

应用于高温复杂环境的曲面共形薄膜温度传感器

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摘要: 服役于复杂高温环境的高端装备如精密机床、空天装备、机器人等关键部件的智能化是提升装备服役性能的关键。大部分零部件呈现形貌曲率分布复杂等特征, 较难原位制备传感器进行健康监测。基于耐高温前驱体陶瓷材料, 开发五轴曲面薄膜传感器制备技术, 实现复杂曲面结构感知一体化传感器制造。通过软件算法开发与工艺参数探究, 实现不同曲率及不同图案化直写。基于曲面共形制造工艺, 在直径 30mm 氧化铝圆柱制备薄膜温度传感器并进行高温测试。结果表明, 室温至 800°C 多次循环测试重复性较好。选取轴承、螺栓等不同表面制备薄膜传感器进行测试, 不同温度段动态循环测试误差均较小且响应时间优于标准热电偶。通过对曲面共形薄膜温度传感器的研究, 为复杂高温环境零部件智能化传感检测提供一定参考。

关键词: 共形制造; 曲面; 聚合物前驱体陶瓷; 薄膜; 温度传感器

Curved conformal thin film temperature sensor for high temperature and complex environment

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Abstract: The intelligence of key components such as precision machine tools, aerospace equipment, and robots serving in complex high temperature environments is critical to improving equipment service performance. The majority of the components have complex topography and curvature distribution, making it difficult to prepare sensors in situ for health monitoring. The preparation technology of five-axis curved thin film sensor is developed based on the high temperature-resistant precursor ceramic material to realize the integrated sensor manufacturing of complex curved structure perception. Different curvatures and patterned direct writing are realized through software algorithm development and process parameter exploration. A thin film temperature sensor was produced on an alumina cylinder with a diameter of 30 mm and tested at

high temperature using the curved surface conformal fabrication approach. The results demonstrate that numerous cycle tests from room temperature to 800°C have good repeatability. For testing, thin film sensors were produced on various surfaces such as bearings and bolts. In different temperature regions, the dynamic cycle test errors were minor. It gives a certain reference for the intelligent sensing detection of parts in complex high temperature environments through research on the surface conformal thin film temperature sensor.

Keywords: Conformal fabrication; Curved surfaces; Polymer derived ceramics; Thin films; Temperature sensor

1 传感器设计背景和应用价值

对于工作于高温、高速、重载等复杂工况下的航空发动机、高铁、机床等高端装备的预测和健康管理有助于提高其服役寿命、运行可靠性、安全性等。温度变化作为构件失效的直接结果是反应部件健康状态的关键参数。大多数电子学和光电子学利用电子材料在二维平面、刚性和脆性基板(如硅晶圆或玻璃板)上制造。^[1-3]尽管这种已建立的二维电子结构相当适合于许多应用,但由于光刻的图案、沉积、蚀刻、材料生长和掺杂固有的二维平面性质,它们在本质上与复杂的曲线表面不兼容均较难准确实时反应构件表面温度。因此,在制备可应用于曲面的温度传感器对于原位在线健康监测具有重大意义。

温度是传感领域的重要研究对象,许多学者进行了许多探究。传统的分立式传感器具备检测温度高的优点^[4],但其存在封装困难^[5]、干扰被测物体温度场以及破坏被测物体等缺陷。为进一步满足航空飞行器等热端部件高温测试需求,薄膜温度传感器具备对被测机构与环境干扰小、响应速度快、精度高、结构简单等特点,在高温检测中具备极大潜力^[4,6]。磁控溅射法(PVD)工艺可控性强且致密性与连续性较好是制备薄膜电子元器件的常用方法,其制备的温度传感器具备耐温高、稳定性好等优点^[7,8],但其较难在曲面制备均匀薄膜,当前对于PVD曲面薄膜温度传感器的研究鲜见报道。柔性温度传感器相比于传统刚性传感器具备可弯曲性、灵活性、与不规则表面的兼容性而获得了极大的研究兴趣^[9],许多科学家制备了不同柔性温度传感器应用于人体温度监测^[10],开关设备温度监测^[11],飞行器位姿识别^[12]等,但其仍存在耐温低、黏附可靠性等问题。

