高精度球面滚子精度进化加工
理论与试验研究

Study on the Precision Evolutionary Machining Theory and Experiment of High Precision Spherical Roller

一级学科：____________________

研究方向：____________________

作者姓名：____________________

指导教师：____________________

____

二〇二三年十一月

摘要

调心滚子轴承是一种具有自动调心性能的滚动轴承，适用于传动系统末端载荷工况复杂、轴心位置需要实时调整的风电、盾构、直升机、高铁、大型船舶以及核电等领域的大型复杂机械装备。球面滚子作为调心滚子轴承的关键零件，其滚动面的几何精度（形状精度和直径尺寸一致性）直接影响调心滚子轴承的使用性能和服役寿命。目前，生产实践中普遍采用无心磨削加工技术保证球面滚子滚动面的几何精度。但无心磨削属于典型的母性加工技术，受母性原理精度退化的制约球面滚子滚动面的几何精度远不能适应高端装备的发展需求。针对母性加工原理导致的球面滚子滚动面几何精度不足的行业痛点，本文就球面滚子的精度进化加工理论与技术展开研究，具有重要的理论意义和实用价值。

圆柱滚子双盘式循环研磨是一种精度进化加工方法，本文借鉴该方法“多样本直接比较”“材料选择性去除”的基本思想，提出一种高精度球面滚子精度进化加工新方法--轴套式循环研磨。分析形成球面滚子滚动面的切削运动创成，即球面滚子绕自身轴线的自转运动保证了滚动面的圆度，球面滚子沿圆环沟槽的回转运动既保证了滚动面的圆弧廓形，同时也保证了圆环沟槽工作面的磨损均匀性，球面滚子沿直线沟槽的往复直线运动保证了直线沟槽工作面的磨损均匀性。解析了球面滚子滚动面与圆环沟槽工作面和直线沟槽工作面的共轭接触特性。研究结果表明，滚子滚动面与圆环沟槽工作面的接触线形态为十字交叉接触线，与直线沟槽工作面的接触线形态为圆弧接触线。

基于球面滚子在轴套式循环研磨体系下的力学与运动学条件，建立球面滚子自转理论模型，解析球面滚子连续稳定自转的工艺条件。结果表明：交叉接触线II对应的起始角在 0-π/2 范围内，球面滚子滚动面与直线沟槽工作面之间的摩擦系数 μ_2 大于与圆环沟槽工作面之间摩擦系数 μ_1 的 1.067 倍时，即可保证球面滚子发生自转。通过对球面滚子运动行为仿真分析，滚子在研磨条横截面内存在不同程度的窜动；当滚子连续稳定自转时，滚子滚动面与研磨条工作面之间的相对滑动率小于 5%。根据自转理论与仿真分析结果，建立了各接触线处相对运动速度理论模型，为滚子尺寸一致性演化机理提供理论支撑。

为揭示轴套式循环研磨球面滚子尺寸一致性演化规律，首先，采用基于影响系数法的有限长线接触理论对球面滚子滚动面与研具工作面的接触特性进行理论建模与分析。其次，根据最低能量原理和变形协调条件，建立研磨区内各球面滚子的研磨载荷分配模型，最后，结合球面滚子滚动面材料去除模型，建

立研磨系统内球面滚子材料选择性去除模型，并对其进行分析可知，球面滚子批直径变动量呈现先快速收敛后慢速收敛的演化过程。

为探究工艺参数对球面滚子几何精度的影响规律，开展了球面滚子轴套式循环研磨试验。通过对试验参数域、试验方案及策略探究，证明轴套式循环研磨方法具备实现高精度球面滚子批量加工的能力。为提高研磨效率将研磨过程分为半精加工和精加工两道工序。精加工后的球面滚子圆度误差达到 0.75 μm，批直径变动量达到 2 μm，轴截面廓形批直径变动量达到 0.59 mm，表面粗糙度达到 0.02 μm。通过具有 CMA、CNSA 资质的国家轴承质量检验检测中心对精加工后的球面滚子进行检测，检测结果满足《JB/T 14579-2023 滚动轴承球面滚子》技术标准中I级技术要求，且加工精度高于现阶段国内外球面滚子批量加工精度水平。轴套式循环研磨方法提高了批量生产条件下球面滚子的几何精度，为提升我国高端调心滚子轴承的制造技术水平提供基础理论与技术支撑。

关键词：球面滚子；轴套式研磨；精度进化；圆度误差；尺寸一致性；轴截面廓形；表面粗糙度

ABSTRACT

Spherical roller bearings are rolling bearings with automatic alignment capabilities, suitable for large and complex mechanical equipment in wind power, shield tunneling, helicopters, high-speed rail, large ships, nuclear power, and other fields where the load conditions at the end of the transmission system are complex and the shaft center position requires real-time adjustment. The geometric precision (shape precision and diameter size consistency) of the rolling surface of spherical rollers, which are the key components of spherical roller bearings, significantly affects the performance and service life of these bearings. Currently, centerless lapping technology is widely used in production practice to ensure the geometric precision of the rolling surface of spherical rollers. However, this technology is not sufficient to meet the development needs of high-end equipment due to the degradation of precision caused by the principle of maternity. In response to the industry pain point of insufficient geometric precision of the rolling surface of spherical rollers caused by the principle of maternal processing, this paper studies the precision evolution processing theory and technology of spherical rollers, which has important theoretical significance and practical value.

