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Research Article

Study on Dynamic Behavior of a Titanium Alloy Drill Pipe in Complex Wells

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Traditional steel drill pipes can no longer meet the requirements of complex wells with ultradeep, ultrahigh pressure, and long horizontal section; hence, titanium alloy drill pipes are an ideal substitute. This paper explores how titanium drill pipes behave in complex wells. The extrusion and tensile test of titanium alloy pipe was first established. Then, based on the experimental data, the downhole mechanical behavior of a titanium alloy drill pipe was studied from the buckling, contact force, and operating friction with an actual complex well. Meanwhile, the mechanism of friction reduction is analyzed and discussed. The research achievements indicate that the strength of a titanium alloy drill pipe is equal to that of a steel pipe and has good plastic deformation capacity. The titanium alloy drill pipe is more prone to buckling during operation, but it has a smaller contact force, which can effectively reduce the operation friction. It was found that the influent of buckling on slide force was much less than of the gravity and stiffness by mechanism analysis. The research achievements can provide specific theoretical and practical references for the revelation of the mechanical behavior and functional performance of titanium alloy drill pipe in the field operation.

1. Introduction

With the increasing global consumption of oil and gas resources, the exploration and development of "three high" oil and gas wells under complicated working conditions such as ultradeep, ultrahigh temperature, and ultrahigh pressure has attracted more and more attention [1–3]. Oil and gas from the complex wells greatly expand the worldwide energy supply [4–6]. However, in the process of drilling complex wells, the tools are required to cycle for a long time under adverse conditions [7, 8]. The conventional steel drill pipe usually has a short fatigue life and even fracture failure due to fatigue damage, wear, and corrosion, which has brought safety loopholes to the well operation [9–11]. In China, the steel drill pipe failure problem is even worse; for instance, in an oilfield in Xinjiang, China, most wells are horizontal complex wells with a depth of more than 6,000 m and a horizontal section of more than 1,000 m; the failure of drilling tools often happens in this oil field. The drill string failed in operations due to rotation fatigue and high friction, which caused a downhole accident and brought great loss for the company. Therefore, it is urgent to solve the problem of steel drill pipe failure.

In recent years, many countries have been looking for more efficient new drill pipe applications for complex trajectory wells [12]. Titanium alloy drill pipe is considered as an ideal substitute for steel pipe by many oil field developers due to its advantages such as low density, low modulus of elasticity, high flexible, and excellent corrosion resistance [13–16]. Grant Prideco, RTI Energy Systems, and Torch Drilling Services in the United States first used titanium drilling pipes for industrial applications in 2000. In recent years, many scholars have carried out relevant research on titanium alloy drill pipes; Jackie et al. [17] studied the processing method of titanium alloy drill pipes and used simulation technology to model and analyze titanium alloy drill pipe operation in ultradeep wells. Yang et al. [18] tested the tensile, torsional, and internal pressure resistance of titanium alloy drill pipe, and the structure showed that the strength of a titanium alloy drill pipe was equivalent to that of a steel drill pipe. Moreover, they [18] devoted themselves to the engineering research on the surface of titanium alloy drill pipe and improved the antiwear and anticorrosion performance of drill pipe through microarc oxidation coating. Zhu et al. [19] analyzed the extended drilling capability of titanium alloy drill pipes in long horizontal sections of shale gas wells. Liu et al. [20] investigated the first failure accident of the titanium alloy drill pipe in ultrashort radius horizontal well drilling and found that there are many microcracks on the surface of titanium pipes that cannot be detected by current standards. During the drilling process of titanium pipes, the pipe body is slightly deformed, and these microcracks rapidly spread to the entire wall thickness, eventually leading to the fracture of the drill pipe. Peng et al. [21] analyzed the friction between titanium pipes and steel pipes under different operating methods. The results show that the friction force of a titanium alloy drill pipe in horizontal wells is only 60% of that of steel drill pipe under the same conditions. However, this study did not analyze and explain the mechanism of low friction of titanium alloy drill pipe. Despite several studies having been conducted on titanium alloy drill pipes, the titanium pipe is not widely used in oil field due to its high price and immature technology; the experiments and theories on titanium alloy drill pipes are seldom reported in the literature. The performance of titanium alloy drill pipes is very different from that of a traditional steel pipe, and its mechanical behavior in complex wells is still unknown.

Hence, in this work, extrusion and tensile test of titanium alloy drill pipes were first established to evaluate string performance. Second, based on the experimental data, the downhole mechanical behavior of titanium alloy drill pipes was studied from the aspects of buckling, contact force, and operating friction with an actual complex well. Meanwhile, the mechanism of friction and drag reduction of titanium alloy drill pipes is analyzed and discussed. The research achievements can provide certain theoretical and practical references for the revelation of the mechanical behavior and practical performance of titanium alloy drill pipes in the field test, respectively.

2. Mechanical Performance Test

In complex wells, the drill pipes are often subjected to complex forces such as pulling, pressing, and twisting force; the action of these forces will lead to the deformation and even failure of the drill pipe [22, 23]. However, due to the high cost of titanium alloy drill pipes, the extrusion test of titanium alloy drill pipes has not been carried out in previous studies. To clarify the mechanical behavior of titanium alloy drill pipes in the downhole, the extrusion and tensile tests were first carried out to analyze the strength and plastic deformation capacity of the pipe.

2.1. Tube Body Extrusion Test. The extrusion test sample with the length of 45 mm is axially obtained from the titanium alloy drill pipe and its chemical composition is as follows: Al—5.44, Cr—1.14, Mo—2.80, Ni—0.50, Fe—0.02, Si—0.08, and Ti—balance. The deformation capacity and collapsing strength of titanium alloy drill pipes can be determined by an extrusion test; the testing machine was used to carry out the test. The tube body before the experiment is shown in Figure 1.

The load and compression displacement of each period from the beginning to the end of the experiment were recorded, and the result is displayed in Figure 2.

It can be seen from Figure 2 that the relationship between the load and displacement is linear in stage AB; at this point, the load is removed and the displacement disappears, and the tube body is in the stage of elastic deformation. On continuing the experiment, the pipe body begins to enter the plastic deformation in stage BC; at this time, the load increases slowly and the displacement increases rapidly; the pipe body appears to have undergone an obvious and irreversible shape change. At point C, the yield limit of the material is reached and the load is 68 kN. At stage CD, the tube body began to collapse and the experiment at point D ended; the sample after extrusion test is shown in Figure 3.

The extrusion experiment of a drill pipe is further studied by numerical simulation. As shown in Figure 4, a finite element model of the extrusion test is established using ABAQUS CAE to comparison and analysis.

