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钢丝的微动磨损及其损伤疲劳行为研究

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前言

微动损伤(Fretting damage)是存在于近似“静止”配合的机械零件中的一种损伤方式，其定义为：两个相互接触表面在一定的法向载荷作用下，若表面间存在小幅的相对振动运动，接触表面上所出现的损伤现象。微动磨损、微动疲劳和微动腐蚀是微动损伤的3种模式。

作为连接提升容器与提升机的钢丝绳，是矿井提升系统中的重要组成部分，它的强度大小及其寿命长短对提升机的可靠性水平直接影响到提升机的安全运行和矿井生产。提升钢丝绳内部股与股、丝与丝之间存在的微动磨损将降低钢丝绳的疲劳强度，加速钢丝绳的疲劳断丝。钢丝绳内部的损伤形式是一种混合的损伤形式，涉及到微动磨损和微动疲劳，同时在交变应力的作用下会形成微动磨损缺口的疲劳断裂。因此，通过研究微动磨损来减少疲劳断丝是延长钢丝绳服役寿命的有效途径，也是保证钢丝绳使用可靠性的关键措施。

开展钢丝的微动磨损和微动磨损钢丝的疲劳寿命实验，研究钢丝微动磨损与疲劳强度之间的关系，其研究所得的实验结果和理论分析必将对钢丝绳的强度和疲劳理论发展起到积极的推动作用，具有十分重要的工程应用价值。针对这一工程背景，从1995年开始，我就和我的老师葛世荣教授以微动磨损为出发点，根据提升钢丝绳的组成结构以及钢丝绳的微动损伤特点，计算了钢丝绳内部绳股与绳股、钢丝与钢丝之间接触压力、相对错动位移、错动频率等与微动损伤相关的参数；根据钢丝之间的接触应力及相对滑动位移的规律，简化了钢丝绳中的钢丝与钢丝之间的微动磨损模

型，并由此研制出了钢丝微动磨损试验机。然后在自制的钢丝微动磨损试验机上开展不同条件下的微动磨损实验。

实验发现了钢丝试样在微动磨损参数变化时摩擦系数、微动磨损深度的变化规律及微动磨损机理。同时，我们还建立了钢丝微动接触的有限元模型，从力学计算上找到了微动接触区的应力大小、应力分布状况以及应力梯度的规律，并实验分析了磨损深度变化时接触面积和接触应力的变化规律，提出了采用综合参数 pv 值和 pvt 值来表征接触载荷、微动时间和微动振幅等参数对微动磨损量的影响关系，并利用综合参数 pvt 值推导出钢丝微动磨损的理论计算式。对微动磨损的钢丝试样进行了拉—拉疲劳实验，得到了不同应力比和应力幅下微动磨损钢丝的疲劳寿命变化曲线，建立了钢丝疲劳寿命与微动磨损量的对应关系，并根据疲劳断口的微观形貌分析了钢丝疲劳断裂的过程及其规律。

经过大量系统深入的实验、微观分析和理论分析工作，我们先后完成了由煤炭部科学基金资助的“提升钢丝绳微动磨损及其断裂行为研究”项目和由煤炭高校跨世纪人才基金资助的“钢丝绳微动磨损研究”科研工作，并获得了一些具有创新性的研究成果。在此，将从中的一些实验结果和获得的点滴启发和结论整理、汇编成书，以期为同行和今后的工作提供借鉴和帮助。

本书是在导师葛世荣教授的悉心指导下完成的，导师在学术上给予了我不断的启发和帮助，其渊博的专业知识、严谨的治学态度、勤奋的工作作风、活跃的学术思想以及无私奉献的精神都成为我在研究工作中勇于进取、善于探索的动力，在此谨向导师致以深深的谢意；感谢所有关心、支持、帮助过我的各级领导、老师、同事和朋友们；感谢多年来父母、妻子给予我深深的理解和全力支持。

本书是在我博士论文的基础上整编而成，并得到了研究生院的“中国矿业大学优秀博士论文”出版资助，还得到了国家杰出青年科学基金(50225519)、国家自然科学基金(50405042)和高等学