航空轴承、高温紧固螺栓等具有圆柱面共性特征的零部件常服役于高温恶劣条件,极易产生疲劳、点蚀及断裂等失效问题。温度是衡量服役状态的基础指标,圆柱面零部件上实现

高温原位无损检测对关键零部件的状态监测与早期故障诊断具有重要意义。通过曲面共形制备技术，实现曲面薄膜温度传感器的制备，并进行标定测试。结果表面，800°C下六轮温阻循环测试重复性较好，单轮温阻曲线拟合优度大于 0.99，TCR 达-6000ppm/°C，800 度保温 20min 电阻漂移率仅 0.7%，此外其高温动态响应迅速且响应时间优于标准热电偶，电阻变化率小于 6%，精度达 5.03%FS，展现出较好的响应特性和恶劣环境耐受性。

2 创新点与优势

为推动航空发动机等装备智能化发展，开发曲面共形薄膜温度传感器可满足恶劣环境下高温温度原位无损实时监测，其创新点有：

(1) 传感薄膜化。相比于传统分立式传感器，本传感器对被测零部件结构无损伤（无需开孔安装或焊接粘贴），可准确反映零部件的原位温度；薄膜厚度小于 10 微米，对环境几乎无干扰；

(2) 传感共形化。本作品采用曲面共形直写系统突破传统溅射工艺等难在高曲率圆周表面制备均匀薄膜的瓶颈；该系统具备无需掩膜、可编程图案化及高效低成本优势，解决溅射工艺曲面掩膜困难、工艺复杂、昂贵耗时等缺陷；

(3) 传感耐高温化。大部分薄膜热电阻型温度传感器碍于传感材料高温稳定性差，测温上限仅达 600°C。针对目前高温下陶瓷薄膜易氧化、市面上大于 600°C 的高温薄膜热电阻鲜见等问题，提出高热稳定性的 TiB₂ 复合聚合物前驱体（PDC）前驱体陶瓷薄膜调控工艺，实现 800°C 高温稳定性测试。

3 实现方案简介

3.1 设计原理

敏感材料是高温薄膜传感器的核心组成部分，其化学、电学稳定性对薄膜传感器恶劣环境耐受性能影响巨大。前驱体陶瓷具有耐高温、耐腐蚀、抗氧化性、高温半导体等性质^[13-15]，有望作为高温传感应用的新材料。收缩率大是陶瓷聚合物的固有属性，极易造成孔洞和裂纹不利于敏感薄膜的导电性能。为进一步提高薄膜质量，添加活性调料或惰性填料有助于陶瓷前驱体近净成形。^[16,17] TiB₂ 具备活性填料特性^[18]且具有一定粘附力增强作用^[19,20]以及导电特性，是抑制陶瓷薄膜缺陷产生及提高导电性能解决方法。

薄膜温度传感器结构由曲面基底、电阻栅、焊点、引线组成如图 1 所示。聚合物前驱体陶瓷浆料共形敷设于曲面基底形成梳齿状电阻栅。焊点由聚合物前驱体陶瓷浆料与带槽氧化铝片构成，其将电阻栅与铂丝通过陶瓷浆料键合形成与外部电路信号传输。

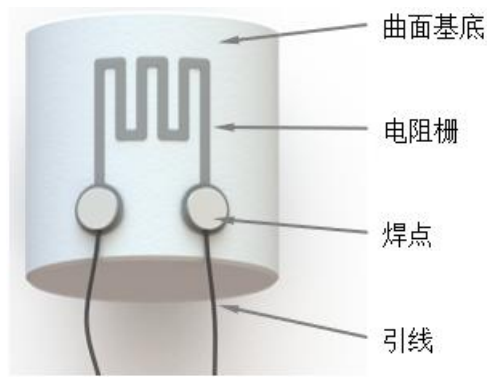


图1 曲面传感器结构

3.2 设计方法

当前针对于薄膜温度传感器的研究局限于平面^[21-27],将前驱体陶瓷应用于曲面有助于提高其实用性。传统三轴曲面喷印装置仅能在一个方向上层层堆叠。当打印零件较复杂时,需要打印大量的支撑结构作为辅助,既浪费材料又影响加工效率,存在液体超前和滞后现象,且易产生“台阶效应”而影响打印质量不利于均匀成膜^[28]。五轴作为制造曲面零部件的常用设备,具备灵活性高、适应性强等优点。因此,选用五轴联动平台结合实验室自主开发的基于韦森堡原理的直写装置开发复杂曲面薄膜直写系统,如图2所示。韦森堡直写装置安装与五轴平台Z轴,通过五轴联动控制实现复杂曲面图案化薄膜沉积。

