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Friction and Wear Behavior of Wear-Resistant Belts in Drill Joints for Deep and Ultra-Deep Wells

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The friction and wear of an new material for the drill joint were compared with those of traditional wear-resistant belt materials using an SD-1 test rig against a 42Mn2V steel counterface under deep and ultra-deep well conditions. This provides recommendations as to the tribological application of the wear-resistant belt. The results obtained strongly indicate that the friction and wear of a polycrystalline diamond (PCD) composite are much lower than those of the traditional wear-resistant belt materials. Among those materials, the friction and wear behavior of a FeNiNb alloy are higher than those of a FeCrMnMo alloy. Of the three wear-resistant belt materials, the bilateral protection performance of a PCD composite is the best one. It is feasible to use this composite as the wear-resistant belt material in the drill joint for deep and ultra-deep wells. The dominant wear mechanism of the wear-resistant belt materials is the microcutting wear, accompanied by the adhesive one. In addition, the wear degree of the PCD composite is the least one.

Keywords: friction, wear behavior, wear-resistant belt, drill joint, polycrystalline diamond.

Introduction. Along with the sustainable development in the oil-gas exploration area and the progress of the modern science and technology, the deep and ultra-deep well technology rises continuously. Moreover, the application in the deep and ultra-deep well technology has been expanding gradually, especially the application of the wear-resistant belt in drill joint [1–4]. During the drilling process of a great number of deep and ultra-deep wells, the causing heavy loss made by the casing wear and drill-pipe wear problems are serious, which would bring forward higher requirements to the wear-resistant belt material in drill joint [3–5]. To improve performance, high-performance protective materials have been researched and developed [6–8]. With the depth of drilling increase, the wear problem of drilling tubulars gets more urgent. Consequently, the research on new wear-resistant belts is needed.

The wear-resistant belt in drill joint provides a bilateral protection feature, and its properties are key factors that affect its bilateral protection function. It can reduce not only the casing wear, but also the drill-pipe wear. Polycrtystalline diamond (PCD) is a wear-resistant belt material with excellent properties. It can not only increase the strength of the drill pipe, but also reduce the casing wear [9]. In our previous study, a new wear-resistant belt was made from a PCD enforced composite by the pressureless infiltration method in order for the drill pipes to successfully use PCD [8–11]. As wear-resistant belt material, the properties of the PCD enforced composite were excellent. The wear resistance and the life of drill pipe are enhanced, and the casing wear is also reduced.

During the drilling of the deep and ultra-deep well, downhole instance is complexity, and drilling time is longer. However, little research has been done under this condition. It is not clear that the new wear-resistant belt could also display the superior performance under the deep and ultra-deep well condition. Thus, the friction and wear performance of this PCD enforced composite need to be investigated, which is important to the study of the deep and ultra-deep well wear technology (see Fig. 1).

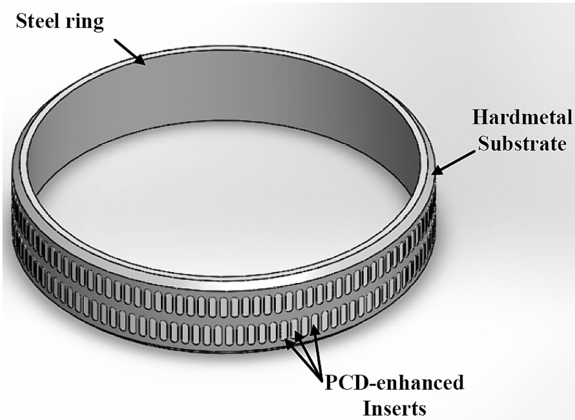

Fig. 1. Schematic description of the PCD composite ring.

1. Experimental Details.

1.1. Preparation of Drilling Fluid and Specimen. In this study, drilling fluid was prepared according to the actual working state, the composition of which is shown in Table 1. Apparent viscosity is 38.75 mPa·s, plastic viscosity is 10 mPa·s.

The wear-resistant belt materials were prepared with PCD composite and other two wear-resistant belt materials included a FeCrMnMo alloy and a FeNiNb alloy, which are widely used. The PCD composite was made by pressureless infiltration. The detailed fabrication process of this composite can be found in our published articles and granted patents [8–11].

Table 1

Composition of Drilling Fluid

Compound	Content (wt.%)
Bentonite	2
CMC viscosifier	0.25
XC	0.25
Sand (30~40 mesh)	10

The casing materials were prepared with 42Mn2V steel which is approximately represented the common casing materials, and quartz materials were used as the rock materials.

