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Effect of wear scar characteristics on the bearing capacity and fracture failure behavior of winding hoist wire rope

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ABSTRACT

Surface wear is an inevitable damage of wire ropes used in winding hoist. It always reduces the service life of the wire rope and threatens the mine safety. The characteristics of the surface wear scar caused by sliding contact between ropes were discussed in a quantitative and qualitative method for this paper. A series of breaking tensile tests were carried out to investigate the effects of the wear characteristic parameters on the bearing capacity of the rope. Furthermore, the fracture failure behaviors of the rope with different wear scars were analyzed. Results show that the wear scar changes from distributing on one strand to evenly distributed on two adjacent strands as the sliding wear position changes from the strand peak to valley. When the wear region concentrates on one strand, the maximum wear depth increases from approximately 0.46 mm to approximately 0.64 mm with the increase of wear area. Broken wires seriously affect the elongation and breaking force of the rope. The maximum breaking force is approximately 42 KN and the maximum local elongation is approximately 1.5 mm under the condition of broken wires. Additionally, the external wires of the strand are easier to fracture caused by torsion and tension together. Furthermore, the shear lip and the fibre region on the fracture surface of the wires become not very obvious with the increase of the wear scar parameters.

1. Introduction

With a shortage of global resources and energy, exploring more deeply into the earth for mineral resource has become an important strategic choice in China [1]. Because of the limitation of the multi-rope friction hoist in hoisting height (the maximum height is 1700 m), multi-layer winding hoist has become the most suitable lifting equipment for ultra-deep coal mines (the hoisting height is more than 2000 m) [2–4]. Additionally, wire rope is a key part of the mine hoisting system because of its high strength-to-weight radio, great flexibility and compactness [5,6]. Therefore, the performance of the wire rope determines the safety level of a coal mine hoisting. However, considering the system vibration and repeated bending of the rope in the winding hoist process, there is serious extrusion contact, relatively sliding and torsion fatigue between the wire rope in different layers, in particular for the ultra-deep coal mine [7,8]. Then, it will cause severe plastic deformation and surface wear, which are the primary degradation mechanisms for the winding hoist wire rope and determine the service life [9,10]. Moreover, according to the coal mine safety rules in China [11], in a vertical shaft, the number of winding layers of the rope on the drum must be no more than two layers. This severely limits the application of the multi-layer winding hoist in deep coal mines. The reason is also that the wear characteristic and its effect on the degradation of the rope performance have not been understood. Therefore, it is significant to explore the characteristics of surface wear scars and conduct studies about the effect of wear parameters on the bearing capacity and breaking failure behaviors of the rope, which could be helpful for the safety use and maintenance of the wire rope, then prolong its service life.

In the past, several studies on the related performance of wire ropes have been conducted by other scholars. Considering the damage of fretting fatigue between the internal wires, Wang et al. [12]

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investigated the fretting fatigue behaviors of steel wires under different displacement amplitudes. The results show that the fretting damage accelerates with increasing displacement amplitude. Additionally, the wear parameters of wires were measured and quantitatively analyzed [13]. Cruzado et al. [14–17] explored the effects of contact load and crossing angle on the fretting of thin steel wires through experiments. Then, to reduce the economic cost and experimental time, a simulation method was developed, which can accurately predict the wear scar parameters. Furthermore, Zhang et al. [18] researched the characteristics of the fretting fatigue for wires under different crossing angles and found that surface wear is more serious under the crossing angle of 90°. Wang et al. [19] studied the fretting fatigue behaviors of steel wires under tension and torsion loads. They found that the wear scar becomes large with the increase of torsion angle. Due to the working condition of hoisting wire rope is very complex, McColl et al. [20] explored the fretting wear properties of wires under different lubrication conditions. Xu et al. [21] researched the fretting wear behaviors of hoisting rope wires in acid medium and found that the wear depth is larger in the acid medium than that under dry-friction condition. To quantitatively analyze the effect of corrosive media on anti-wear properties, Wang et al. [22] investigated the effects of three corrosive media on anti-wear properties of steel wires and found that the anti-wear property is better in the high-pH corrosive media. Considering the sliding contact between wire ropes and rollers, Oksanen et al. [23,24] described the wear characteristics between the roller and the wire rope in laboratory and in-service conditions. The wear mechanism and fatigue cracks were analyzed. However, the structure of the rope is complex and contact forms are diversified. To investigate wear properties between ropes, Peng et al. [1,25] studied the sliding friction and wear characteristics between ropes under cross contact and winding contact.

