research on the optimization design method of thermal properties of the assembly interface driven by thermal contact performance was conducted. We identified internal factors (thermal conductivity) and external factors (boundary temperature gradient) affecting thermal contact performance. Our findings revealed the behavior of thermal contact performance under various temperature boundary conditions and clarified the relationship between temperature gradient and thermal conductivity. This resulted in a method for optimizing assembly interface thermal properties, significantly improving thermal contact performance, and completed the application verification of high-end CNC machine tools.

5. Taking the flip-chip packaging system, whose service performance is extremely sensitive to temperature distribution as the research object, the assembly thermal performance analysis and optimization design research were carried out. A precise analysis model for assembly thermal performance considering double-layer thermal interface materials was constructed, revealing the key factors affecting the thermal contact performance and assembly thermal performance and their influencing rules. By comparing the existing thermal design method of filling thermal interface materials with the innovative thermal design method of the “heterogeneous” assembly interface proposed in this study, the advancement and effectiveness of the proposed assembly interface design method were verified.

The precise analysis and regulation methods for thermal contact performance at assembly interfaces proposed in this study helps enrich the “high-performance assembly theory” and “mechanical design theory” system, provides a new solution for ensuring the thermal performance of complex mechanical product assemblies. It has important theoretical value and broad engineering application prospects.

KEY WORDS: Assembly interface; Assembly stress; Thermal contact resistance; Optimal design; Surface topography

TYPE OF DISSERTATION: Application Fundamentals