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提升钢丝绳的疲劳及其寿命预测的研究仍在进行中。本书的观点和论述难免有不尽完善之处，敬请读者和同行提出批评和指正。

作者

2005年4月

摘 要

提升钢丝绳内部股与股、丝与丝之间存在的微动磨损将降低钢丝绳的疲劳强度，加速钢丝绳的疲劳断丝。因此，研究钢丝的微动磨损及由损伤引起的疲劳断裂对延长钢丝绳服役寿命和提高钢丝绳的使用可靠性具有重要的意义。

本书以 6×19 点接触式钢丝绳为研究对象，分析了提升钢丝绳中钢丝的受力状况，对钢丝绳中的钢丝进行了实验室模型化，研制了钢丝微动磨损试验机。在此试验机上，研究了钢丝试样在微动磨损过程中和在微动振幅、接触载荷、微动时间等参数变化时摩擦系数、微动磨损深度的变化规律。结果表明，摩擦系数的大小和微动振幅密切相关，而且还和接触应力的大小、接触状态、磨屑等因素直接相关。

微动磨损深度随着微动振幅、接触载荷、微动时间的增加而呈增长趋势，但由于接触面积、接触应力在微动磨损过程中也随着上述参数的变化而变化，同时磨屑作为第三体的介入，使磨损深度在不同的工况下增长速率不同。通过建立的钢丝接触的有限元模型，分析了接触区在不同嵌入深度和不同载荷下的应力大小、应力分布状况以及应力梯度的规律，从力学上验证了磨损深度变化时接触面积和接触应力的变化规律。根据磨损试样磨屑的大小、形状、分布和微动磨痕形貌的变化规律分析了微动磨损机制的变化。

本书提出了采用综合参数 pv 值和 pvt 值来替代接触载荷、微动时间和微动振幅等参数来研究其对微动磨损量的影响关系，并利用综合参数 pvt 值与磨损深度的拟合线性关系建立了钢丝微动

磨损的理论模型，实验结果和理论计算结果变化趋势一致，误差较小。

将微动磨损后的钢丝试样在液压伺服疲劳试验机上进行了疲劳实验，研究了在不同应力比和应力幅下，微动磨损深度对钢丝疲劳寿命的影响。结果表明，微动磨损深度、应力比和应力幅是影响钢丝疲劳寿命的重要因素。从疲劳断口微观形貌分析可知，断口对应不同的疲劳阶段可分为裂纹萌生区、裂纹扩展区和裂纹瞬断区。微动磨损缺口为裂纹的疲劳源。

关键词：钢丝；微动磨损；磨损深度；综合参数；应力集中；疲劳寿命；形貌

ABSTRACT

The fretting wear between strands inside hoisting rope and between wires inside strands will decrease the fatigue intensity of the hoisting rope and accelerate the fatigue fracture of the hoisting rope. So investigations on fretting wear of steel wires and fatigue fracture caused by fretting damage are of great importance in prolonging the hoisting rope's life and improving the reliability of hoisting rope.

This paper, taking the 6×19 point contact hoisting rope as the study object, analyzed the loading condition of steel wires inside the hoisting rope when the winder was running and developed fretting wear model to simulate the steel wire's condition in lab. And the fretting wear rig of steel wires was set up according to the decided fretting wear parameters. Using the fretting wear rig, research on fretting wear of steel wire specimens was performed, which focused on variation rules of friction coefficient and fretting wear depth when parameters, such as fretting amplitude, contact load and fretting time, were changed. The results showed that friction coefficient was closely related to fretting amplitude as well as directly to contact load, contact conditions and wear debris, etc.

Fretting wear depth increased with the increasing of the fretting amplitude, contact load and fretting time. However, the increasing trends of wear depth varied at different conditions due to wear debris and the simultaneous variations of contact area and contact stress in the process of fretting wear. The developed finite

element model of contact condition between wire specimens, is used to analyze the value, distribution and grads of contact stress in different insert depth and under different load, which in view of mechanics validated the variation law of contact area and contact stress as wear depth varies. From the SEM morphologies of the size, shape and distribution of wear debris and fretting wear trace, the changing rules of wear mechanism were analyzed.

