摩擦学学报
TRIBOLOGY

定、变载弯曲疲劳钢丝绳失效机理对比研究

王大刚，张俊，朱辉龙，张德坤

Comparative Research on Failure Mechanisms of Steel Wire Ropes during Bending Fatigue under Constant and Variable Loads

WANG Dagang, ZHANG Jun, ZHU Huilong, ZHANG Dekun

在线阅读 View online: https://doi.org/10.16078/j.tribology.2020085

第 40 卷　第 6 期
2020 年 11 月

摩 擦 学 学 报
Tribology

Vol 40　No 6
Nov, 2020

DOI: 10.16078/j.tribology.2020085

定、变载弯曲疲劳钢丝绳失效机理对比研究

王大刚[1,2*], 张　俊[1,2], 朱辉龙[1,2], 张德坤[1,2]
(1. 中国矿业大学 机电工程学院, 江苏 徐州 221116;
2. 江苏省矿山智能采掘装备协同创新中心(省部共建), 江苏 徐州 221116)

摘　要: 为对比揭示定、变载弯曲疲劳钢丝绳断裂机理及磨损演化特性, 运用自制钢丝绳弯曲疲劳试验机开展钢丝绳定载、变载弯曲疲劳试验, 通过人工拆股统计法和VW-9000系列高速度数码显微系统对比研究钢丝绳断丝分布、断丝数、断口和磨痕形貌等断裂机理, 对比分析钢丝绳未断钢丝和断丝的磨痕尺寸演化特性. 结果表明: 与钢丝绳定载弯曲疲劳相比, 变载弯曲疲劳钢丝绳断丝出现较晚, 芯股、螺旋股外层断丝数分别较多、较少, 芯股外层钢丝断口挤压变形较大, 芯股各层钢丝断口裂纹扩展区占比较低, 芯股和螺旋股的各层钢丝磨痕尺寸总体较小, 钢丝绳更易达到报废水平.

关键词: 钢丝绳; 定载弯曲疲劳; 动载弯曲疲劳; 断裂机理; 磨损演化
中图分类号: TH117.1　　**文献标志码:** A　　**文章编号:** 1004-0595(2020)06–0762–12

Comparative Research on Failure Mechanisms of Steel Wire Ropes during Bending Fatigue under Constant and Variable Loads

WANG Dagang[1,2*], ZHANG Jun[1,2], ZHU Huilong[1,2], ZHANG Dekun[1,2]

(*1. School of Mechatronic Engineering, China University of Mining and Technology, Jiangsu Xuzhou 221116, China*
2. Jiangsu Province and Education Ministry Co-sponsored Collaborative Innovation Center of
Intelligent Mining Equipment, Jiangsu Xuzhou 221116, China)

Abstract: In order to comparatively reveal fracture mechanisms and wear evolution characteristics of steel wire ropes during bending fatigue under constant and variable loads, the self-made bending fatigue test rig of steel wire rope was employed to carry out bending fatigue tests of steel wire ropes under constant and variable loads. The statistical method by disassembling strands manually and VW-9000 series high-speed digital micro system were employed to comparatively investigate distributions and number of fractured wires, morphologies of fractures and wear scars at fractures of steel wires, evolutions of wear scar dimensions of unfractured and fractured wires in the rope. The results showed that as compared to bending fatigue of steel wire rope under the constant load, the bending fatigue of steel wire rope under the variable load presented later occurrences of fractured wires, more and fewer fractured wires in the outer layers of core and outer strands, respectively, larger extrusion deformations at fractures of outer layer wires in the core strand, lower ratios of crack propagation zones at fractures of steel wires at various layers in the core strand, overall smaller dimensions of wear scars of steel wires in various layers, and easier discarding of steel wire rope.

Key words: steel wire rope; bending fatigue under the constant load; bending fatigue under the variable load; fracture mechanism; wear evolution

---

Received 16 May 2020, revised 1 July 2020, accepted 22 July 2020, available online 28 November 2020.

*Corresponding author. E-mail: wangdg@cumt.edu.cn, Tel: +86-15162110590.

The project was supported by the National Natural Science Foundation of China (51875565), China Postdoctoral Science Foundation Funded Project (2019M652001), A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions, Top-Notch Academic Programs Project of Jiangsu Higher Education Institutions.

国家自然科学基金面上项目(51875565), 中国博士后科学基金面上项目(2019M652001), 江苏高校优势学科建设工程项目和江苏省高校品牌专业建设工程项目资助.

提升钢丝绳连接着提升机和提升容器，担负着运输煤炭、生产设备和煤矿工作人员的任务[1]. 作为提升机关键承载和传动部件，提升钢丝绳承载强度和服役寿命直接决定提升安全性和传动可靠性. 在提升循环中，钢丝绳承受循环静张力和时变动张力[2]，即定载、变载弯曲疲劳，均导致钢丝绳(钢丝和股捻成的螺旋结构)断丝和磨损现象，造成钢丝绳横截面积和承载强度均降低. 然而，定载、变载弯曲疲劳导致差异的钢丝绳断裂机理和磨损演化特性，故开展定载、变载弯曲疲劳钢丝绳失效机理对比研究，对提升钢丝绳服役寿命预测具有重要理论意义.

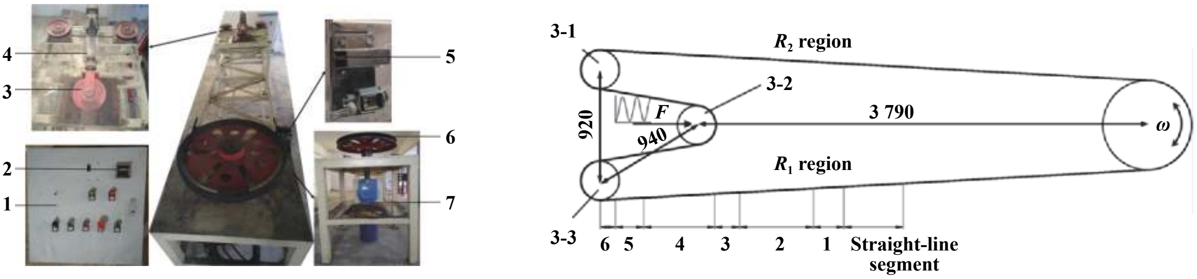
在定载弯曲疲劳钢丝绳失效机理方面，贾小凡等[3]和Zhang等[4-5]研究了预张力、滑轮材料、预制断丝分布对钢丝绳损伤量值、外部断丝数和弯曲疲劳寿命的影响规律；胡吉全和胡正权[6]考察了弯曲应力对钢丝绳疲劳寿命的影响；尹涛等[7]考察了弯曲疲劳钢丝绳钢丝强韧性和显微硬度；殷觊恺等[8]研究了轮/绳直径比和绳端张力对钢丝绳弯曲应力和寿命的影响规律；Chen等[9]分析了弯曲疲劳钢丝绳内部钢丝摩擦磨损特性；Argatov等[10]探讨了轮/绳直径比对钢丝绳接触参数的影响规律；Onur等[11]分析了滑轮尺寸和预张力对钢丝绳弯曲疲劳寿命的影响规律. 针对钢丝绳变载弯曲疲劳方面，Zhang等[12]研究了变载弯曲疲劳钢丝绳断丝数和钢丝磨损深度特性. 然而，定载、变载弯曲疲劳作用下钢丝绳断裂机理(断丝数演化、断口形貌)和磨损演化特性(未断、断裂钢丝磨痕)对比性研究尚未见报道.

1　钢丝绳弯曲疲劳试验装置

依据GB/T5972–2006研制了1台钢丝绳弯曲疲劳试验机，其实物图和原理图分别见图1(a)和图1(b). 由图1可知，钢丝绳弯曲缠绕于主动轮6和从动轮3-1、3-2、3-3，电动缸4往复伸缩推动从动轮3-2实现钢丝绳交变载荷的施加(电动缸位置不变实现钢丝绳的恒定预张力)，通过变频器控制变频电机7的转速，变频电机7带动主动轮6转动，当钢丝绳运行至指定位置时接近开关5给变频电机7发出反转信号，进而实现钢丝绳往复弯曲疲劳，主动轮正反转次数通过控制柜1上计数器2进行计数. 当钢丝绳绕经(绕入和绕出)1个从动轮时，经历了2次弯-直(或直-弯)变化，因此记弯曲疲劳次数为2次，故主动轮正反转1次，同一根钢丝绳区段1~6(长度见表1)对应的弯曲疲劳次数分别为2、4、6、8、10和12次. 钢丝绳沿试验机长度方向对称布置，R_1区和R_2区钢丝绳均各有区段1~5，仅R_1区有区段6. 弯曲疲劳试验机参数列于表1中.