Finite element analysis results are obtained by outputting extrusion displacement and load curve as displayed in Figure 5; compared with Figure 2, the trend of the curve and the deformation of the sample are basically consistent with the real test curve, and the reliability of the test is verified. Figure 6 reveals the stress distribution of the sample at the beginning of destruction. It can be seen that the stress value at the four ends of the sample is the largest, up to 980.3 MPa. By means of extrusion experiment and finite element modeling, the maximum compressive load of titanium alloy drill pipe is up to 70 kN and the pipe body has good plastic deformation capacity, which can meet the operation requirements of wells with complex trajectory.

2.2. Tensile Test. The tensile test refers to the test method to determine the properties of materials under axial tensile load. The elongation, elastic modulus, tensile strength, yield point, yield strength, and other tensile properties of the material can be determined by using the data obtained from the tensile test. Then, the quality of the tube can be judged. To verify the actual tensile properties of the titanium alloy drill pipe, the tensile test was carried out on the MTS810 material testing machine, with a tensile speed of 5 mm/min, and the tensile samples and dimensions are shown in Figure 7.

A MTS tensile testing machine was used to test the tensile mechanical properties of the samples according to national standard "National Technical Committee for Steel Standardization. Metallic materials: tensile testing at ambient temperature: GB/T 228.1—2010 [S]" [24]. Figure 8

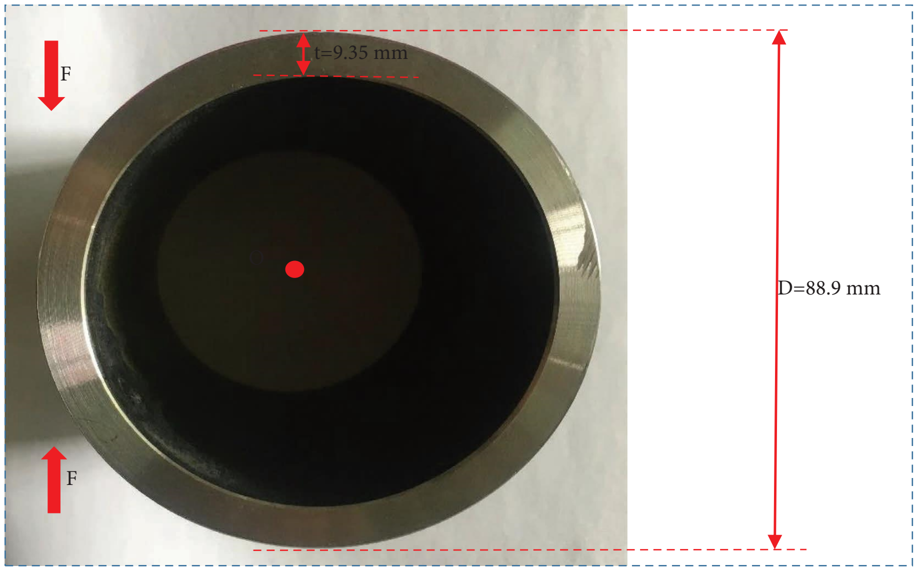

Figure 1: Specimen of the titanium alloy drill pipe.

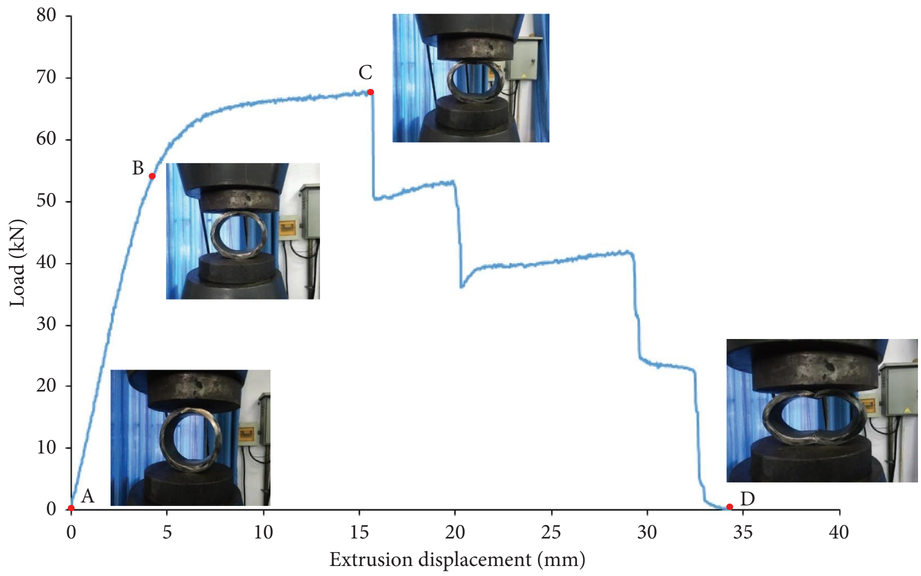

Figure 2: Load-displacement curve of the tube body extrusion test.

illustrates the tensile test results of the tube body sample. It can be seen from Figures 8(a) and 8(b) that with the increase of tensile force, the specimen has elastic deformation. When the stress reaches 860.53 MPa, it begins to have plastic deformation; so, the yield strength of sample 1 is 860.53 MPa. When the stress exceeds 938.55 MPa, the specimen enters the necking deformation phase, which means that the tensile strength of specimen 1 is 938.55 MPa. As the tension continues to increase, the specimen 1 finally breaks with a fracture elongation of 12.58%. In a similar way, the yield, tensile strength, and elongation of samples 2 and 3 can be obtained and the results are shown in Table 1. According to Table 1, the average yield strength of the titanium alloy drill pipe sample is 882.96 MPa, the average tensile strength is 955.94 MPa, and the elongation is 13.37%.

The strength of S135 steel was also tested in the laboratory, and the yield strength, tensile strength, and elongation were 915 MPa, 1012 MPa, and 13.37%, respectively. Figure 9 shows the strength comparison between the titanium alloy and steel drill pipe; it is observed that the strength of titanium alloy drill pipes is basically equal to that of S135 pipe. However, the density of titanium is only half that of steel, so the titanium alloy drill pipe has high specific strength, which has great significance for horizontal well load reduction.