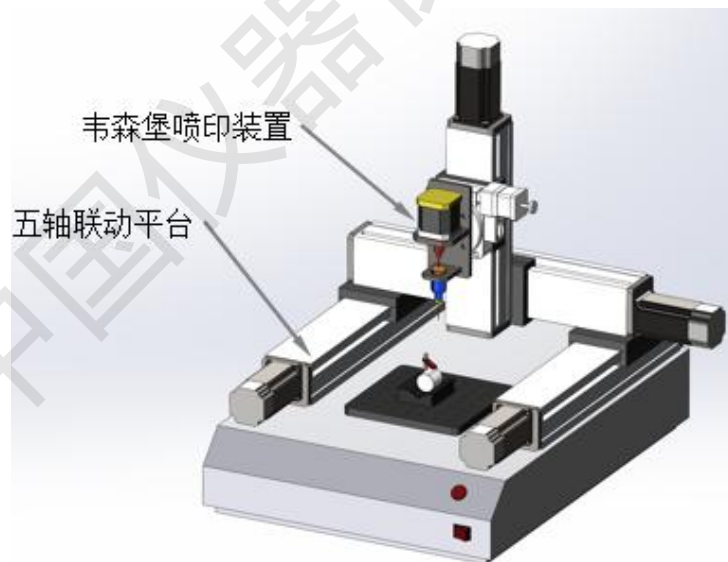


图2 复杂曲面薄膜直写系统

传统的平面增材制造中,笛卡尔坐标系的Z轴上的坐标在单层中不会改变。相比之下,在共形增材制造中,Z轴坐标连续变化。为进一步提高个性化直写能力,开发复杂曲面共形直写算法控制直写过程中喷头始终平行于曲面法线方向,有助于薄膜均匀成形。表面光洁度可反应3D打印部件的质量。^[29,30]通过控制层厚,可消除由逐层制造产生的台阶效应。因此,

根据曲面的法线方向开发针尖距离基底间距可控的共形算法，实现不同膜层厚度控制，为薄膜传感器性能探究奠定基础。

3.3 实验验证过程

曲面薄膜温度传感器的制备流程如图 3 所示。将 TiB_2 粉末与液态聚合物混合进行磁性搅拌 1 小时形成聚合物前驱体溶液；韦森堡直写装置加载聚合物前驱体溶液，并通过曲面共形直写算法，获取曲面离散轨迹 G 代码实现聚合物前驱体溶液的曲面共形直写；在敏感栅两端制备引线焊点并进行 $150^{\circ}C$ 保温 1 小时后，进行曲面薄膜温度传感器高温热解。



图 3 曲面薄膜温度传感器制备流程

为进一步验证传感器的高温性能，在氧化铝圆柱表面制备了如图 所示的曲面薄膜温度传感器。通过高温标定平台进行测试，结果表明六轮 $800^{\circ}C$ 循环测试重复性较好，电阻温度系数达 $6000\text{ppm}/^{\circ}C$ 。

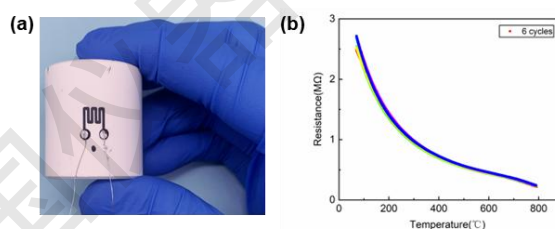


图 4 氧化铝圆柱温度传感器及测试信号图

为了拓展曲面共形制造工艺的应用，在轴承及螺栓上制备了如图 所示的薄膜温度传感器。测试结果趋势与氧化铝薄膜温度传感器一致，表明该传感器制备在轴承及螺栓上同样可作为 $50\sim 800^{\circ}C$ 测温范围的温度传感器使用。

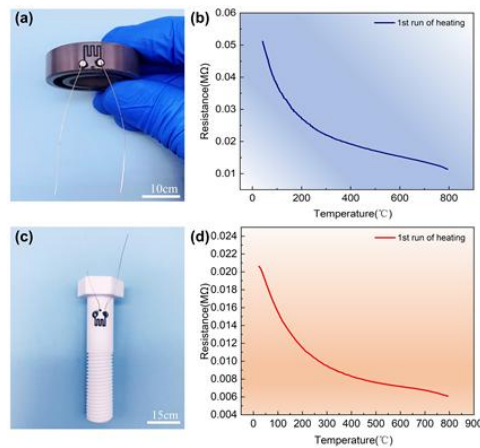


图5 轴承/螺栓温度传感器及测试信号图

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