2　试验参数与测试方法

选用6×19W+IWS钢丝绳，具体结构参见图2，结构参数列于表2中. 依据文献[3, 13]，选择钢丝绳弯曲疲劳试验参数(见表3)，对比恒定张力和变张力对钢丝绳弯曲疲劳损伤的影响规律. 通过人工拆股统计钢丝绳断丝数和断丝位置，运用VW-9000系列高速度数码显微系统观察钢丝绳、绳股表面磨痕和断丝形貌以及钢丝断口和磨痕形貌.



(a) Test apparatus　　(b) Schematic diagram

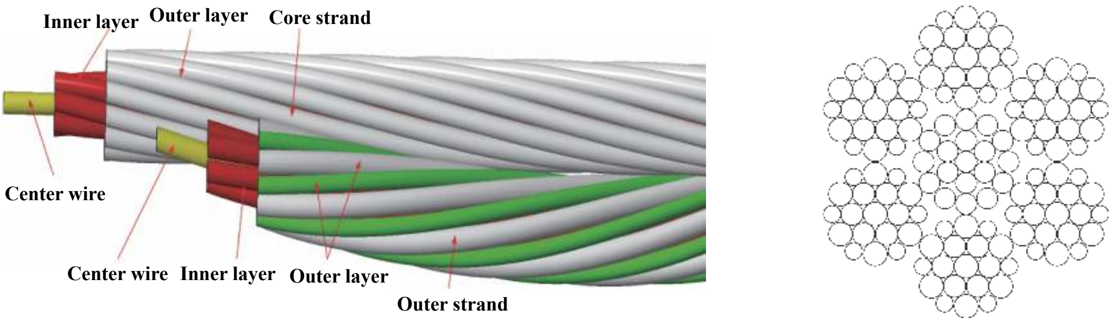
Fig. 1　Bending fatigue test apparatus of wire rope

图 1　钢丝绳弯曲疲劳试验机

表 1　弯曲疲劳试验机参数及各区段钢丝绳长度

Table 1　Parameters of bending fatigue test apparatus and rope lengths at different segments

Positive and negative rotation period of driving pulley	Material of driving and driven pulleys	Driven pulley diameter	Driving pulley diameter	Maximum thrust of electric cylinder	Lengths of steel wire rope in each segment					
					Seg. 1	Seg. 2	Seg.3	Seg.4	Seg.5	Seg.6
30 s	Cast steel	284 mm	694 mm	20 kN	43 cm	104 cm	35 cm	100 cm	40 cm	13 cm



(a) Three-dimensional structure (b) Cross-section

Fig. 2 Structure of 6×19W+IWS steel wire rope

图 2 6×19W+IWS钢丝绳结构

表 2 钢丝绳结构参数

Table 2 Structural parameters of steel wire rope

Parameter	Specification
Rope diameter/mm	12
Lay length/mm	78
Outer strand, lay length of strand /mm	36
Outer strand, diameter of center wire /mm	0.9
Outer strand, diameters of steel wires in the inner layer /mm	0.85
Outer strand, diameters of steel wires in the outer layer/mm	0.9/0.65
Core strand, Lay length of strand(upper lay)/mm	42
Core strand, lay length of strand(lower lay)/mm	21
Core strand, diameter of center wire /mm	0.8
Core strand, diameters of steel wires in the inner layer /mm	0.8
Core strand, diameters of steel wires in the outer layer /mm	0.8
Minimum breaking load/kN	90.7
Weight/(kg/m)	0.549
Sum of cross sections of rope wires/mm^2	68.64

表 3 钢丝绳弯曲疲劳试验参数

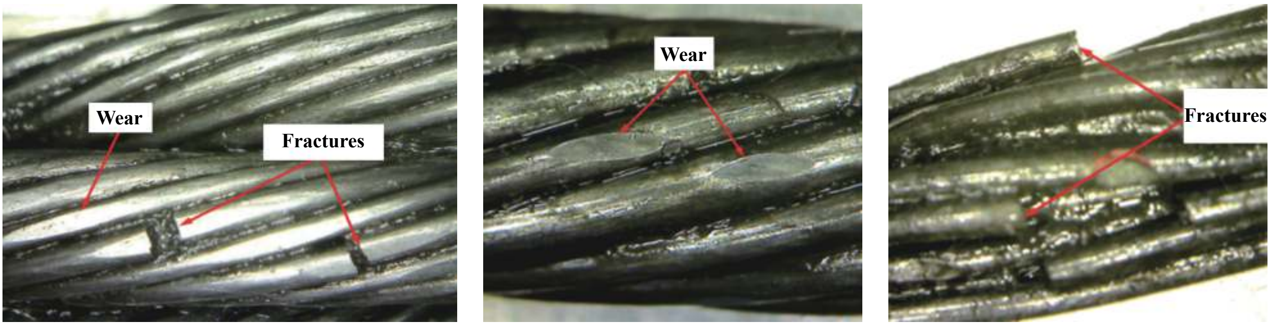
Table 3 Test parameters of bending fatigue of wire rope

Test condition	Rope tension/ kN	Bending fatigue cycles /10^4					
		Seg.1	Seg.2	Seg.3	Seg.4	Seg.5	Seg.6
1	11.5	1.7	3.4	5.1	6.8	8.5	10.2
2	9.2	2.6	5.2	7.8	10.4	13.0	15.6
3	9.2~11.5	1.7	3.4	5.1	6.8	8.5	10.2
4	9.7~11.0	1.7	3.4	5.1	6.8	8.5	10.2

3 结果与分析

3.1 钢丝绳断丝数

在钢丝绳弯曲疲劳试验后，通过人工拆股统计仅发现钢丝绳螺旋股(Outer strand)外层钢丝(与滑轮接触位置)和芯股(Core strand)外层钢丝(与螺旋股接触位置)出现断裂，且表面磨损严重，如图3所示；不同试验工况下钢丝绳断丝数统计结果见表4(仅列举出现断丝对应循环次数的数据). 由表4发现，当钢丝绳恒定张力为11.5 kN时，在弯曲疲劳次数8.5×10^{4}时，区段5钢丝绳螺旋股外层钢丝出现断丝现象；在弯曲疲劳次数10.2×10^{4}时，区段6钢丝绳螺旋股和芯股的外层钢丝均出现断丝现象. 当钢丝绳恒定张力为9.2 kN时，在弯曲疲劳次数13.0×10^{4}时，区段5钢丝绳芯股和螺旋股的外层钢丝均出现断丝现象，且芯股外层断丝数大于螺旋股外层断丝数；在弯曲疲劳次数15.6×10^{4}时，区段6钢丝绳芯股外层断丝数亦大于螺旋股外层断丝数. 当钢丝绳变张力为9.2~11.5 kN时，钢丝绳螺旋股外层



(a) Fracture and wear of steel wires in the outer layer of outer strand (b) Wear of steel wires in the outer layer of core strand (c) Fractures of steel wires in the outer layer of core strand

Fig. 3 Fracture locations of steel wires and wear conditions of steel wire rope

图 3 钢丝绳内部断丝位置和磨损情况

表 4　不同区段钢丝绳断丝数

Table 4　Number of broken wires at different segments of steel wire rope

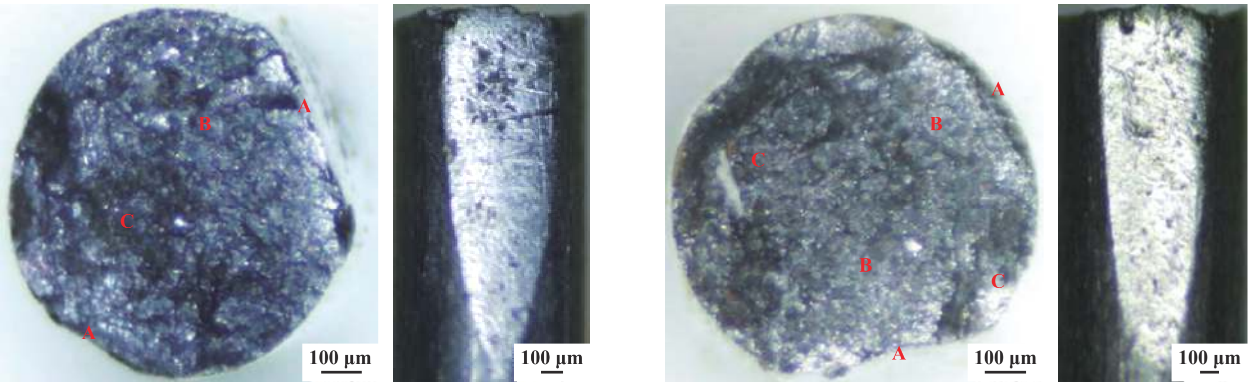
Test condition	segment	Outer strand						Core strand						Bending fatigue cycles/10^4
		Outer layer		Inner layer		Center wire		Outer layer		Inner layer		Center wire		
		R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2	
1	5	1	1	0	0	0	0	0	0	0	0	0	0	8.5
1	6	1	1	0	0	0	0	1	1	0	0	0	0	10.2
2	5	0	1	0	0	0	0	5	2	0	0	0	0	13.0
2	6	1	1	0	0	0	0	3	3	0	0	0	0	15.6
3	6	0	0	0	0	0	0	3	3	0	0	0	0	10.2
4	6	0	0	0	0	0	0	0	0	0	0	0	0	10.2

钢丝未出现断丝现象；在弯曲疲劳次数10.2×10^4时，区段6钢丝绳芯股外层钢丝出现断丝现象. 当钢丝绳变张力9.7~11.0 kN时，在弯曲疲劳次数10.2×10^4时，钢丝绳螺旋股和芯股的各层钢丝均未出现断丝现象.