As the spiral structure of the wire rope determines its complex mechanical properties, many scholars have presented theoretical methods to calculate the response of wire ropes [26,27]. Additionally, Wang et al. [6] presented a brief parameterized modelling method for rope wires and strands. Wu et al. [28] developed a mechanical model for the wire rope to accurately calculate the deformation and elongation of ropes under known tension. To compare the experimental and theoretical results, Onur et al. [29] explored the mechanical characteristics of rope strands subjected to tensile load through theoretical calculation and experimental analysis. The results show that outer wires suffer greater strain and stress values in the direction of wire axis than in the direction of strand axis. Furthermore, based on the strong simulation ability of the finite element (FE) method, Stanova et al. [30–33] established mathematical geometric models and finite element models for wire ropes and strands with different shapes. The mechanical behaviors of the rope and strand subjected to different axial loads were analyzed. Moreover, the three-dimensional finite element model was also used to study the mechanical properties of wire ropes used in different working conditions [34,35].

The reasons for the degradation of the rope performance vary from service conditions. To understand the failure behavior of the ropes, Chaplin [2] and Schrems et al. [36] analyzed the working condition and degradation characteristics of the mine hoist wire rope. Performances of in-service ropes with different damages were investigated using a series of experiments. Mahmoud et al. [37] analyzed the broken wires obtained from an in service bridge cable and the carrying capacity of the cable was estimated. Peterka et al. [38] conducted many mechanical tests to explore the evolution of the wire rope used in real hoisting conditions and understand the cause of damage after a short period of use. Singh et al. [10] provided a brief review on failure behavior of the wire rope and presented two case studies of failed wire ropes used in two different Indian coal mines. Additionally, Urchegui et al. [39] and Zhang et al. [40] investigated the wear evolution and bending fatigue life of wire ropes by a series of bending fatigue experiments. Then, the effects of the broken wire on the degradation characteristics were analyzed. Furthermore, in order to explore the wear degradation of wire ropes better, Argatov et al. [41] presented the Archard's wear law based mathematical model of fretting wear between wires to estimate the fatigue life for the wire rope. Then, to investigate the effect of fretting wear on fatigue fracture properties of the steel wire, Wang et al. [42] established the relationship between the crack propagation life and the initial fretting wear depth of steel wires. Moreover, Zhao et al. [43] predicted the fatigue life of wire ropes based on the theory of stress field intensity and liner fatigue cumulative damage theory. However, the previous studies focus mainly on the fretting wear behavior of steel wires, the mechanical properties and the failure mechanisms of ropes and strands under different service conditions. The sliding wear scar characteristics on the rope surface and the effects of the wear properties on the bearing capacity and breaking failure behaviors for the hoisting wire rope have not been developed yet.

Therefore, the aim of this article is to quantitatively and qualitatively analyze the surface wear scars of the wire rope and investigate the relationships between the wear characteristics and the fracture failure behaviors. The morphology distribution and characteristic parameters of the wear scars were obtained using optical microscope and the confocal three-dimensional contour measuring instrument (SM-1000), respectively. The mechanical response of the damaged wire ropes was analyzed by breaking tensile experiments, which were conducted in a tensile testing machine (ZCGD-W100KN). Additionally, the fracture behavior and the wear defect of wires in the breaking location were investigated by the scanning electron microscopy (SEM). Moreover, all the work is meaningful for enhancing the utilization efficiency of the wire rope and improving the operational reliability of the winding hoist.

2. Experimental details

2.1. Wire rope samples

The research object of this paper is the wear-out 6 × 19 + FC (fibre core) wire rope. Fig. 1 presents the wear test rig and the rope sample. The test apparatus can realize the reciprocating sliding between wire ropes under different contact loads, strokes, velocities and crossing angles. Additionally, the surface wear scars on the rope samples studied in this paper were caused by the wear tests from the previous work [44]. The detailed parameters of the tests were listed in Table 1. The crossing contact can reflect the multi-wire and multi-strand contact behaviors of the wire ropes and the sliding parameters are easier to be controlled under the crossing angle of 90°, which is better to investigated the effects of the parameters on the wear properties of the wire rope and provide reference for the multi-layer winding hoist. Thus, the sliding contact form of the wire ropes was simplified, as shown in Fig. 1c. The two wire ropes, lower sliding rope and upper loading rope, contact with each other with the crossing angle of 90° and complete the reciprocating sliding. Then, different surface wear scars were obtained by adjusting the contact parameters (stroke and velocity). Additionally, more detailed introduction about the friction experiments and the rope sample parameters can be found in literature [1,4,44]. Furthermore, the upper loading ropes with the wear scar were selected to investigate, as shown in Fig. 1d.

2.2. Test procedure and analysis methods

To study the influence of the wear on the rope performance, the characteristics of the wear scar were analyzed quantitatively and qualitatively. Fig. 2 shows two typical contact locations and wear scars. It can be seen that the rope surface is very complex, which contains several spiral strands and the strand valleys and peaks appear alternately, as shown in Fig. 2a. Therefore, the wear scar changes from concentrating on one strand to evenly distributed on two adjacent strands gradually when the contact region changes from the peak to the valley, as shown in Fig. 2b and c. Additionally, the wear regions can be