In order to depict fretting wear more thoroughly, integrated parameter *pv* value and *pvt* value, were introduced to replace the parameters such as contact load, fretting time and fretting amplitude to find the effect of the former parameters on amount of fretting wear. Based on the fitted linear relation between integrated parameter *pvt* value and wear depth, the theoretic model of fretting wear between wires was developed. The results of theoretic calculation fitted that of experiment mostly.

After the process of fretting wear, the steel wire specimens were then performed on fatigue experiment using hydraulic servo fatigue test rig. The effect of fretting wear depth on fatigue life of steel wires under different stress ratio and different stress amplitude was investigated too. The result showed that the wear depth, stress ratio and stress amplitude were the most important factors to effect the fatigue life.

It can be drawn from SEM morphologies of fracture section that fatigue fracture were divided into crack initiation, crack propagation and crack break corresponding to different fatigue phases. The fretting worn notch was the crack initiation source because of stress concentration.

Keyword: Steel wire, fretting wear, wear depth, integrated

parameter, stress concentration, fatigue life, morphology

ABSTRACT

(Detail Abstract)

Winder is a very important equipment to carry coal, people and material in coalmines. Hoisting rope is the indispensable part of winder and its strength and life play a critical role not only on the reliability of winder, but also on the operation of winder and even on the production of coalmine. When hoisting rope is bent or drawn axially, there will exist fretting wear with little amplitude between strands inside rope and between wires inside strands, which will lead to micro damage to the hoisting rope and thus accelerate the fatigue fracture of the rope. So investigations on fretting wear of steel wires and fatigue fracture caused by fretting damage are of great importance in prolonging the hoisting rope's life and improving the reliability of hoisting rope.

This paper, taking the 6×19 point contact hoisting rope as the study object, analyzed the loading condition of steel wires inside the hoisting rope when the winder was running and developed fretting wear model to simulate the steel wire's condition in lab. And the fretting wear rig of steel wires was set up according to the decided fretting wear parameters. Using the fretting wear rig, research on fretting wear of steel wire specimens was performed, which focused on variation rules of friction coefficient and fretting wear depth when parameters, such as fretting amplitude, reciprocating frequency, contact load and fretting time, were changed. The results showed that friction coefficient was closely related to fretting amplitude as well as directly to contact load, contact conditions and

wear debris, etc. The steady friction coefficient was larger at large fretting amplitude and lower at little amplitude.

Fretting wear depth increased with the increasing of the fretting amplitude, contact load and fretting time. However, the increasing trends of wear depth varied at different conditions due to wear debris and the simultaneous variations of contact area and contact stress in the process of fretting wear. The wear depth increased sharply at initial phase of fretting wear and changed slowly after reaching a certain value of fretting time, and the increasing rate of wear depth was larger with the changing amplitude in little fretting amplitude. The wear depth increased in linear relation to the contact loads and fretting time.

The SEM morphologies of wear debris and fretting wear trace showed that the size, shape and distribution of wear debris, morphologies of wear trace, were affected directly by fretting amplitude, contact load and fretting time. The fine wear debris accumulated equably and its amount were large at the condition of light contact load or short fretting time. And much fibre shape or bar shape debris was produced at little amplitude. However, much big grain debris or flake shape debris or crisp shape debris was broken off from contact surfaces, which caused by contact fatigue at large contact load or longer fretting time. The adhesive of material and smear of debris mechanism gave priority to the morphologies of wear trace at light load or short fretting time. With the increasing of fretting time, the amount of debris increased. So the abrasive mechanism of ploughing trace and gouge trace was the main wear mechanism because of the intervention of debris. But at larger load or longer fretting time, the wear traces appeared the morphologies of debris broken off or rimple shape because the probability of contact fatigue between surface increased.