对比试验工况1和2，当钢丝绳恒定张力分别为11.5和9.2 kN时，钢丝绳芯股外层出现断丝时对应的弯曲疲劳次数范围分别是$8.5\sim10.2\times10^4$、$10.4\sim13.0\times10^4$(弯曲疲劳次数为10.4×10^4时芯股外层钢丝未发现断丝现象)，说明钢丝绳恒定张力下降导致钢丝绳弯曲疲劳寿命提高. 对比试验工况3和4，钢丝绳变张力平均张力水平相同，张力变化幅值降低导致钢丝绳弯曲疲劳寿命提高. 对比试验工况1(恒张力11.5 kN)和试验工况3(变张力9.2~11.5 kN)，发现变张力工况下钢丝绳断丝出现较晚、螺旋股外层断丝数较小、芯股外层断丝数较多，这说明变张力工况的钢丝绳芯股外层钢丝弯曲疲劳寿命较小.

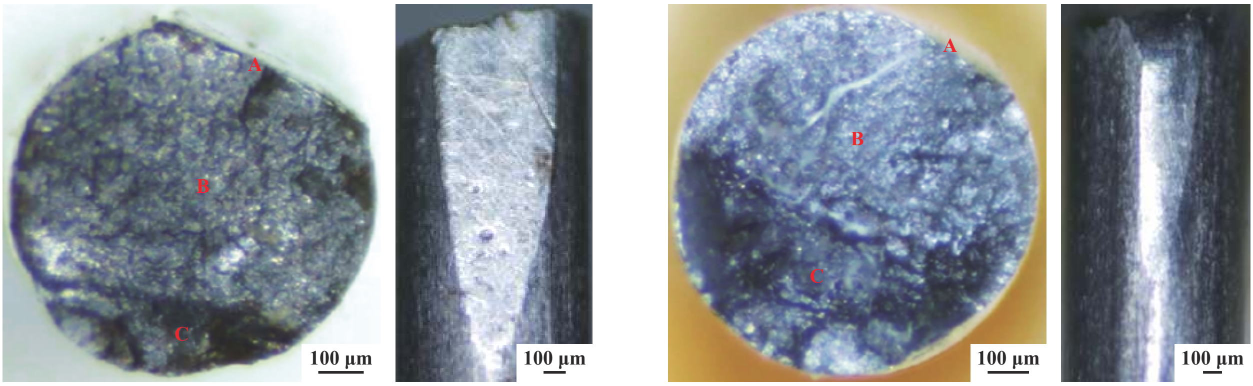
3.2　钢丝绳断丝断口与磨痕形貌

由图4可知，依据裂纹扩展速率和裂纹面倾斜程



(a) R_1 region–fractured wire in the outer layer of outer strand in Seg.5

(b) R_2 region–fractured wire in the outer layer of outer strand in Seg.5



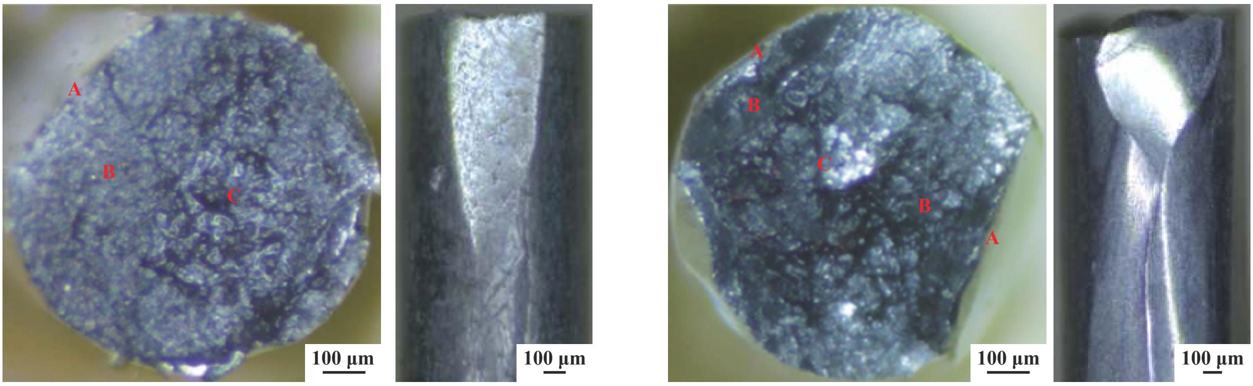
(c) R_1 region–fractured wire in the outer layer of outer strand in Seg.6

(d) R_1 region–fractured wire in the outer layer of core strand in Seg.6

Fig. 4　Morphologies of fractures and wear scars of steel wires in the rope in the case of constant tension of 11.5 kN(test condition 1)

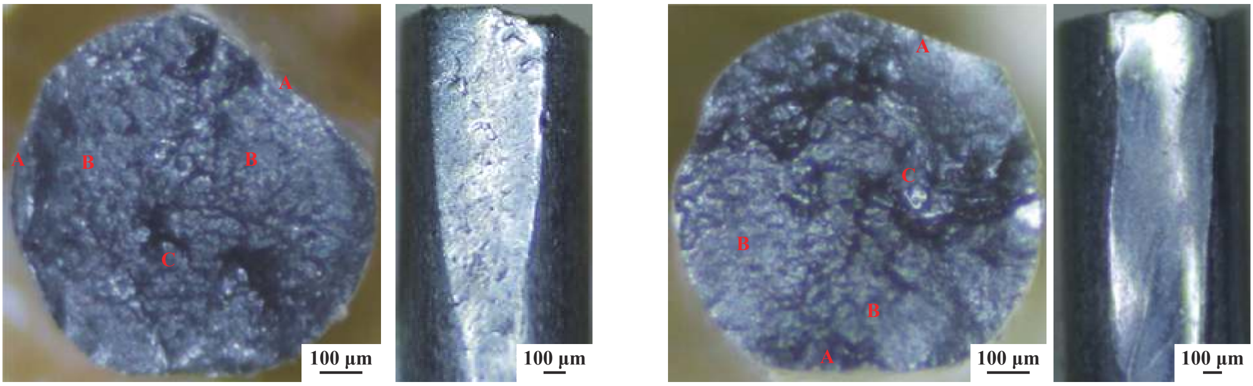
图 4　恒定张力11.5 kN时(试验工况1)钢丝绳内部钢丝断口和磨痕形貌

度(相对于疲劳钢丝轴线)，钢丝断口可分为裂纹萌生区(A区)、裂纹扩展区(B区)、瞬断区(C区). 由图4可知，螺旋股和芯股的外层钢丝断口B区均较平整，且裂纹面近似垂直于疲劳钢丝轴线，故裂纹型式为I型裂纹；螺旋股外层钢丝断口B区较C区的占比大，芯股较螺旋股的外层钢丝断口C区占比大；螺旋股外层钢丝断口处磨痕均呈椭圆状，且断口偏离钢丝磨痕中心一定距离处. 由图5可知，各区段螺旋股和芯股的外层钢丝断口B区均占比较大，螺旋股外层钢丝断口处磨痕呈规则椭圆状，而芯股外层钢丝断口处磨痕变形严重. 这是因为芯股外层钢丝断裂后，断裂钢丝释放承受的拉伸应力，弯曲疲劳过程中断丝将发生错位并与其他螺旋股外层钢丝接触，断裂钢丝受到复杂挤压变形的作用，故芯股外层钢丝断口处磨痕变形严重，同时断口因挤压变形严重而难以准确判别B区和C区分界线[见图5(b)]. 由图6可知，区段6钢丝绳芯股钢丝断口挤



