Using Wolfram-Doped Diamond-Like Carbon Film to Extend Lifetime of Spinneret Punching Needle in Production Line

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Abstract. Punched by needle, spinneret is a critical component of chemical fiber production equipment. Increasing order and short lifetime of punching needle seriously drags the production schedule of enterprise. W-DLC (wolfram-doped diamond-like carbon) film was deposited on the needle in a magnetron sputtering system, and the doping content of wolfram was controlled by adjusting the ratio of Ar to C2H2. A systematic investigation was conducted on the structural and punching performances of the coated needle. The results show that, (1) W-DLC film has a dense structure, and W element exists in phase of W1.5C. (2) W-DLC film plays an important role of the needle protection, and can prolong its lifetime in evidence. (3) W-DLC film coated punching needles can punch up to 6000 times per needle, and its lifetime can be increased to about 200% in the production line.

1. Introduction

Being as spinneret manufacturer, Beijing Huayu Innovation Tantalum Niobium Technology Company is suffering from punching needle trouble. The spinneret order shows an increasing tendency. But the short lifetime of punching needle seriously drags down the enterprise’s production progress. The production line data indicates that, each punching needle can produce at most one spinneret (about 2000 punching pores), and then can’t be used. Beijing Huayu Company has a large usage of the needle, more than 4000 needle each day. The needle manufacturing process is complex, and depends on pure manual operation to ensure the needle accuracy. Even the most skilled craftsmen can only grind nearly 200 per day. Such large usage and slow preparation efficiency of the needles make the production delay a lot. In addition, changing the punching needle in the production line requires rigorous test and replacement procedure, and slows down the production schedule. These two predicaments jointly urge the company to have an urgent demand for improving the punching performance of the needles.

With a good application prospect, DLC film contains both sp²-C and sp³-C hybrid carbon bonds, and has both good properties of diamond and graphite. But DLC film also has two inherent drawbacks of poor stability and high internal stress [1]. Three main methods for the improvement are element doping, applying gradient transitional layer and constructing multilayer structure. Recent attention has drawn on the element doping to modify DLC film. One typical research [2] indicated that, W (wolfram) element doping can partly reduce the residual stress and improve the friction properties and hardness of the film.

This work is intended to extend the lifetime of the needle through depositing W-DLC carbon film on the surface of the needle. The W-DLC film is deposited on FAX38 sheets and punching needles in a
magnetron sputtering system, and the doping content of wolfram is controlled by adjusting the ratio of Ar to C$_2$H$_2$. A systematic characterization like X-ray diffraction is conducted to detect the structure of W modified DLC film. Also, the punching performances of uncoated needles and coated punching needles were compared in a field test, and the failure of uncoated needles is analyzed.

2. Experiment Part

2.1. Through Pore and Punch of Spinneret

Spinneret is a critical component for the chemical fiber spinning. The surface of spinneret has regular and uniform micro-pores, and the size and arrangement of pores directly affect the structure and properties of the drawn chemical fiber. Figure 1 shows sale champion product of Beijing Huayu Company, hat-shaped tantalum spinneret. Production requirements for this spinneret include surface roughness (about 0.059 μm), hardness (600-700 HV), and finish degree (about 12).

![Figure 1. Physical drawing of tantalum spinneret.](image)

Figure 2 shows the perforating procedure for the spinneret. As shown in Figure 2(a), the perforating procedure can be divided into two steps, the through pore and the punch pore. First step, the bottom surface of the spinneret is polished to form a micro-conical pore; Second step, a high-speed steel needle is used to stretch and shape the micro-tapered pore. Figure 2(b) shows an automatic device used in the production line for needle punching. As shown in Figure 2(b), the punching needle and the spinneret are respectively fixed at the upper and lower ends of the device; the position of the punching needle is controlled by a computer, and the punching needle is punched vertically downward within a controllable frequency. Accordingly, uniform distributed pores with the same size are punched on the spinneret surface. Figure 2(c) shows the micro-pores section of the spinneret after punching. The final shape of the micro-pores is composed of a conical pore formed by a through pore and a straight pore formed by a punching pore. The purpose of this work is to prolong the service life of punching needles and to improve the punching performance of needles in the production line.

![Figure 2. Punch program of spinneret (a) through pore and punch sketch, (b) physical drawing of automatic punch, (c) pore section sketch.](image)
2.2. Film Preparation

W-DLC film was deposited on the substrate in a magnetron sputtering system [3]. FAX38 high speed steel sheets and punching needles were selected as the substrate. The substrate was pretreated to improve the nucleation density and uniformity. The substrate was mechanically polished to a mirror state (surface roughness about 0.2 μm), then dipped in anhydrous ethanol for 30-min ultrasonic bath. After drying with clean nitrogen, the substrate was put into a vacuum chamber ready for deposition.

Table 1. Main deposition parameters of W-DLC film

| Sample | Deposition time/min | Pressure/10⁻¹ Pa | Ar flow/sccm | C₂H₂ flow/sccm | W target current | Bias voltage/V |
|--------|---------------------|------------------|--------------|----------------|-----------------|----------------|
| a      | 60                  | 7                | 320          | 260            | 21              | 110            |
| b      | 60                  | 7                | 340          | 240            | 21              | 110            |
| c      | 60                  | 7                | 360          | 220            | 21              | 110            |

The distance between the substrate and the cathode target was adjusted to 200 mm. Pumping down to base vacuum of 2*10⁻³ Pa, introduced Ar (argon) gas for a glowing clean, and let C₂H₂ gas in for film deposition. Table 1 lists the main parameters of magnetron sputtering for W-DLC films. As can be seen from Table 1, the doping amount of W element was realized by adjusting the ratio of Ar gas to C₂H₂ gas. Total gas flow was constant (about 580 SCCM), and the flows of Ar and C₂H₂ gases were adjusted to vary W doping content of W-DLC films.