1.2. Test Equipment and Experimental Procedures. The tribological performance of the wear-resistant belt was evaluated using an SD-1 type test rig (developed by ourselves, China), which could simulate the real working condition of the deep and ultra-deep well. The schematic diagram of the SD-1 type test rig is shown in Fig. 2. The upper cylinder sample with a size of $\varnothing 22\times 28$ mm was made of the passive pair materials including casing materials and rock materials. The lower ring with a size of $\varnothing 70\times 15$ mm was made of wear-resistant belt materials. According to the real working condition of the deep and ultra-deep well, the experiments were conducted under drilling fluid lubrication condition. The speed of revolution should keep steady 180 rpm, the load should be set 400 N at the same time. Because of the fast wear rat of rock materials, the testing time of rock was less than that of casing. Therefore, the duration of casing wear test is 60 min, and duration of rock materials is 10 min. Before and after the experiment, the test specimens were cleaned by supersonic wave with acetone. The worn surface topography was examined by scanning electron microscopy tests (Quanta 200F, FEI, China). The weight changes of specimens were quantified by using high precision electronic balances (SartoriusA120S, China). Each test was tested three times, the average of three experiment results was reported in this paper.

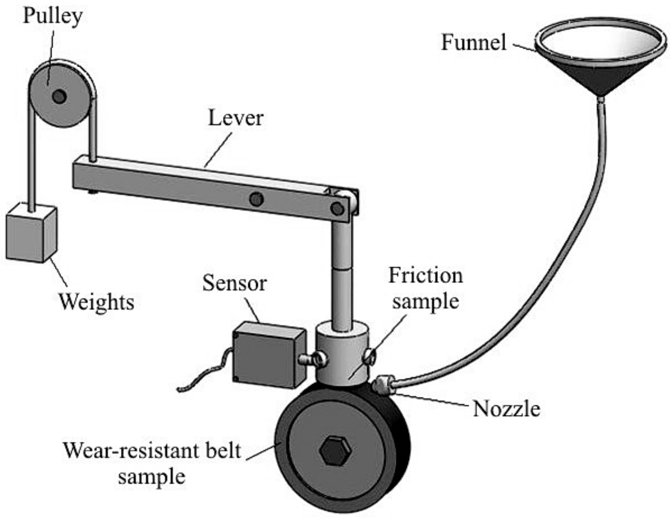

Fig. 2. Schematic diagram of the SD-1 type test rig.

2. Evaluation Method of Wear-Resistant Belt Material. An ideal wear-resistant belt should have the following three features: high abrasion resistance that protects the tool joint from being worn by rock; considerable abrasion reduction that allows the contact friction with the casing to give a less severe wearing, thus protecting the casing; small friction coefficient that can reduce the friction resistance when in contact friction with the formation or casing [12, 13].

1) The wear-resistant belt's abrasion resistance refers to the ability to resist the wear of wear-resistant belts when in contact friction with rock [14, 15]. Under the same working conditions, wear-resistant belts of the same structure and different materials undergo weight losses when in contact friction with rock. So the abrasion resistance of a wear-resistant belt can be expressed using its weight loss within the unit time. The formula is as follows:

$$H_s = \frac{W_s}{T}, \tag{1}$$

where H_s is the abrasion resistance value of the wear-resistant belt (g/h), W_s is the total weight loss of the wear-resistant belt within the friction time (g), and T is the friction time (h). In the contact friction with rock, the weight loss of the wear-resistant belt within the unit time is less and its wear resistance is higher by definition. Therefore, the abrasion resistance of a wear-resistant belt is inversely proportional to its weight loss within the unit time period. That is, the lower the H_s value is, the better the abrasion resistance performance is.

2) Abrasion reduction capacity refers to the wear-resistant belt's ability to reduce the casing wear when in contact friction with the casing [14, 15]. Under the same working conditions, the casing undergoes weight losses when wear-resistant belts of the same structure and different materials are in contact friction with the casing. So, the abrasion reduction capacity of an abrasion resistance band can be expressed using the casing's weight loss within the unit time. The formula is as follows:

$$H_t = \frac{W_t}{T}, \qquad (2)$$

where H_t is the abrasion reduction capacity of the wear-resistant belt (g/h) and W_t is the total weight loss of the casing within the friction time (g). When in contact friction with casing, the weight loss of the casing within the unit time is less, the ability to reduce the casing wear is higher. Thus, the abrasion reduction capacity of the wear-resistant belt is inversely proportional to the casing's weight loss within the unit time. That is, the lower the H_t value is, the better the abrasion reduction capacity is.