3. Downhole Dynamic Behavior Analysis

The drill pipe is subjected to various complex forces underground. When the axial stress of the drill pipe exceeds its

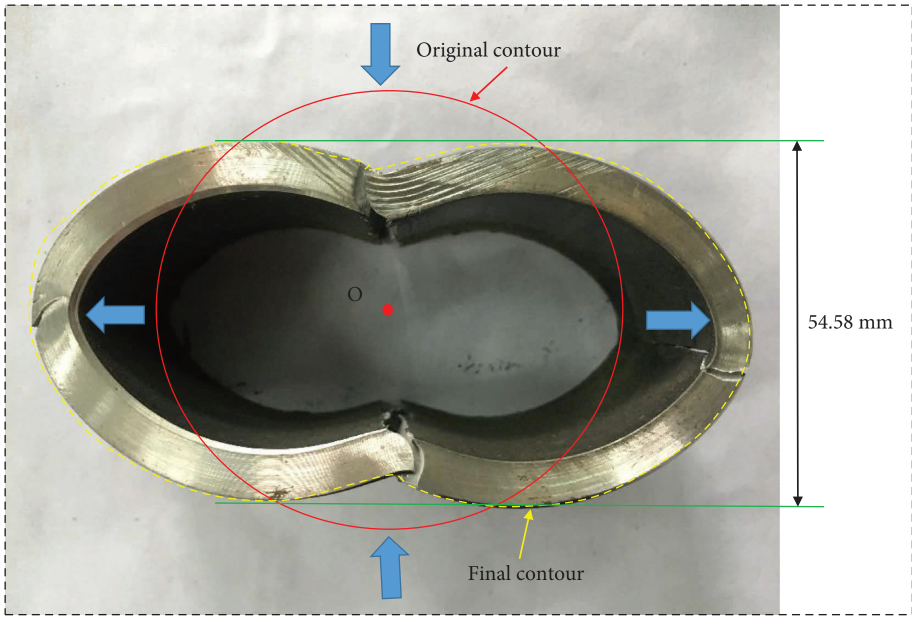

Figure 3: Specimen of the tube body after extrusion.

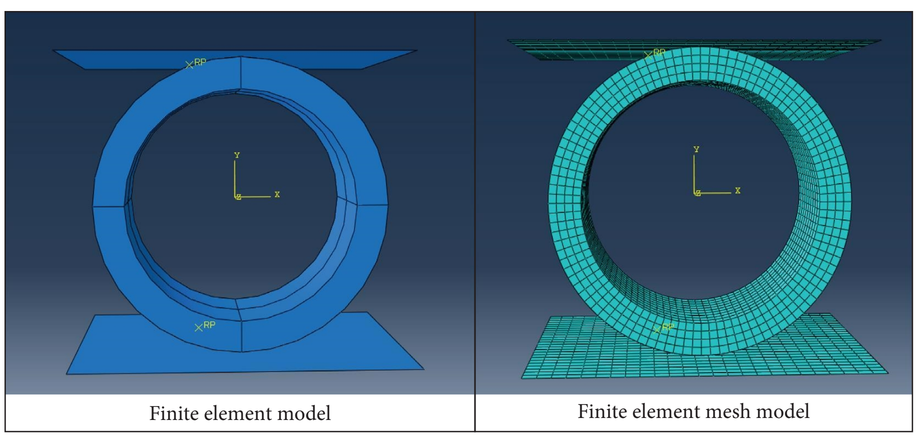

Figure 4: Finite element models for tube extrusion of titanium alloy. (a) Finite element model and (b) finite element mesh model.

critical buckling load value, the drill pipe will buckle and deform, which is not conducive to the transmission of power, affects the process of operation, and even leads to premature fatigue failure and drilling accident. Experiments indicate that the titanium alloy drill pipe has high strength and good plastic deformation ability, which can meet the requirements of complex wells. However, titanium alloy drill pipes are more prone to deformation than steel pipe, so it is necessary to analyze and study the mechanical behavior of titanium alloy drill pipes in downhole. The critical load of sinusoidal buckling of drill pipes in the inclined straight section is calculated as follows [25, 26]:

$$F_{\mathrm{cr}} = 2\sqrt{\mathrm{EIW}_e \frac{\sin\theta}{r}}. \tag{1}$$

The critical load calculation formula of helical buckling can be obtained by using the following expression:

$$F_{\mathrm{hel}} = 2\left(2\sqrt{2}-1\right)\sqrt{\frac{EIW_e}{r}}, \tag{2}$$

where F_{cr} and F_{hel} are sinusoidal and spiral buckling critical loads of the string, N, respectively; E is the modulus of elasticity, Pa; I is the polar moment of inertia, m^4; W_e is the effective weight per unit length, N/m; and r is the gap between the string and the wellbore.

According to the calculation formula, the critical buckling load of different sizes of titanium alloy and steel drill pipe is analyzed; the results are shown in Figures 10 and 11.

It can be seen from Figures 10 and 11 that with the increase of hole diameter, the critical buckling load of string decreases gradually, which indicates that string buckling is more likely to occur in large-diameter wells. With the increase of borehole inclination, the critical buckling load of the same borehole diameter pipe string increases gradually.

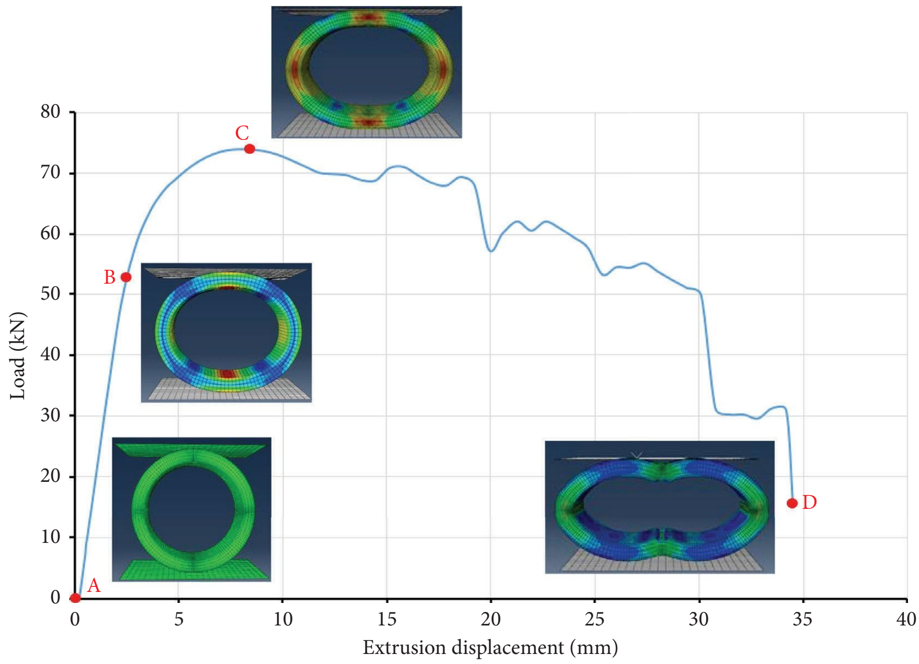

Figure 5: Finite element analysis results of the extrusion experiment.