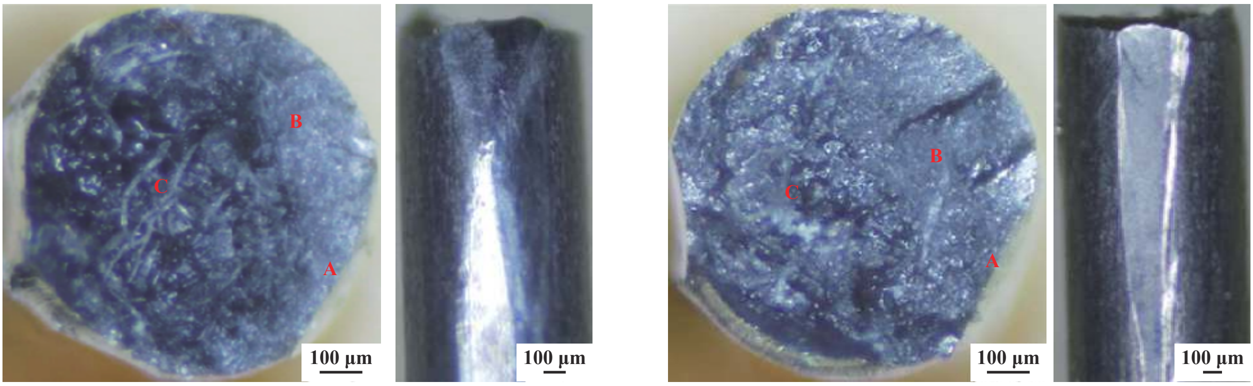
(a) R_2 region–fractured wire in the outer layer of outer strand in Seg.5

(b) R_2 region–fractured wire in the outer layer of core strand in Seg.5



(c) R_1 region–fractured wire in the outer layer of outer strand in Seg.6

(d) R_1 region–fractured wire 1 in the outer layer of core strand in Seg.6

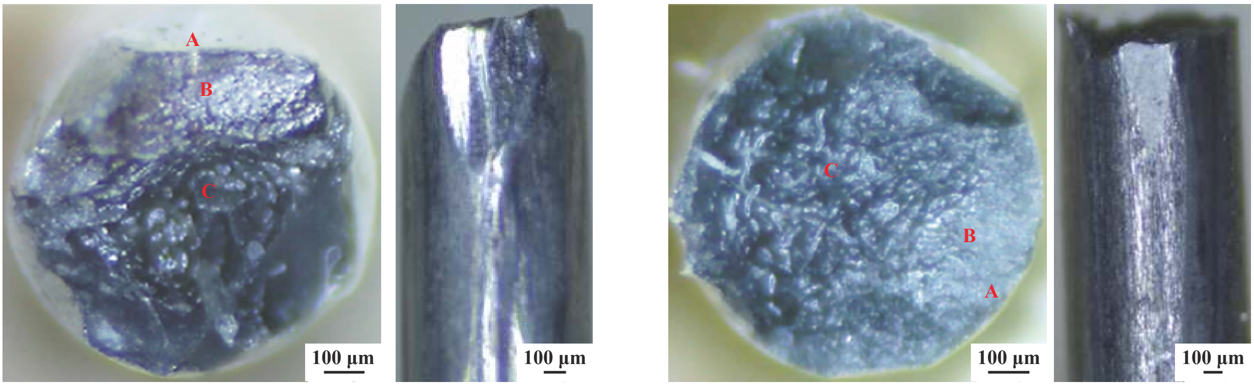


(e) R_1 region–fractured wire 1 in the outer layer of core strand in Seg.5

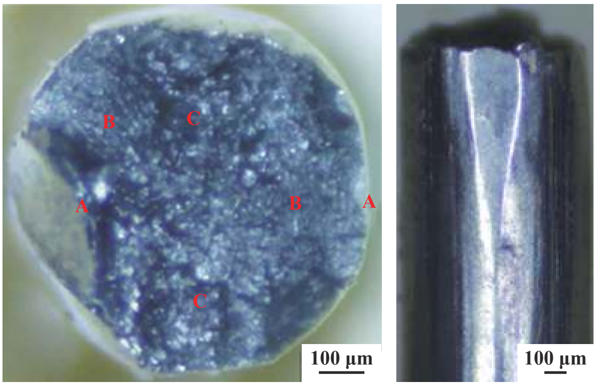
(f) R_1 region–fractured wire 2 in the outer layer of core strand in Seg.5

Fig. 5 Morphologies of fractures and wear scars of steel wires in the rope in the case of constant tension of 9.2 kN(test condition 2)

图5 恒定张力9.2 kN时(试验工况2)钢丝绳内部钢丝断口和磨痕形貌



(a) Fractured wire 1 in outer layer of core strand in Seg.6　(b) Fractured wire 2 in outer layer of core strand in Seg.6



(c) Fractured wire 3 in outer layer of core strand in Seg.6

Fig. 6 Morphologies of fractures and wear scars of steel wires in the rope in the case of variable tension of 9.2~11.5 kN(test condition 3)

图 6　变张力9.2~11.5 kN时(试验工况3)钢丝绳内部钢丝断口和磨痕形貌

压变形严重，断口周围呈多个挤压面，导致断口分区困难，断口位置磨痕呈挤压和扭曲变形，磨痕形貌亦呈不规则椭圆状. 由表4和图4~6可知，与恒张力工况相比，变张力工况下区段6钢丝绳断丝数较多，芯股外层钢丝断口挤压变形更大，这是因为变张力工况易加剧钢丝绳断裂钢丝错位，导致断裂钢丝更易发生挤压变形.

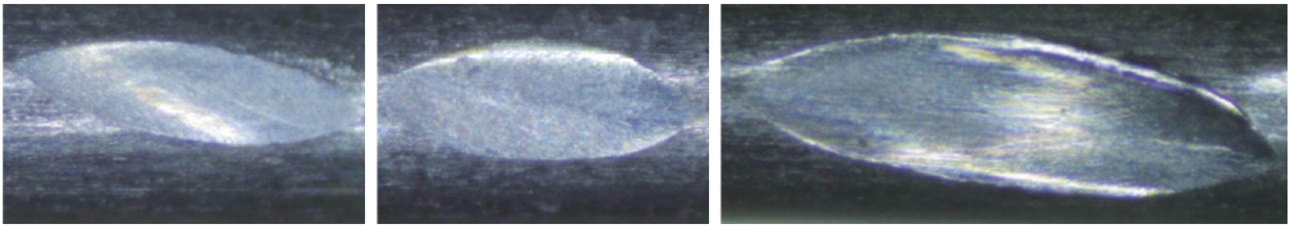
3.3　钢丝绳内部钢丝磨痕尺寸

通过钢丝绳人工拆股统计，发现钢丝绳磨损位置主要为芯股-螺旋股、螺旋股-螺旋股和螺旋股-滑轮的接触位置，故本文中选择这4类典型接触位置对钢丝磨痕形貌进行分析[见图7(a~d)]. 针对每个区段钢丝绳每个典型接触位置，选取3根钢丝进行磨痕尺寸测量[见图7(e)]，测量结果如图8~11所示. 由图7(a~d)可知，各接触位置钢丝磨痕均呈长条形椭圆状，采用图7(e)方式测量磨痕尺寸；为便于分析，标记与芯股、螺旋股、滑轮接触的螺旋股外层钢丝位置分别为位置S_1、位置S_2和位置S_3，标记与螺旋股接触的芯股外层钢丝位置为位置S_4.

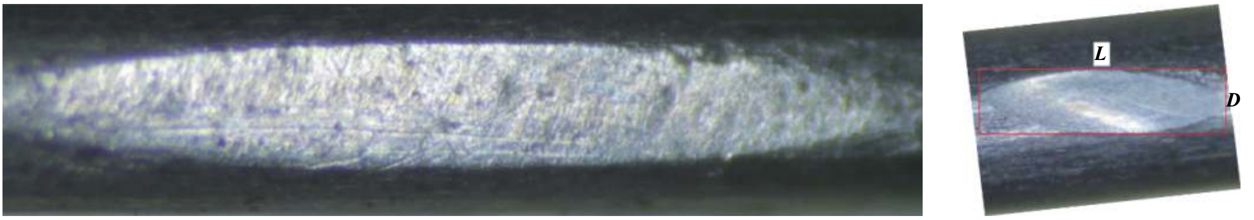
由图8~9可知，在恒定张力11.5和9.2 kN时，钢丝绳螺旋股外层钢丝磨痕尺寸降低次序均为位置S_3、位置S_1和位置S_2；对比螺旋股、芯股的外层钢丝磨痕尺寸，发现芯股较螺旋股的外层钢丝磨痕尺寸大；各接触位置钢丝磨痕尺寸较大值均位于钢丝绳区段5或6. 由图9可知，随着弯曲疲劳次数的增加，钢丝绳各接触位置钢丝磨痕尺寸总体呈增大趋势. 然而，考虑到钢丝绳内部钢丝磨损离散性和钢丝选取随机性，图8所示各接触位置钢丝磨痕尺寸随弯曲疲劳次数变化存在一定随机性.

