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Breaking failure analysis and finite element simulation of wear-out winding hoist wire rope

Xiang-dong Chang[a,b,c], Yu-xing Peng[a,b,c,*], Zhen-cai Zhu[a,b], Xian-sheng Gong[d], Zhang-fa Yu[e,f,g], Zhen-tao Mi[a,b], Chun-ming Xu[a,b]

[a] *School of Mechanical and Electrical Engineering, China University of Mining and Technology, Jiangsu Province, Xuzhou 221116, China*
[b] *Jiangsu Key Laboratory of Mine Mechanical and Electrical Equipment, China University of Mining &Technology, Jiangsu Province, Xuzhou 221116, China*
[c] *Jiangsu Collaborative Innovation Center of Intelligent Mining Equipment, Xuzhou, China*
[d] *College of Mechanical Engineering, Chongqing University, Chongqing 400044, China*
[e] *Citic Heavy Industries Co. Ltd, Luoyang, China*
[f] *Luoyang Mining Machinery Engineering Design Institute Co. Ltd, Luoyang, China*
[g] *State Key Laboratory of Mining Heavy Equipment, CITIC HIC, Luoyang, China*

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ABSTRACT

Surface wear is the main reason for the breaking failure of the wire rope in service, particularly in the multi-layer winding hoist system of a coal mine. Understanding the effect of wear scars on the failure and mechanical properties of the rope is the effective way to ensure the safety of multi-layer winding hoist. In this paper, the breaking failure characteristics of hoist ropes with different wear scars were investigated by the breaking tensile test. The temperature rise in the wear scar regions was obtained and analyzed. Additionally, the finite element method was used to simulate the mechanical properties of the wear-out strands subjected to tensile load. Results show that the severe plastic deformation and obvious temperature rise occur in the wear scar region. The temperature rise curves during the breaking tensile test can reflect the number and the order of the fractured strands. The wear-out outer wires fracture earlier than the internal wires, and the wires with irregular wear scar always fracture along the sliding wear direction at the location with the maximum wear depth. Additionally, the wear scar caused by left cross contact will cause stress concentration and uneven distribution, and the wear depth makes it more obvious.

1. Introduction

Wire rope is a critical component of multi-layer winding hoist system because of its unique mechanical properties (high axial capability and flexibility in bending) [1,2]. It determines the mine hoist safety and hoisting capacity for the system. However, during the winding hoist, in particular for an ultra-deep coal mine, the hoisting system vibration caused by the changing vertical rope length and inertial load will result in dynamic tension of the rope at both end [3,4], which will cause severe extrusion and relative sliding between wire ropes among layers. Additionally, winding hoist wire rope always operate at high stress and almost invariable subject to fluctuating loads [5,6]. It is easy to lead to external wear and plastic deformation, the primary degradation mechanism of wire rope operating on mine hoisting drums [7], under that condition. Furthermore, as the wire rope winds on and off drums in the process of

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[*] Corresponding author at: School of Mechanical and Electrical Engineering, China University of Mining and Technology, Jiangsu Province, Xuzhou 221116, China.

E-mail address: pengyuxing@cumt.edu.cn (Y.-x. Peng).

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hoisting, this degradation will occur periodically and be accelerated, which seriously affects its mechanical properties, reduces the service life and ultimately leads to breaking failure of the rope [8]. Moreover, to reduce the effects of the wear on the safety use for wire ropes, the number of winding layers on the drum is limited to two layers according to the coal mine safety rules in China [9], which will cause the increase of the drum size for the winding equipment and hinder the development of resource exploitation in the ultra-deep coal mine. Therefore, it is of great importance to investigate the effects of the surface wear on the breaking failure behaviour and the mechanical properties for the winding hoist wire rope, which contributes to the reasonable use of the wire rope and provides the basis for the design of the multi-layer winding hoist in ultra-deep coal mines.