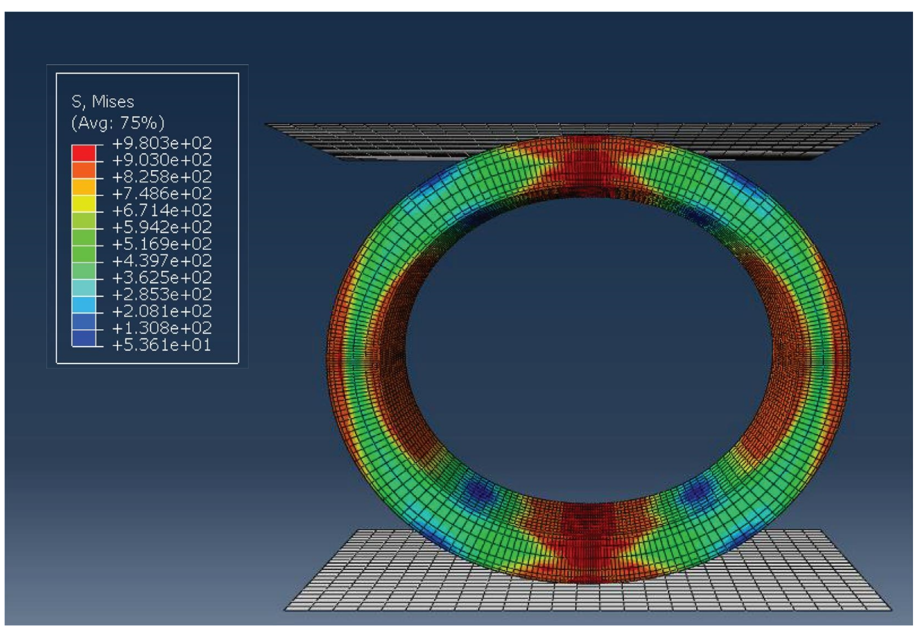

Figure 6: Stress distributions during tube failure.

By comparing Figures 10 and 11, it can be seen that the critical load of helical buckling of the string is about 2.83 times that of sinusoidal buckling. Besides, under the same hole diameter and inclination angle, the critical buckling load of titanium alloy drill pipes is lower than that of steel, indicating that the titanium alloy drill pipe is easier to buckling than that of a steel pipe under the same conditions.

When the drill pipe buckling happened, the contact state between the drill pipe and the borehole wall and the contact force is changed. In order to better study the downhole movement of titanium alloy drill pipe, the mechanical finite element model of the whole wellbore of titanium alloy drill pipe was first established, as shown in Figure 12; the depth of the well is 6,200 m, the build-up point is 3,100 m, the maximum slope angle is 90°, and the horizontal section is 3,000 m.

In the model, two kinds of drill pipe combinations, steel and titanium alloy drill pipes are used, respectively. Considering the economic efficiency of practical operation, in the titanium alloy drill pipe assembly, the titanium alloy drill pipe is only used below the deflecting point, while the steel

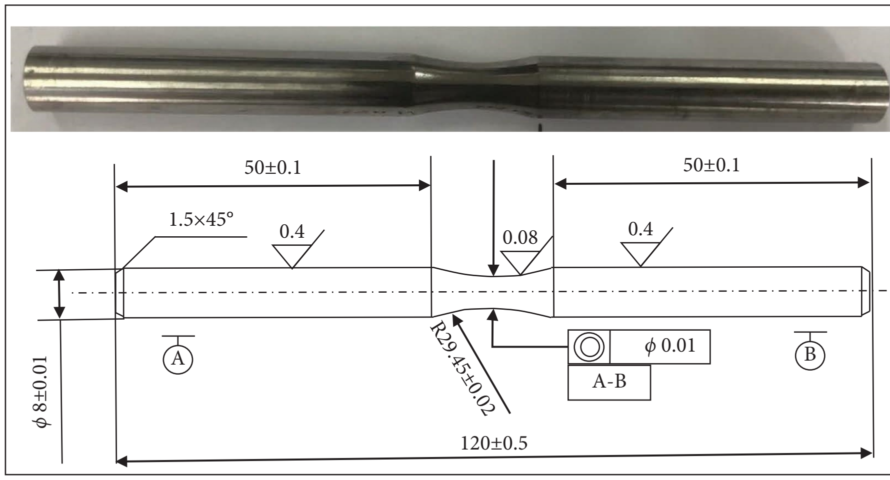

Figure 7: Tensile specimen of the titanium alloy drill pipe.