由图10和图11可知，在变张力工况时，钢丝绳螺旋股外层钢丝磨痕尺寸降低次序均为位置S_3、位置S_1和位置S_2；针对螺旋股和芯股接触位置，芯股较螺旋股的外层钢丝磨痕尺寸总体要大；针对各接触位置，螺旋股-滑轮接触位置螺旋股外层钢丝(位置S_3)的磨痕尺寸最大，说明钢丝磨损最严重. 随着弯曲疲劳次数的增加，各接触位置钢丝磨痕尺寸呈现一定随机性；区段3、5和6钢丝绳内部钢丝磨痕尺寸总体较大.

对比图8~10可知，发现各接触位置钢丝磨痕尺寸



(a) Outer layer of outer strand in contact with core strand (b) Outer layer of outer strand in contact with outer strand (c) Outer layer of core strand in contact with outer strand



(d) Outer layer of outer strand in contact with pulley (e) Schematic diagram of measurement method of wear scar size

Fig. 7 Morphologies of wear scars of typical positions of steel wires

图 7 钢丝典型位置处磨损形貌

均在恒定张力9.2 kN时最大，这是因为弯曲疲劳次数大(见表3)导致磨损量增加，故磨痕尺寸最大. 由图8~11中的图(a)和图(d)可知，芯股与螺旋股接触时，在变张力9.7~11.0 kN时，接触钢丝磨痕尺寸均最小；与恒定张力11.5 kN工况相比，变张力9.2~11.5 kN工况分别呈现较大(小)的螺旋股(芯股)外层钢丝磨痕尺寸. 由图8~11中的图(b)和图(c)可知，与螺旋股、滑轮接触的螺旋股外层钢丝磨痕尺寸均仅次于恒定张力9.2 kN时；与螺旋股接触时，在恒定张力11.5 kN时，螺旋股外层钢丝磨痕尺寸最小；而与滑轮接触时，在变张力为9.2~11.5 kN时，螺旋股外层钢丝磨痕尺寸最小.

3.4 弯曲疲劳失效报废评估

由上可知，当弯曲疲劳次数较少时，钢丝绳均未发现断丝现象；当弯曲疲劳次数大于一定循环次数时，钢丝绳均发现断丝现象. 通过钢丝绳钢丝磨痕尺寸发现，钢丝磨痕数据庞大和统计随机性导致钢丝磨痕尺寸随弯曲疲劳次数呈不规律变化. 然而，弯曲疲劳过程中钢丝绳断丝数易于准确统计，且统计结果呈现一定规律性. 因此，选取弯曲疲劳钢丝绳断丝数作为钢丝绳报废评估标准.

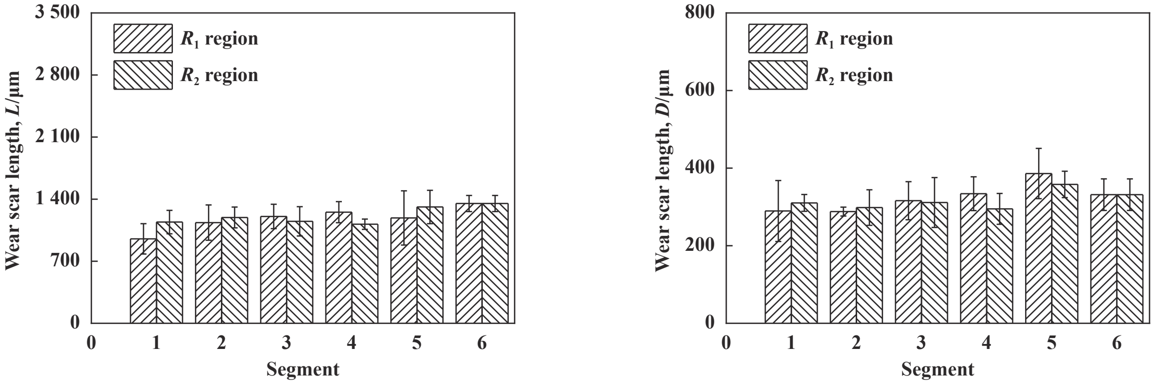
《煤矿安全规程》规定：摩擦式提升机提升钢丝绳报废年限为2年，如果钢丝绳的断丝、直径缩小和锈蚀程度不超过相关规定标准，可继续使用1年；若钢丝绳在1个捻距内断丝断面积与钢丝绳总断面积之比达到10%，则钢丝绳达到报废标准. 依据钢丝绳报废标准和表2所示的钢丝绳内部钢丝总断面积，由上文分析发现钢丝绳断丝主要发生在芯股，故当1个捻距内钢丝绳芯股断丝数达到13.7根时钢丝绳应报废. 由表2可知，钢丝绳捻距为78 mm；依据表1中各区段钢丝绳长度，区段5和6钢丝绳长度增至1个捻距时比例系数分别为1.95和6，故各区段钢丝绳实际断丝数乘以比例系数即为1个捻距长度的断丝数. 依据表4，不同试验工况时区段5和6对应的1个捻距内钢丝绳芯股断丝数见表5. 由表5可知，针对试验工况2和3，区段6钢丝绳已达到报废标准. 因此，一旦钢丝绳芯股出现首根断丝，芯股将在较小弯曲循环次数后出现集中性断丝现象，直至钢丝绳报废.

4 结论

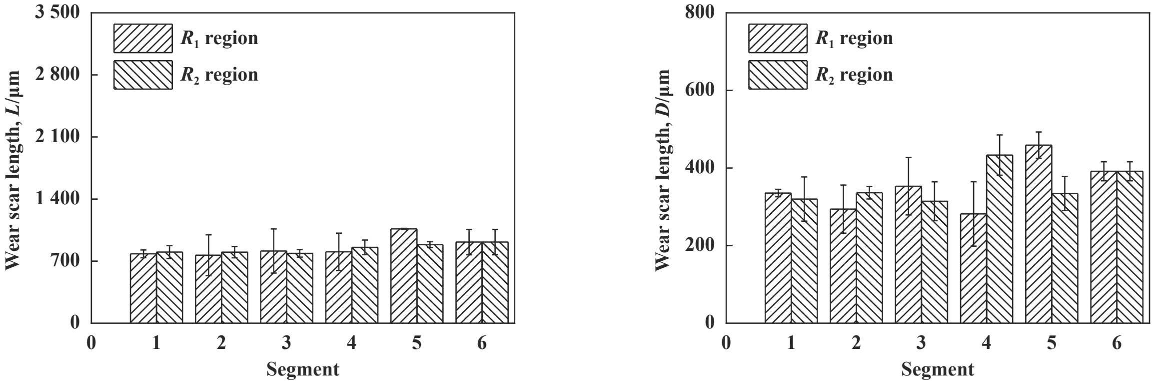
a.定载、变载弯曲疲劳钢丝绳均在芯股、螺旋股外层发生断丝现象；与定载弯曲疲劳相比，变载弯曲疲劳钢丝绳断丝出现较晚，芯股外层断丝数较多、螺旋股外层断丝数较少，芯股外层钢丝弯曲疲劳寿命较短.

b.定载、变载弯曲疲劳钢丝绳钢丝断口均包括裂纹萌生区、扩展区和瞬断区；与定载弯曲疲劳相比，变载弯曲疲劳钢丝绳钢丝断口的裂纹扩展区占比较低、挤压变形较大.

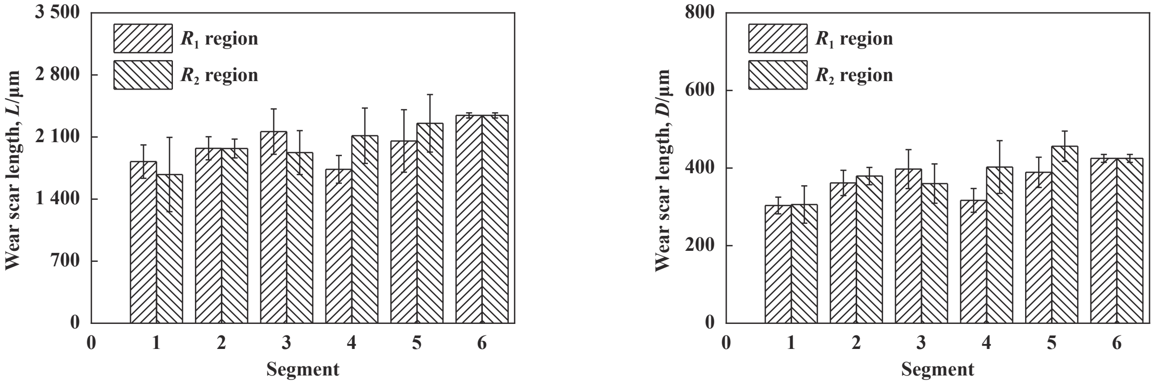
c.定载、变载弯曲疲劳钢丝绳螺旋股外层钢丝磨痕尺寸降低次序均为与滑轮、芯股和螺旋股接触处；与定载弯曲疲劳相比，变载弯曲疲劳钢丝绳不同层钢丝磨痕尺寸总体较小，钢丝绳更易达到报废水平.