Several studies have been conducted on the related characteristics of the wire rope by others in the past decades. As the wear is one of the main reasons for the failure of the wire rope, Zhang et al. [10] investigated the fretting wear and fatigue mechanisms of the steel wire in hoisting rope through experiments and found that the wear mechanism depends on the contact loads. Wang et al. [11,12] researched the effects of different contact conditions on the fretting fatigue damages of the mine rope wires in different corrosive media. The results show that the fretting damage and crack nucleation accelerate with increasing displacement amplitude. Additionally, the effect of the terminal mass on the fretting parameters during a lifting cycle was also analyzed [4]. Cruzado et al. [13,14] studied the effect of contact pressure and crossing angle on the fretting wear scar and the coefficient of wear for thin steel wires. The finite element method was also used to simulate and predict the variation of the wear scars in the fretting regions [15,16]. They found that the wear occurring in the steady state period is rather mild. Furthermore, to analyze the failure behaviour of the wire rope, Chaplin et al. [5,17] analyzed the failure mechanisms of the hoisting wire rope in different applications, which is important in realising the potential rope life. Considering the specific working conditions of multi-layer winding hoist, Rebel et al. [7] discussed the influence of different winding hoist parameters on the rate of rope deterioration, which will aid in the design of winding system due to a better understanding of the key factors that influence rope performance on multi-layer drums. Mahmoud et al. [18] determined the fracture strength of a cracked suspension bridge wire based on liner elastic fracture mechanism and presented a case study for a group of in situ wire breaks retrieved from a suspension bridge cable. Singh et al. [6] carried out detailed research for the causes of failure of two wire ropes from two different Indian underground coal mines. Different damage parameters (wear & corrosion, lubrication, macro & micro-examination and chemical composition) were also investigated and found that the excessive wear and corrosion are the major causes of failure. Peterka et al. [19] researched the reason of the steel rope damage in a hoisting system. The analysis found that the upper wires of the rope with different strength grades will lead to different deformation of the wires and the development of fractures at the weaken places. Piskoty et al. [20] emphasised the importance of making a broad collection of hypotheses at the beginning of failure investigations and presented four case studies of structural failures, where the failed load carrying structure was based on wire rope (steel cables). Additionally, the experience made by a failure analysis is recallable and applicable for different kinds of failed systems. Additionally, Karabay et al. [21] investigated different wire damages and defects during different processing steps of aluminum conductor production and explained the early failure reasons. Yu et al. [22] proposed a theoretical approach and a finite element method model to calculate recovery length and the force redistribution mechanism in a semi-parallel wire cable with broken wires. They found that the twist angle and position of the broken wire will affect the recovery length.

As the safety use and service life of the wire rope are the most important things in different applications, Giglio et al. [23] established two analytical models to investigate the stress and strain of a wire rope subjected to axial and bending loads. The results are in close agreement with the experimental results obtained, which make it possible to reliably predict the fatigue life of a wire rope. To study the defective strand inside the internal structure of a multi-wire rope, Raišutis et al. [24] investigated the propagation of ultrasonic guided waves (UGW) along multi-wire ropes with polymer cores and developed an ultrasonic testing technique to identify defective strands inside the rope, which is sufficient reliability for practical. Zhao et al. [25] analyzed and calculated the fatigue life of a wire rope based on the theory of stress field intensity and linear fatigue cumulative damage theory. Then, the theoretical value was compared with the experimental value and they are close to each other in the fatigue cycle. Additionally, taking into account the complex structure of the wire rope and the high cost (time and economic) for the experimental investigation, the finite element method (FEM) was widely used to study the related characteristics of the wire rope. Lalonde et al. [26,27] proposed a FE modelling strategy for multilayered stands and used this model to study Aluminum Conductor Steel Reinforced (ACSR) subjected to wind-induced loads. The results indicate that fatigue prediction from the Coffin-Manson relation associated with the FE model provide realistic evaluations of service lives. Stanova et al. [28,29] presented the geometric models of the single-lay wire strands and double-lay wire ropes with defined initial parameters and the model was used to predict the strand's behaviour under tensile load through a finite element program. Then, mechanical behaviour of the spiral triangular strands and oval strands under axial loads were also analyzed [30,31]. Wang et al. [32,33] explored the fretting fatigue parameters and stress distributions of the hoisting rope and three-layered strand using the finite element method. They established the relationship between the crack propagation life of steel wire and the initial fretting wear depth and found that the relative displacement is easier to cause crack initiation compared to contact load. Furthermore, considering the effects of the contact condition and lateral loading behaviour on the local stress distribution and lifetime performance, Yu et al. [34] developed a serial 3D FE model of a seven-wire stand to discover the interface mechanism under longitudinal and lateral loading. They found that lateral loading can lead to uneven stress distribution and micro slip mainly occurred between helical wires. Kastratović et al. [35] created the suitable finite element model of the wire rope and investigated its mechanical behaviour with special emphasis on different types of contacts and different types of axial loadings, which provide a better understanding and prediction of the mechanical response for the sling wire ropes. Prawoto et al. [36] performed a study on the failure mechanism of wire rope using both numerical and experimental approaches. Further, they found that the wire rope failure models involved shearing in addition to regular necking. However, from the literature mentioned above, previous efforts focus mainly on the wear characteristics of rope wires, failure behaviour of the service wire rope and the finite element analysis for