2.3. Surface Analysis Method

The surface performance, composition and structure of the films, and the punching performance of the needles were investigated. The valence bond structure and doped elements of the films were detected using FT-Raman Spectrometer and X-ray diffraction (XRD), respectively. The punching performance of the films was evaluated using Automatic Punching Machine in a field test in the production line, and the punching performances of the coated and uncoated needles were compared.

3. Results and Discussion

3.1. Bonding Structure and Doping Elements of W-DLC Films

Figure 3 shows the Raman spectra of the DLC films and the W-DLC films. There is an asymmetric peak near 1550 cm⁻¹. After Gaussian Function fitting, the Raman spectra of the DLC film have two characteristic peaks, D peak around 1329 cm⁻¹ and G peak around 1599 cm⁻¹. And the Raman spectra of the W-DLC films shows that D peak is around 1353 cm⁻¹ and G peak around 1594 cm⁻¹. The shift of G peak to a lower number indicates a decrease in the residual stress of the film [4]. This suggests that wolfram doping can reduce the internal stress of DLC film.

![Figure 3. Raman spectra of (a) DLC film and (b) W-DLC films.](image)

On the other hand, the I_D/I_G ratio of the DLC film is 0.96, and the I_D/I_G ratio of W-DLC films is 1.91 which is bigger than that of the DLC film. We can learn that the structure disorder of DLC film is
reduced, and the content of $sp^2$-C is increased by doping wolfram. Moreover, the doping of wolfram may promote the release of film stress and the enhancement of film-based bonding strength [5].

![Figure 4. XRD patterns of W-DLC films.](image)

Figure 4 shows the XRD patterns of W-DLC films. There are three strong absorption peaks, and these peaks indicate that the doped W atoms exist in the form of $W_{1-x}C$ phase in the carbon-based amorphous network [6]. The peaks appear at $37.8^\circ 2\theta$ and $44.1^\circ 2\theta$ represent W atoms exist in the form of WC phase, and $72.5^\circ 2\theta$ represents W atoms exist in the form of $W_2C$ phase. As a result, W atoms exist in the form of $W_{1-x}C$ phase in the DLC film, and such structure is favorable for obtaining good mechanical properties of the films [7].

3.2. Field Test in Production Line
The performance of coated punching needle is measured by a field test in actual production line of Beijing Huayu Company. Figure 5 shows the automatic optical image coordinate measuring instrument. The automatic optical image coordinate measuring instrument shown in Figure 5 is used to inspect whether the coated punching needle meets the punching requirements of production line, including the diameter and finish of the punching needle. Only the needle passing the inspection can conduct the field test in the production line. Figure 6 shows the automatic positioning punching instrument. The automatic positioning punch as shown in Figure 6 is used to carry out the punch test in production line. By setting the punching speed and punching position, the surface punching of spinneret is carried out, and the service life of the coated punching needle is measured.

![Figure 5. Automatic Optical Image Coordinate Instrument.](image)

![Figure 6. Automatic positioning punching machine.](image)

The field test is to test the number of spinnerets that each punching needle can punch to determine the punching times of punching needles. There are about 2000 micro-pores on each spinneret. Three spinnerets can be completely punched with one coated punching needle, and the field test result is 6000 pores per needle. As a result, the field test result of coated punching is about 6000 pores per needle. Compared with 2000 pores of uncoated needle, the production efficiency can be increased by 200%. 

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3.3. Comparison of Punching Performance

We can measure the punching performance by comparing the punching performance of coated punching needle with uncoated punching needle. Choose these two punching needles with the same punching times (2000 times), and use three different magnification SEM image to make contrast observation. Figure 7 shows the SEM image of coated punching needle and uncoated punching needle after 2000 times punching tests. At 100 μm scale, the surface of both needles is smooth and the diameter meets the punching requirements. At 10 μm scale, the needle tip of the two punching needles was worn out each for 2000 times. But the coated punching needle was smoother and more completed than that of the uncoated needle. At 2 μm scale, the needle body of two kinds of punching needle has worn each. The needle body of the uncoated punching needle appears large scratches, which cannot meet the punching requirements. The needle body of the coated punching needle still meets the requirements of the punching finish and aperture due to the protection of the film layer. In this way, we can see that the surface of the DLC film coated with wolfram is smoother than that of the uncoated film, and has a better wear resistance. The test results show that the service life is increased because of the existence of the film, and the production efficiency can be increased to about 200%.

4. Conclusion
The W-DLC film was deposited on steel substrates in a magnetron sputtering system. The valence bond and doping element structure of W doped diamond films were characterized by Raman and XRD. The lifetime of coated and uncoated needles was compared by field experiments. The results show that:

(1) W-DLC film deposited by magnetron sputtering are dense and uniform, with high bond strength and low residual internal stress. W element exists in the film in the form of W1−xC, and the structure is stable.

(2) W-DLC film plays an important role of the needle protection, and can prolong the needle lifetime in evidence.

(3) The field test results show that the W-DLC film coated punching needles can punch up to 6000 times per needle, and the lifetime of punching needles can be increased to about 200% in the production line.

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