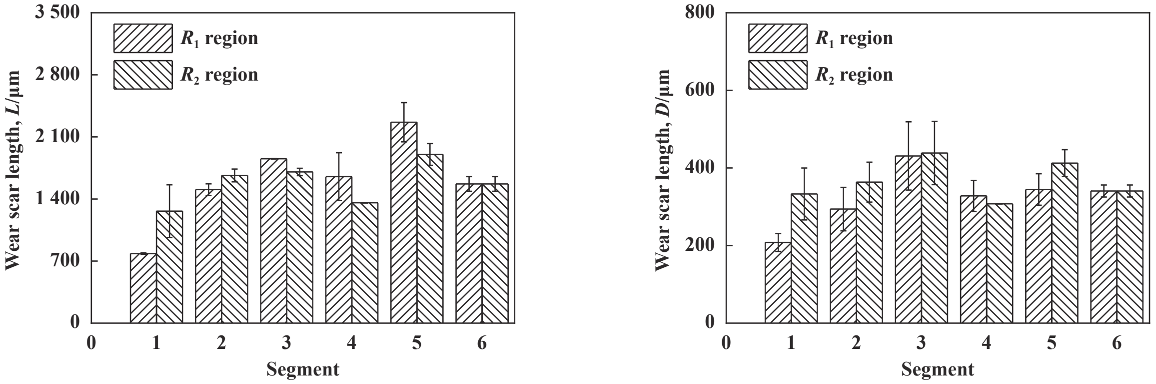
(a) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with core strand



(b) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with outer strand



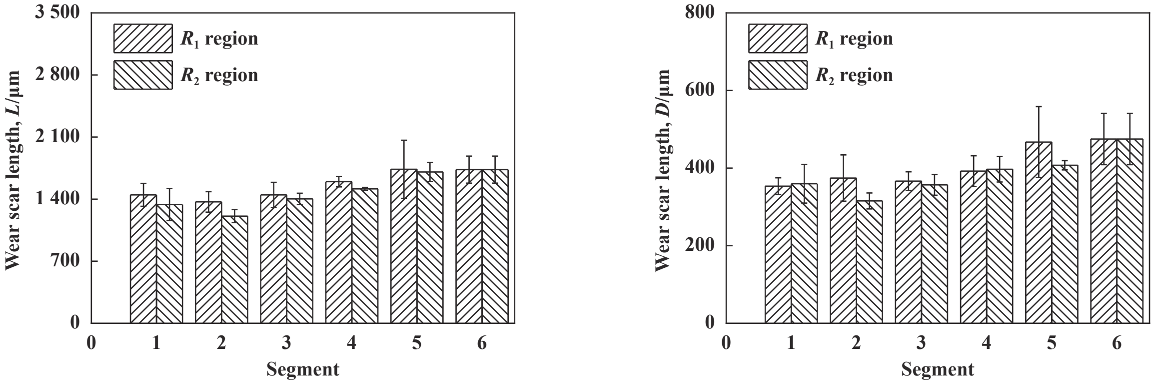
(c) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with pulley



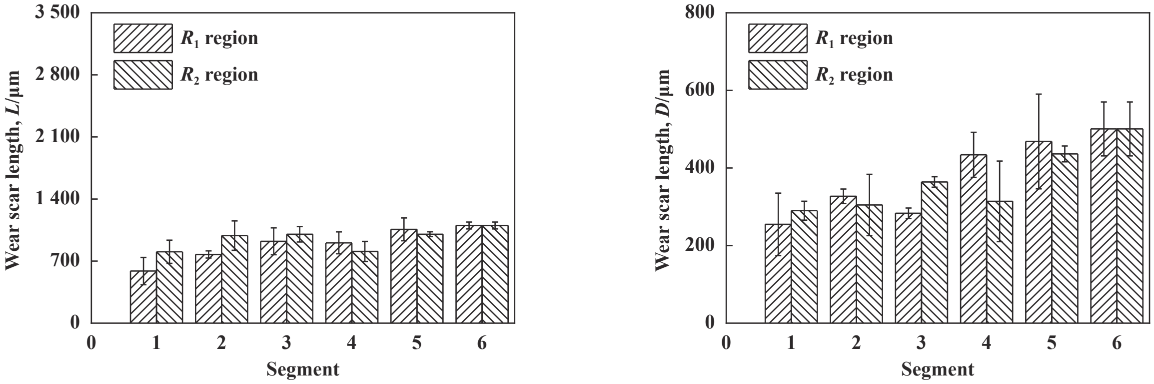
(d) Dimensions of wear scars of steel wires in the outer layer of core strand in contact with outer strand

Fig. 8 Dimensions of wear scars of steel wires in the rope in the case of constant tension of 11.5 kN

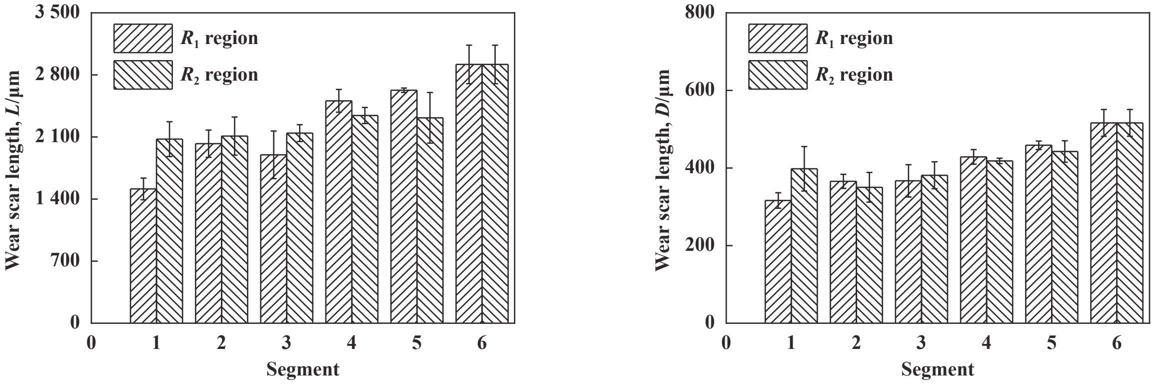
图 8　恒定张力11.5 kN时钢丝绳内部钢丝磨痕尺寸



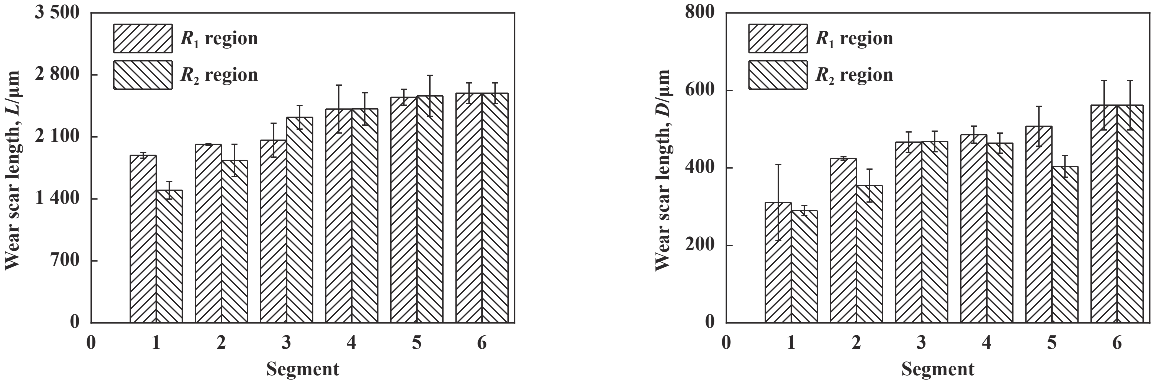
(a) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with core strand