Cylindrical roller double-disk circular lapping is a precision evolution processing method. Drawing on the basic ideas of "direct comparison of multiple samples" and "selective removal of materials" from this method, this paper proposes a new method for precision evolution processing of high-precision spherical rollers - spindle-sleeve circular lapping. The analysis of the cutting motion generation that forms the rolling surface of the spherical roller shows that the rotation of the spherical roller around its own axis ensures the roundness of the rolling surface. The rotation of the spherical roller along the circular groove ensures both the arc profile of the rolling surface and the wear uniformity of the working surface of the circular groove. The reciprocating linear motion of the spherical roller along the linear groove ensures the wear uniformity of the working surface of the linear groove. The conjugate contact characteristics between the rolling surface of the spherical roller and the working surfaces of the circular and linear grooves are analyzed. The results show that the contact line morphology between the rolling surface of the roller and the working surface of the circular groove is a cross-shaped contact line, while the contact line morphology between the rolling surface of the roller and the working surface of the linear groove is an arc-shaped contact line.

Based on the mechanical and kinematic conditions of the spherical roller under the spindle-sleeve circular lapping system, the paper establishes a theoretical model of the self-rotation of the spherical roller and analyzes the process conditions for

continuous and stable self-rotation of the spherical roller. The results show that when the starting angle corresponding to the cross-shaped contact line II is within the range of 0-$\pi/2$, and the friction coefficient μ_2 between the rolling surface of the spherical roller and the working surface of the linear groove is greater than 1.067 times the friction coefficient μ_1 between the rolling surface of the spherical roller and the working surface of the circular groove, the self-rotation of the spherical roller can be ensured. Through simulation analysis of the motion behavior of the spherical roller, it is found that there are varying degrees of (lateral displacement) within the cross-section of the lapping strip. When the roller rotates continuously and stably, the relative sliding rate between the rolling surface of the roller and the working surface of the lapping strip is less than 5%. Based on the theory of self-rotation and simulation analysis results, a theoretical model of relative motion velocity at each contact line is established, providing theoretical support for the evolution mechanism of roller size consistency.

To reveal the evolution law of size consistency of spherical rollers in spindle-sleeve circular lapping, the paper first established a theoretical model of the contact characteristics between the rolling surface of the spherical roller and the working surface of the lapping tool and analyzed it using the finite linear contact theory based on the influence coefficient method. Second, based on the principle of minimum energy and deformation coordination conditions, a lapping load distribution model for each spherical roller in the lapping zone is established. Finally, combined with the material removal model of the rolling surface of the spherical roller, a selective material removal model for the spherical rollers within the lapping system is established and analyzed. It can be seen that the diameter variation of the batch of spherical rollers exhibits an evolution process of rapid convergence followed by slow convergence.

To investigate the influence of process parameters on the geometric precision of spherical rollers, experiments on spindle-sleeve circular lapping of spherical rollers were conducted. Through the exploration of the test parameter domain, test scheme, and strategy, it is proved that the spindle-sleeve circular lapping method can achieve high-precision batch processing of spherical rollers. To improve lapping efficiency, the lapping process is divided into two stages: semi-finishing and finishing. After finishing, the roundness error of the spherical roller reaches 0.75 μm, the diameter variation of the batch reaches 2 μm, the diameter variation of the axial cross-sectional profile reached 0.59 mm, and the surface roughness reached 0.02 μm. The national bearing quality inspection and testing center, which holds CMA and CNSA qualifications, has tested the finished spherical rollers. The results confirm that the technical requirements of Grade I in the "JB/T 14579-2023 Spherical Roller for Rolling Bearings" standard have been met, and the processing accuracy is superior to

the current level of domestic and international batch processing accuracy for spherical rollers. The spindle-type circulating lapping method has significantly improved the geometric accuracy of spherical rollers in mass production, thereby laying a solid theoretical and technical foundation for the advancement of high-end self-aligning roller bearings manufacturing technology in China.

KEYWORDS： Spherical roller; Axle-sleeve typed lapping; Accuracy evolution; Roundness error; Dimensional consistency; Shaft cross-section profile; Surface roughness