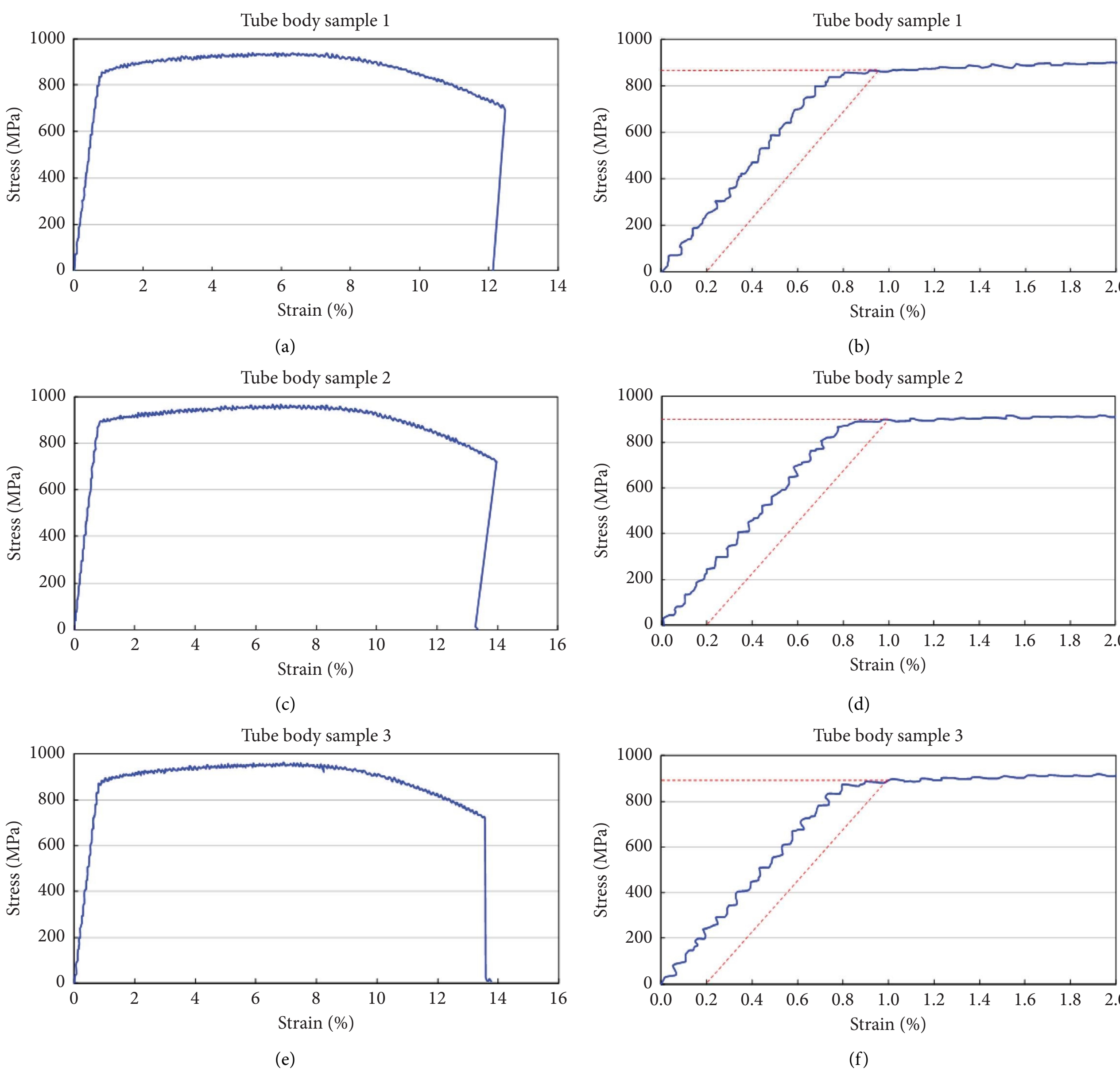

Figure 8: Stress-strain curve of the sample.

Table 1: Test results of tensile mechanical properties of the tube body.

Numbers	*Yield strength* Rp0.2 (MPa)	Mean value	*Tensile strength* σ_b (MPa)	Mean value	*Yield ratio* Rp0.2/ σ_b	Mean value	*Elongation at break* Δ (%)	Mean value
1	860.53		938.55		0.92		12.58	
2	891.33	882.96	963.56	955.94	0.93	0.927	13.90	13.37
3	897.01		965.72		0.93		13.62	

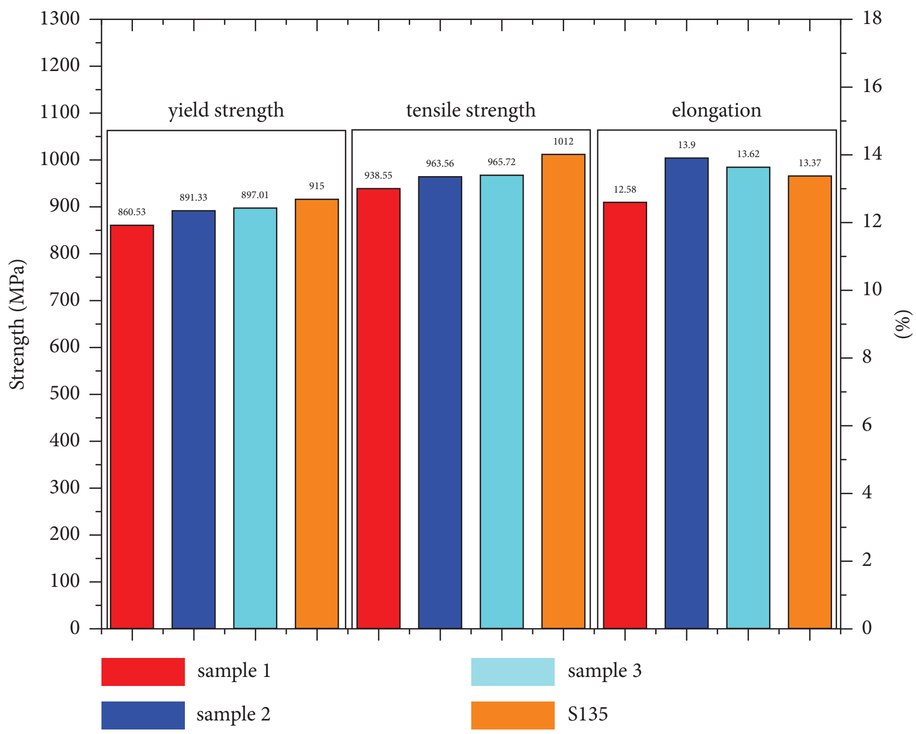

Figure 9: Comparison of tensile test results.