3) Friction occurs when a wear-resistant belt is in contact with rock or the casing. The friction coefficient is an important index showing the friction materials' frictional wear characteristics and friction resistance. Under the simulation experiment conditions, the frictional contact area varies with time, and the frictional coefficient is hard to directly measure. Given a contact pressure, however, the frictional coefficient is directly proportional to the frictional force. So, the level of the frictional force is used to express the differences between different abrasion resistance band materials.

3. Results and Discussion.

3.1. Friction and Wear Behavior. According to the test data along with the indexes used to evaluate the properties of the wear-resistant belts, the frictional wear characteristics of the wear-resistant belts made of different materials are analyzed.

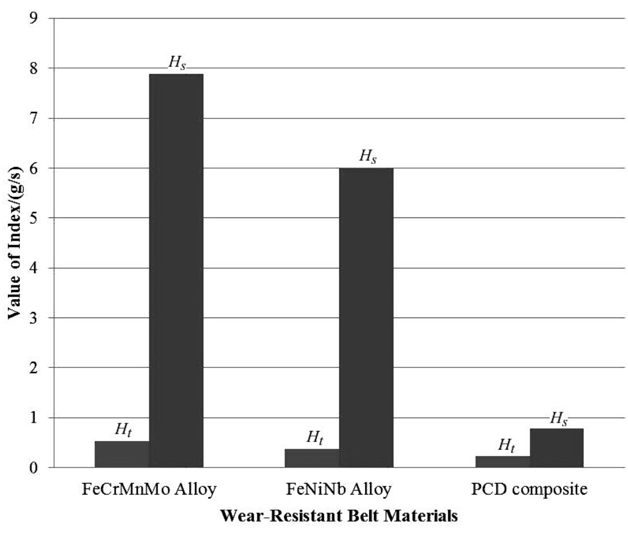

Fig. 3. Evaluation indexes of different wear-resistant belt materials sliding against 42Mn2V steel and quartz.

Figure 3 shows two evaluation indexes of different wear-resistant belt materials sliding against 42Mn2V steel and quartz. Between the general wear-resistant belt materials, the abrasion resistance and abrasion reduction capacity of a FeNiNb alloy are higher than those of FeCrMnMo alloy. The bilateral protection performance of FeNiNb alloy is also higher. Indeed, FeNiNb alloy is often used when the operating requirements are high because of its better performance [4, 5, 14]. Meanwhile, the PCD composite has much better abrasion resistance and abrasion reduction capacity. Consequently, it can be observed that the friction and casing wear of PCD composite are lower than those of traditional wear-resistant belt materials. In other words, the bilateral protection performance of PCD composite is obviously better than that of the wear-resistant belt made of any conventional material.

The intensity of the frictional force reflects the frictional wear characteristics of the wear-resistant belt material and the size of the friction resistance during the drilling. That is to say, the reduction of frictional force means that the friction resistance during the drilling can be reduced. The frictional force comparison of different wear-resistant belt materials sliding against 42Mn2V steel and quartz is shown in Fig. 4. When in friction with quartz, there are small frictional force differences among the wear-resistant belt materials, but also the frictional force of PCD composite is the lowest. But conversely, when in friction with 42Mn2V steel, there are considerable differences. In this occasion, the value of the frictional force of PCD composite is also the minimum. Therefore, the frictional wear characteristics of the PCD composite are better than any other conventional material. Among these three wear-resistant belt materials, the frictions of FeCrMnMo alloy sliding against 42Mn2V steel and quartz are both higher than any other two materials. The friction of FeCrMnMo alloy against 42Mn2V steel is especially high, that is to say, the friction resistance of this material during the drilling is high. It can cause that both the casing and wear-resistant belt materials wear out faster.

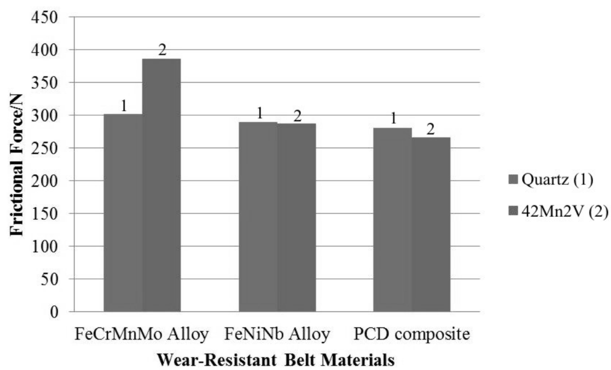

Fig. 4. Frictional force comparison of different wear-resistant belt materials sliding against 42Mn2V steel and quartz.