(b) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with outer strand



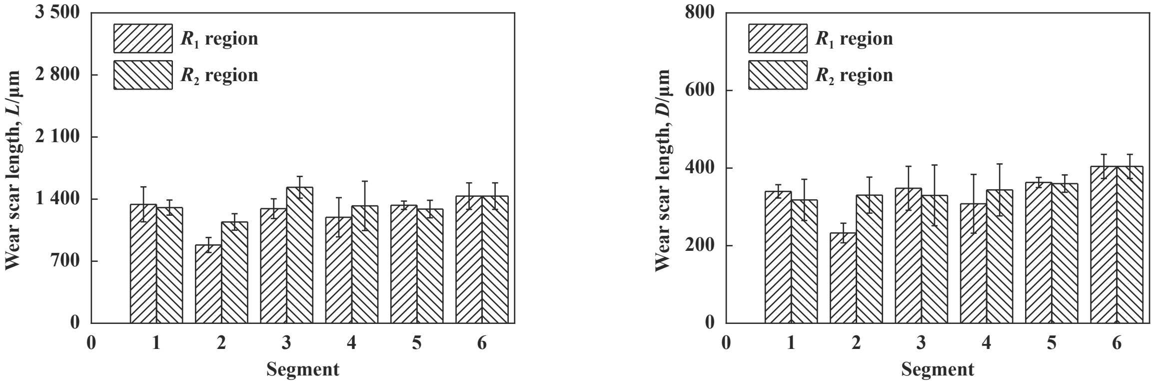
(c) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with pulley



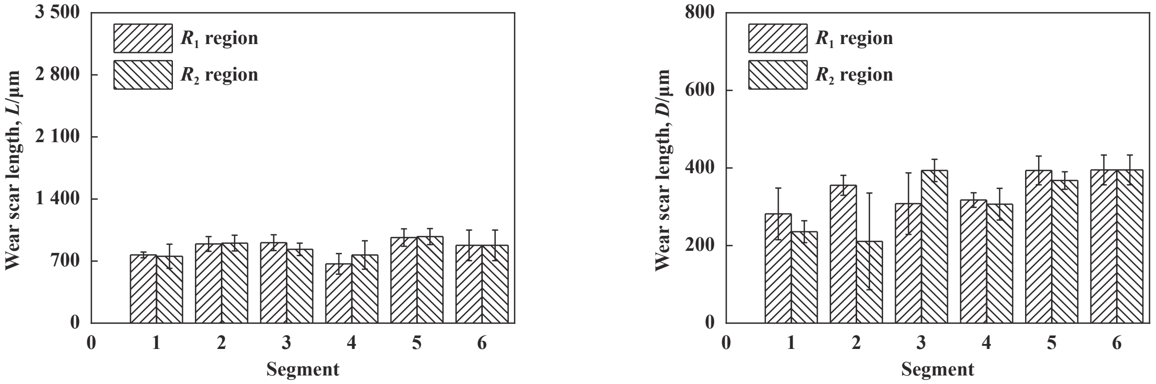
(d) Dimensions of wear scars of steel wires in the outer layer of core strand in contact with outer strand

Fig. 9 Dimensions of wear scars of steel wires in the rope in the case of constant tension of 9.2 kN

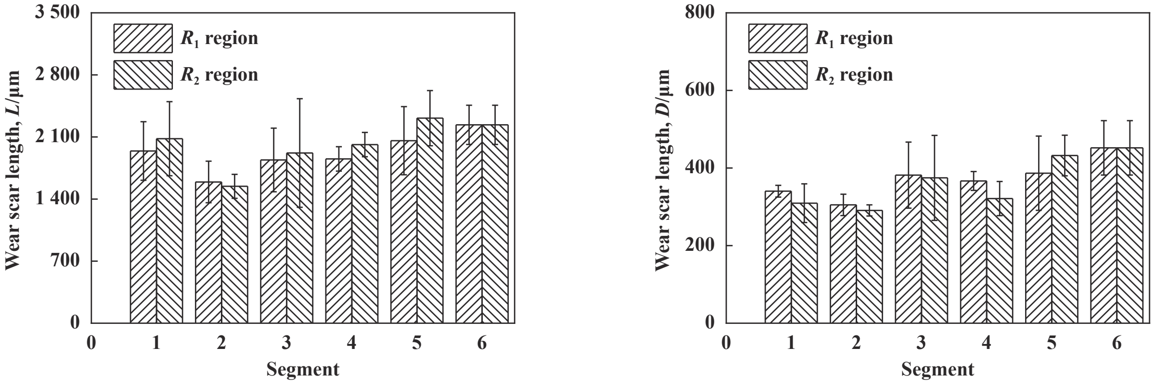
图 9 恒定张力9.2 kN时钢丝绳内部钢丝磨痕尺寸



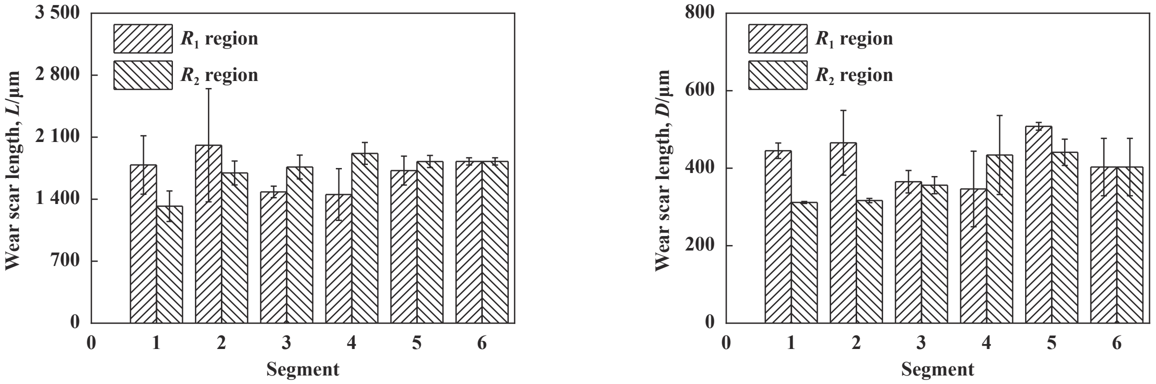
(a) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with core strand



(b) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with outer strand



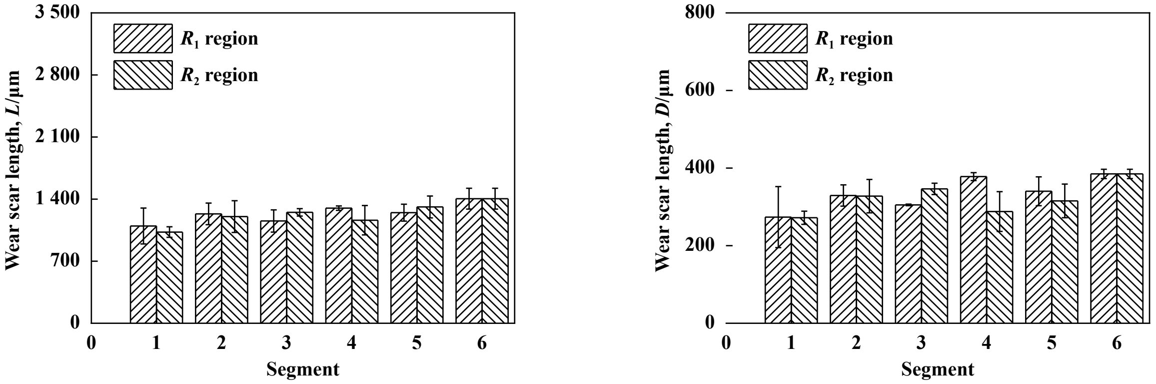
(c) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with pulley



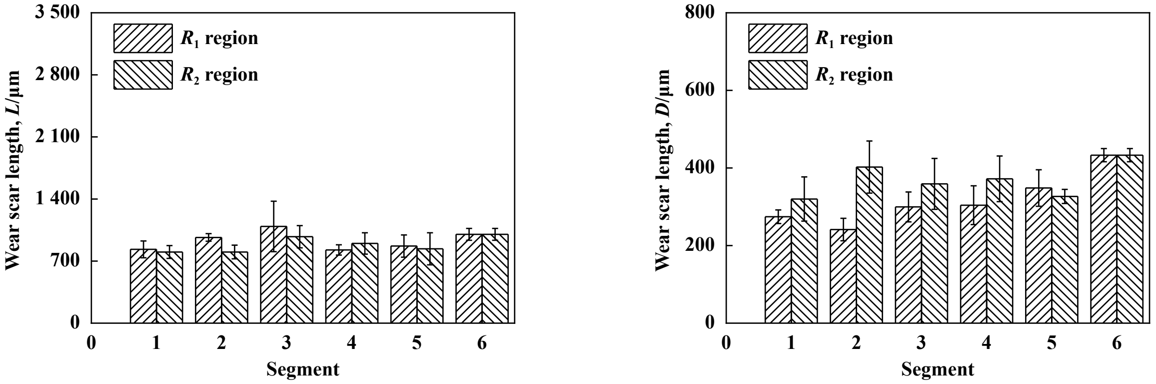
(d) Dimensions of wear scars of steel wires in the outer layer of core strand in contact with outer strand