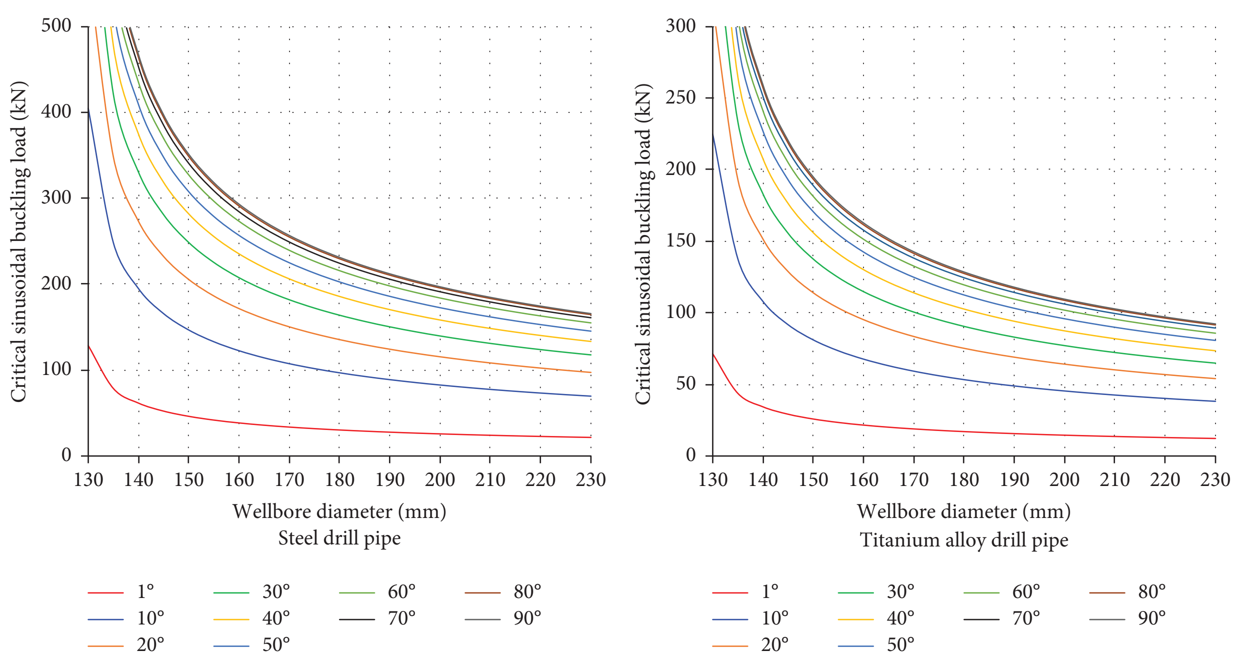

Figure 10: Comparison of sinusoidal buckling critical loads between the titanium alloy and steel drill pipe in an inclined straight section.

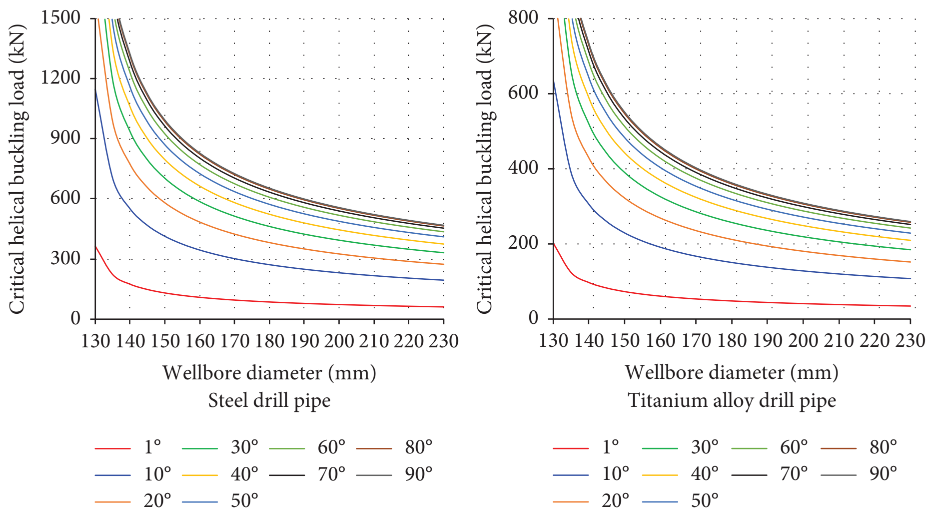

Figure 11: Comparison of critical load of helical buckling of the titanium alloy and steel drill pipe in an inclined straight section.

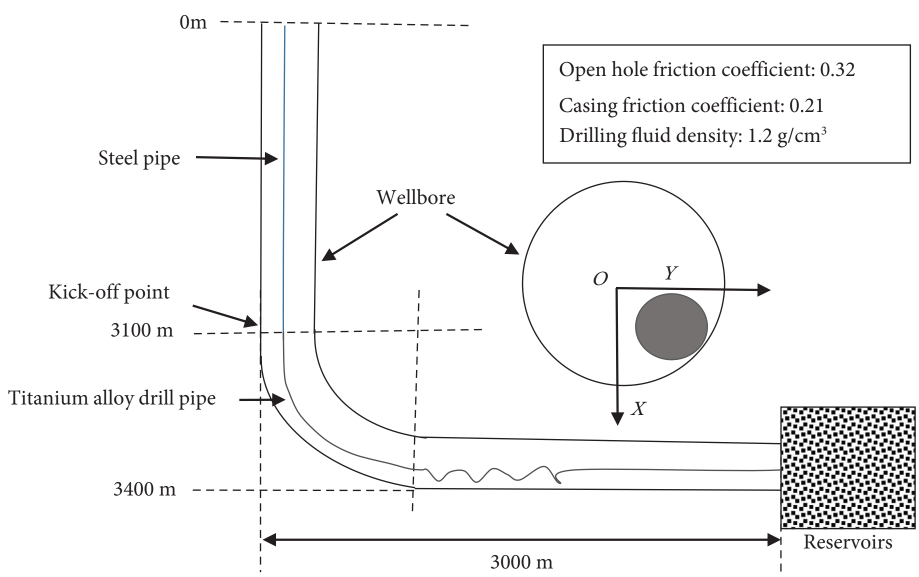

Figure 12: Whole wellbore model of the drill pipe.

drill pipe is still used above the deflecting point. The drill pipe assembly is shown in Table 2.

The downhole mechanics behavior of two kinds of drill pipe under different operations is analyzed. The effective tension of steel and titanium drill pipe is shown in Figures 13 and 14. It can be seen from Figure 13 that the effective force diagram is mainly divided into compression and tensile zone; when the well depth is above 3,100 m (build-up point), the steel drill pipe is mainly in the tensile state; when it reaches the deflector point, the drill pipe changes from tensile to compressive under the constraint of borehole trajectory. In addition, the critical buckling stress of the drill pipe is abrupt in the section with large inclination and azimuth angles, with the maximum buckling stress reaching 5,000 kN. Then, the stress curves of sliding drilling, rotary drilling, dropping out and in did not exceed the sinusoidal buckling and helical buckling critical stress curves, indicating that the steel drill pipe did not buckling during the operation. Moreover, all the operations are within the drill pipe tension limit, which show that strings are in safe status.

As shown in Figure 14, the buckling load of titanium alloy drill pipe increases suddenly at the position with large inclination and azimuth, the maximum buckling stress is 2,900 kN, which is smaller than steel drill pipe. In addition to this, the titanium alloy drill pipe has obvious buckling behavior during sliding and rotating drilling. As shown in Figure 15, during sliding drilling, the titanium alloy drill pipe experienced obvious sinusoidal buckling at 2767–3014 m, 3290–3362 m, and 3701–4669 m, which verifies that the titanium alloy drill pipe is more prone to buckling.

In order to further study the downhole mechanical behavior of titanium alloy drill pipes, we compared the contact forces of two kinds of drill pipes under different operations, as shown in Figure 16. It is clear that in the

Table 2: Two drilling tool assembly schemes.