3.2 SEM Analysis of Worn Surfaces. In order to analyze the considerable differences of the frictional force when in friction with 42Mn2V steel, The surface morphologies of 42Mn2V steel were observed by SEM [16]. Figure 5 shows the worn surfaces SEM micrographs of 42Mn2V steel against different wear-resistant belt materials. The 42Mn2V steel against FeCrMnMo alloy displays severe microcutting wear (Fig. 5a). This is consistent with the high frictional force in such situation. Compared with FeCrMnMo alloy, the microcutting wear on the surface of the steel against FeNiNb alloy is not so acute (Fig. 5b). There are light scratches only, which suggested that the wear mechanism appeared to be obvious microcutting wear. When sliding against PCD composite, the worn surface on a 42Mn2V steel showing the bilateral protection performance appears minor wear characteristics with some slight furrows (Fig. 5c). Figure 5 also shows that all the worn surfaces appear to have partially exfoliated structure, but the degree is different. The degree of PCD composite is the least. Consequently, the wear-resistant belt with PCD composite exhibits the best friction and wear behavior under test conditions. This high-

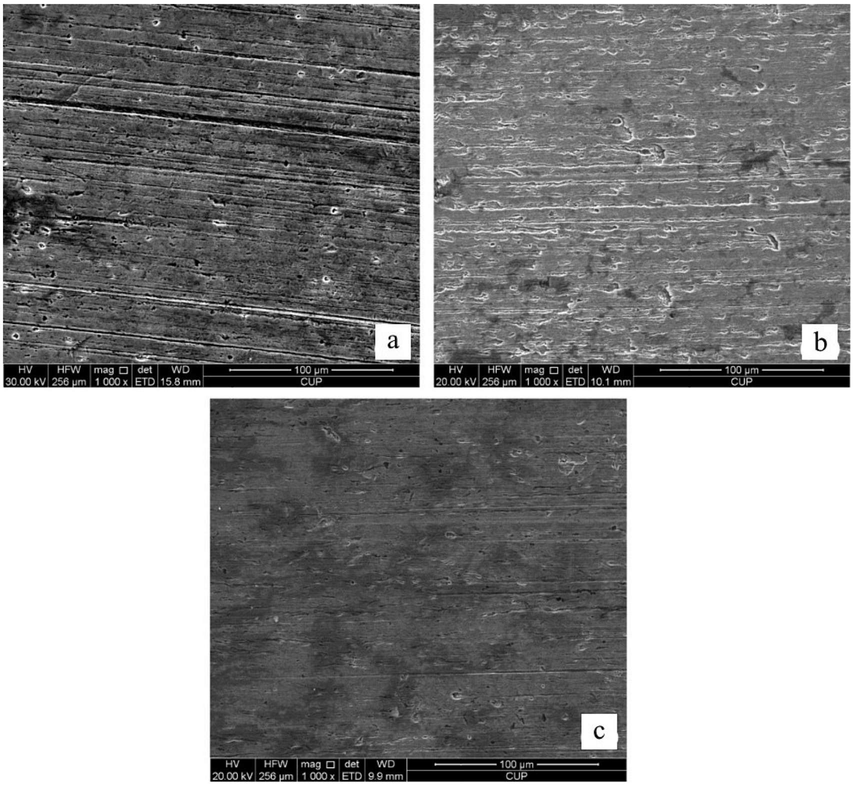

Fig. 5. SEM micrographs of the worn surfaces of 42Mn2V steel: (a) against FeCrMnMo alloy; (b) against FeNiNb alloy; (c) against PCD composite.

performance wear-resistant belt can be ingeniously adaptable in practical use in deep and ultra-deep well drilling process.

During the drilling of the deep and ultra-deep well, the performance of drill pipes is influenced by various factors including fluid dynamics, fluid chemistry and dynamic contact. Although the complex interaction among these factors could not be completely explained from the above discussions, the results of this work suggest that the legitimate choices of wear-resistant belt materials can influence the friction and wear behavior between tool joints and borehole walls during drilling.

Conclusions

1. Among the general wear-resistant belt materials, the abrasion resistance and abrasion reduction capacity of FeNiNb alloy are higher than those of FeCrMnMo alloy. Moreover, PCD composite exhibits much better performance by the abrasion resistance and abrasion reduction capacity criteria.

2. In case of sliding contact with 42Mn2V steel, microcutting wear and adhesive one are the dominant processes damaging 42Mn2V steel.

3. The bilateral protection performance of PCD composite in the wear-resistant belt is much better than that of any conventional material. It is possible to use PCD composite as a wear-resistant belt material.

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