The nominal contact area and average contact stress between wire specimens were of close correlation to contact load and fretting time. The decreasing trend of contact stress and the increasing trend of contact area were the same because the wear depth increased with the increasing fretting time at a certain contact load. But the contact stress and contact area was the same increasing trend with the increasing load at the same fretting time. The developed finite element model of contact condition between wire specimens, was used to analyze the value, distribution and grads of contact stress in different insert depth and under different load, which in view of mechanics validated the variation law of contact area and contact stress as wear depth varies. The maximum stress increased as the contact load increased and decreased as insert depth deepened. The varying grad of stress was large at small insert depth and decreased when the insert depth was up to a certain value. The stress increased quickly with contact load at small insert depth and increased slowly with contact load at large insert depth.

In order to depict fretting wear more thoroughly, integreted parameter *pv* value and *pvt* value, were introduced to replace the parameters such as contact load, fretting time and fretting amplitude to find the effect of the former parameters on amount of fretting wear. The wear depth increased quickly at light contact load and then increased linearly and slowly at large load with the increasing *pv* value when the fretting time was certain. When the contact load was certain, the wear depth decreased with the increasing *pv* value. And the wear depth increased in linear relation to the ingreted parameter *pvt* value. Based on the fitted linear relation between ingreted parameter *pvt* value and wear depth, the theoretic model of fretting wear between wires was developed. The results of theoretic calculation fitted that of experiment mostly.

After the process of fretting wear, the steel wire specimens were then performed on fatigue experiment using hydraulic servo fatigue test rig. The effect of fretting wear depth on fatigue life of steel wires under different stress ratio and different stress amplitude was investigated too. The results showed that the bigger stress ratio, the greater tensile fatigue strength, while with the same maximum load, the bigger stress ratio, the longer tensile fatigue life. With the stable maximum load, the smaller stress ratio, the shorter tensile fatigue life of wires, the more possibility of damage.

Moreover, it can be drawn from SEM morphologies of fracture section that fatigue fracture were divided into crack initiation, crack propagation and crack break corresponding to different fatigue phases. The fretting worn notch was the source of crack initiation because of stress concentration. The crack propagated slowly and fracture section appeared much fine disorder secondary crack at initial fatigue. Then the crack propagated quickly and the crack and secondary crack became widely. When the crack propagation caused the overstress in wire specimen, the wire specimen broke suddenly at the center zone. The fracture crack inclined to the edge of wire specimens at a certain angle.

Keyword: Steel wire, fretting wear, wear depth, integrated parameter, stress concentration, fatigue life, morphology

目　　录

1 绪 论

1.1 引言

矿井提升机是煤矿的重要设备，它是运送煤炭、人员、物料等的咽喉通路。提升钢丝绳是矿井提升机中的重要组成部分，它起到连接提升容器与提升机的作用。钢丝绳的强度大小及其寿命长短对提升机的可靠性水平有重要作用，而且直接影响到提升机的安全运行和矿井生产[1~3]。

在提升机的选型设计时，选择提升钢丝绳的依据是按照《煤矿安全规程》的规定，从它的拉伸强度上校核，根据提升机的不同使用条件选用不同的安全储备系数，这种采用按平均应力考虑的静力安全系数作为钢丝绳的安全储备量是不真实的[4~6]。在分析破坏钢丝绳的复杂外力时，静载荷和动载荷是钢丝绳所受纵向力的主要成分，特别是对于提升能力较大的提升机，动态载荷的作用尤为重要。动态载荷是钢丝绳在运行过程中，由于各种原因引起纵向振动而产生的载荷，是提升系统设计时必须考虑的重要技术参数。通常认为以下几种情况是钢丝绳受力最大和最危险的状态：① 提升容器以最大速度运行时突然被卡住；② 提升过卷；③ 提升系统启动或制动时[7,8]。

无论是静态载荷，还是动态载荷，使提升钢丝绳失效的形式，并不是钢丝绳的突然断裂，往往由首先表现为断丝、断股和直径缩小开始，以致钢丝绳的强度降低，最后达到极限而破坏。钢丝绳断