Steel drill pipe assembly	Titanium alloy drill assembly
φ139.7 mm steel drill pipe + φ127 mm steel drill pipe ∗ 3123 m + φ127 mm heavy weight drill pipe ∗ 54 m + φ139.7 mm screw + φ215.9 mm PDC bit	φ139.7 mm steel drill pipe + φ127 mm titanium alloy drill pipe ∗ 3123 m + φ127 mm heavy weight drill pipe ∗ 54 m + φ139.7 mm screw + φ215.9 mm PDC bit

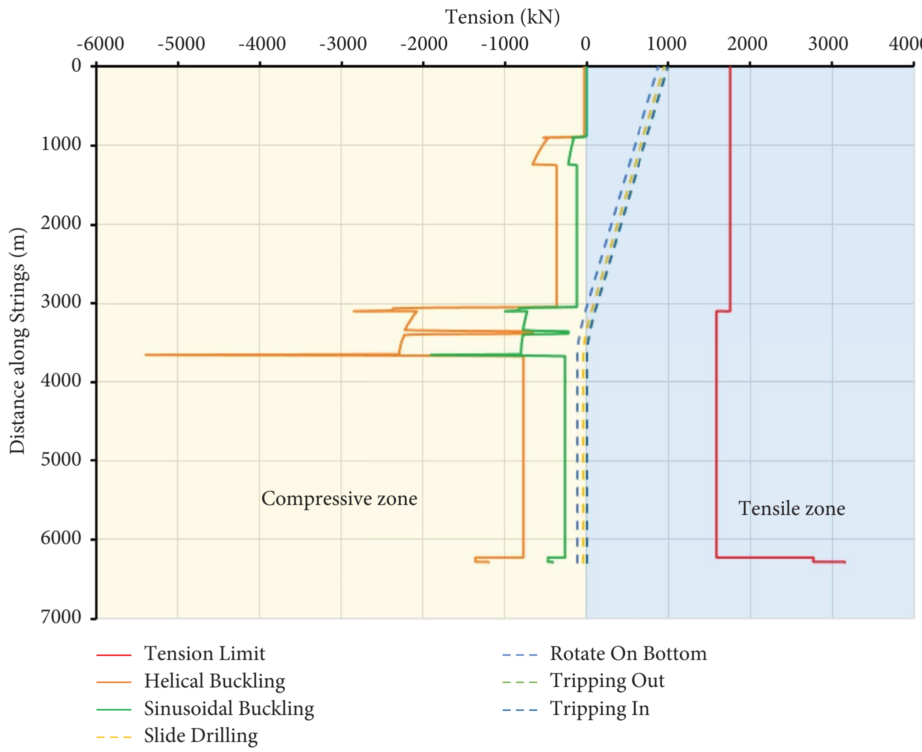

FIGURE 13: Steel drill pipe effective tension diagram.

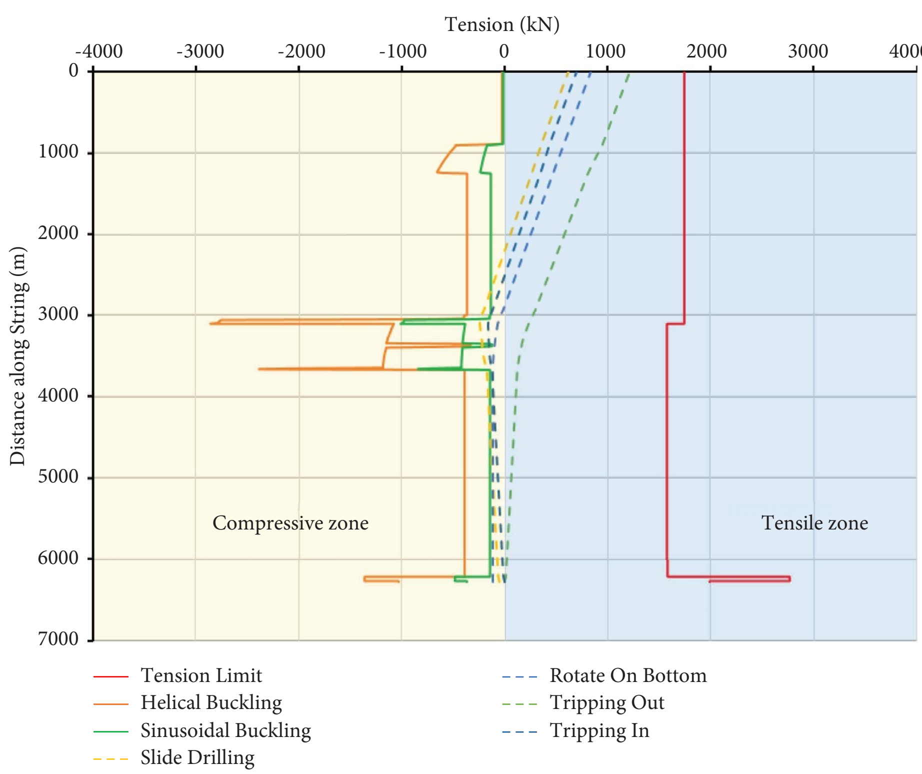

FIGURE 14: Titanium alloy drill pipe effective tension diagram.

straight section, the drill pipe is not in contact with the borehole wall and the contact force is almost zero. When the bending section is reached, the contact force begins to increase due to the contact between the string and the borehole wall. Then, the drill pipe produces the greatest contact force at the kick off point. However, although