Fig. 10 Dimensions of wear scars of steel wires in the rope in the case of variable tension of 9.2~11.5 kN

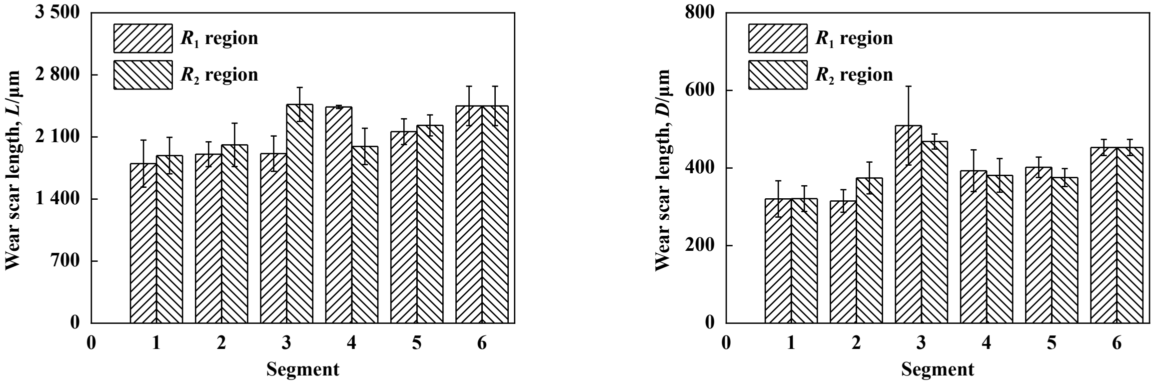
图 10　变张力9.2~11.5 kN时钢丝绳内部钢丝磨痕尺寸



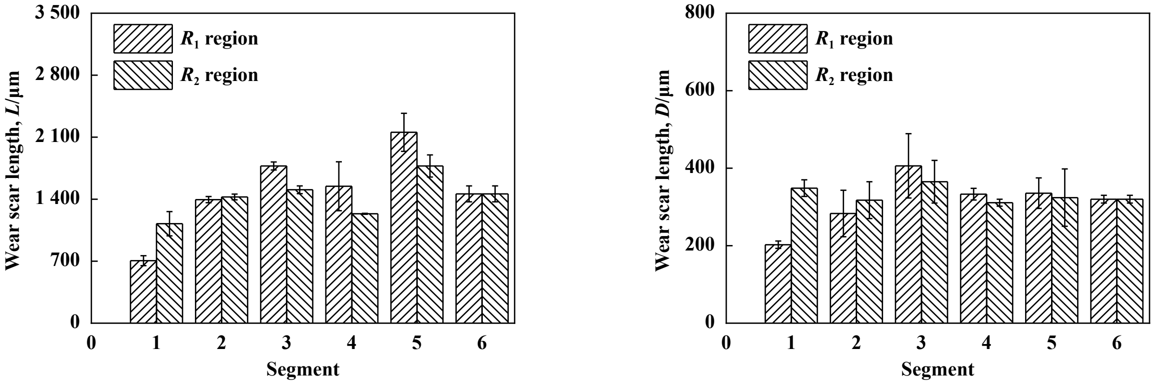
(a) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with core strand



(b) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with outer strand



(c) Dimensions of wear scars of steel wires in the outer layer of outer strand in contact with pulley



(d) Dimensions of wear scars of steel wires in the outer layer of core strand in contact with outer strand

Fig. 11 Dimensions of wear scars of steel wires in the rope in the case of variable tension of 9.7~11.0 kN

图 11 变张力9.7~11.0 kN时钢丝绳内部钢丝磨痕尺寸

表 5　不同试验工况时区段5和6对应的1个捻距钢丝绳芯股断丝数

Table 5　Number of fractured wires of core strand corresponding to a rope lay length in segments 5 and 6 under different test conditions

Specimen	Number of fractured wires of core strand corresponding to 1 rope lay length			
	Test condition 1	Test condition 2	Test condition 3	Test condition 4
Seg.5 R_1 region	0	9.75	0	0
Seg.5 R_2 region	0	3.9	0	0
Seg.6	1.95	18	18	0

参 考 文 献

[1] Zhang Jun, Ge Shirong, Wang Dagang, et al. Prediction of the safety factor of mine hoisting rope based on fretting wear[J]. Journal of Mechanical Engineering, 2019, 55(7): 110–118 (in Chinese) [张俊, 葛世荣, 王大刚, 等. 基于微动磨损预测矿井提升钢丝绳安全系数[J]. 机械工程学报, 2019, 55(7): 110–118]. doi: 10.3901/JME.2019.07.110.

[2] Wang Dagang. Study on fretting damage behaviors and fretting fatigue life estimation of steel wires[D]. Xuzhou: China University of Mining and Technology, 2012(in Chinese) [王大刚. 钢丝的微动损伤行为及其微动疲劳寿命预测研究[D]. 徐州: 中国矿业大学, 2012].

[3] Jia Xiaofan, Zhang Dekun. Bending fatigue damage behavior of bearing wire rope on different pre-tension[J]. Journal of Mechanical Engineering, 2011, 47(24): 31–37 (in Chinese) [贾小凡, 张德坤. 承载钢丝绳在不同预张力下的弯曲疲劳损伤研究[J]. 机械工程学报, 2011, 47(24): 31–37]. doi: 10.3901/JME.2011.24.031.

[4] Zhang Dekun, Feng Cunao, Chen Kai, et al. Effect of broken wire on bending fatigue characteristics of wire ropes[J]. International Journal of Fatigue, 2017, 103: 456–465. doi: 10.1016/j.ijfatigue.2017.06.024.

[5] Zhang Dekun, Chen Kai, Jia Xiaofan, et al. Bending fatigue behaviour of bearing ropes working around pulleys of different materials[J]. Engineering Failure Analysis, 2013, 33(7): 37–47. doi: 10.1016/j.engfailanal.2013.04.018.

[6] Hu Jiquan, Hu Zhengquan. Influence of load property of steel wire rope to its fatigue life[J]. Port Operation, 2005(1): 10–12 (in Chinese) [胡吉全, 胡正权. 钢丝绳受力特性对疲劳寿命的影响[J]. 港口装卸, 2005(1): 10–12]. doi: 10.3963/j.issn.1000-8969.2005.01.005.

[7] Yin Tao, Yao Ge, Yin Wanquan. Analyses of fatigue fracture of wire rope(6×19S-29)[J]. Steel Wire Products, 2001, 27(5): 14–16 (in Chinese) [尹涛, 姚戈, 尹万全. 6×19S-29钢丝绳疲劳断裂分析[J]. 金属制品, 2001, 27(5): 14–16]. doi: 10.3969/j.issn.1003-4226.2001.05.006.

[8] Yin Jikai, Li Jishun, Zou Shengyong, et al. Influence of *D*/*d* and terminal tension on bending stress and service life of steel wire rope[J]. Safety in Coal Mines, 2017, 48(1): 59–62 (in Chinese) [殷觊恺, 李济顺, 邹声勇, 等. *D*/*d*与绳端张力对钢丝绳弯曲应力和寿命的影响[J]. 煤矿安全, 2017, 48(1): 59–62]. doi: 10.13347/j.cnki.mkaq.2017.01.016.

[9] Chen Yuanpei, Meng Fanming, Gong Xiansheng. Interwire wear and its influence on contact behavior of wire rope strand subjected to cyclic bending load[J]. Wear, 2016, 368-369: 470–484. doi: 10.1016/j.wear.2016.10.020.

[10] Argatov I I, Gomez X, Tato W, et al. Wear evolution in a stranded rope under cyclic bending: Implications to fatigue life estimation[J]. Wear, 2011, 271: 2857–2867. doi: 10.1016/j.wear.2011.05.045.

[11] Onur Y A, Imrak C E, Onur T O, et al. Investigation on Bending over Sheave Fatigue Life Determination of Rotation Resistant Steel Wire Rope[J]. Experimental Techniques, 2017, 41(5): 475–482. doi: 10.1007/s40799-017-0188-z.

[12] Zhang Jun, Wang Dagang, Song Daozhu, et al. Tribo-fatigue behaviors of steel wire rope under bending fatigue with the variable tension[J]. Wear, 2019, 428-429: 154–161. doi: 10.1016/j.wear.2019.03.004.

[13] Wang Dagang, Zhang Dekun, Zhang Zefeng, et al. Effect of various kinematic parameters of mine hoist on fretting parameters of hoisting rope and a new fretting fatigue test apparatus of steel wires[J]. Engineering Failure Analysis, 2012, 22: 92–112. doi: 10.1016/j.engfailanal.2012.01.008.