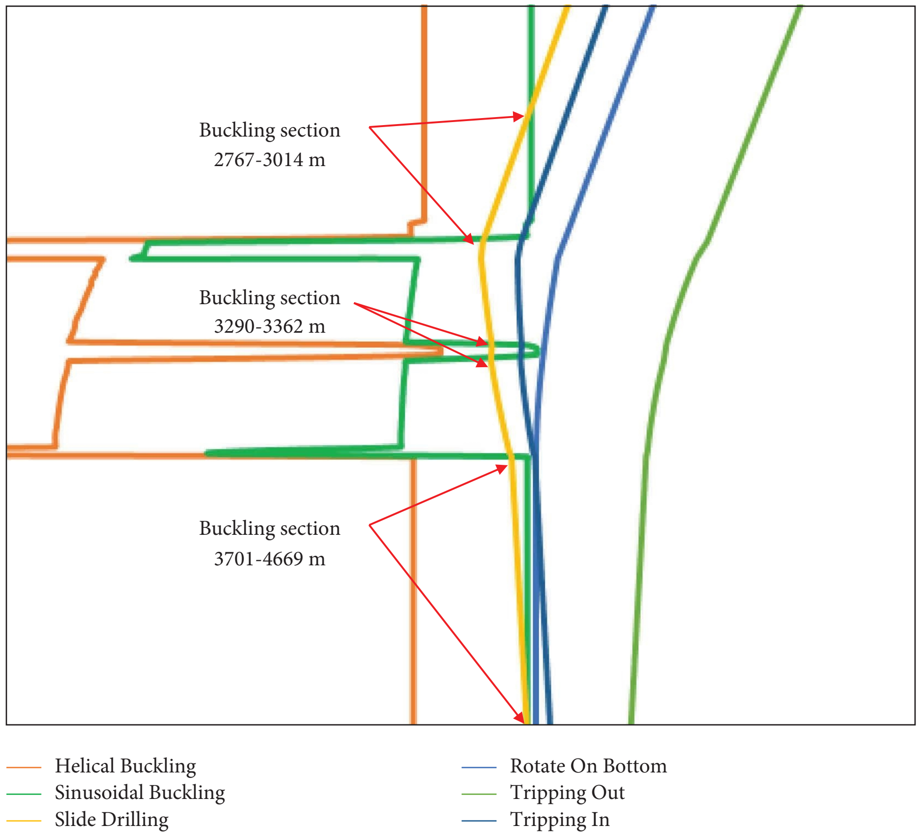

Figure 15: Enlarged view of the buckling region of a titanium alloy drill pipe.

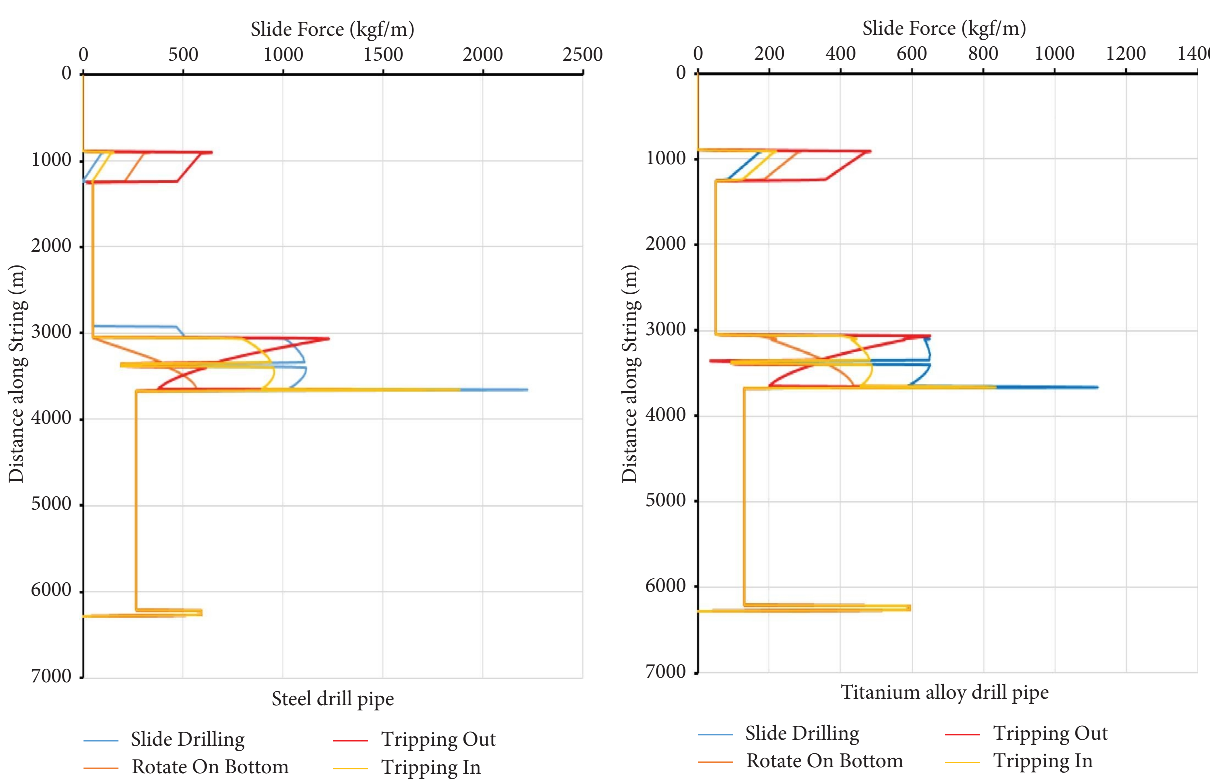

Figure 16: Comparison of the contact forces of two drill pipes under different operation types.

titanium alloy drill pipe buckling occurs in bent well sections, the contact force in each section is smaller than steel drill pipe, which is about 60% of the steel pipe.

4. Discussion

The frictional force of a titanium alloy drill pipe is still smaller than that of steel drill pipe despite buckling; this is because the lateral force is not only related to buckling but also related to other factors. Several factors that influence the contact force are analyzed in the following sections.

4.1. The Force of Gravity. The gravity component is the main reason for the contact force of the drill pipe on the borehole wall; Figure 17 shows the downhole stress of the tube body unit.

The contact force generated by the gravity component can be described as follows:

$$F_a = G \sin\theta, \tag{3}$$

where F_a is the contact force generated by gravity component, N; G is the gravity exerted by the tube body unit, N; θ is the inclination angle of the well where the pipe body is located.

The density of the titanium alloy drill pipe is only 4.40–4.50 g/cm^3, 57% of that of carbon steel. Therefore, under the same conditions, the contact force of titanium alloy drill pipes caused by gravity is smaller than that of steel, which is one of the reasons for the small side force of titanium alloy drill pipes.

4.2. Stiffness Effect. Stiffness is related to material properties, due to the rigidity of the drill string, when the hole has a large dogleg degree, the stiffness of the drill string will generate a lateral force on the borehole wall. A diagram of lateral force generated by stiffness action is shown in Figure 18.

As shown in Figure 18, due to constraints at points A, B, and C, stiffness of the drill pipe, and axial tension, the drill pipe will generate lateral force on the borehole wall [27]. The formula for calculating this lateral force is as follows:

$$F_b = \sqrt{(T \times \Delta\phi \times \sin\overline{\theta})^2 + (T \times \Delta\phi + W \sin\overline{\theta})^2}, \tag{4}$$

where T is the tensile force, N; $\Delta\Phi$ is the change in azimuth in radians; $\overline{\theta}$ represents the average inclination; $\Delta\theta$ is the change in inclination in radians; and W is the mass of the element, N.

When other conditions are constant, the lateral force of the drill pipe is related to the mass and material stiffness at the curved hole. It has been proved that the titanium alloy drill pipe has excellent plastic deformation ability, low elastic modulus, and low stiffness by extrusion and tensile tests. It is easy to pass through the bending well section, while a steel drill pipe can hardly pass through the same area due to its high stiffness, which may generate a sizeable lateral force.

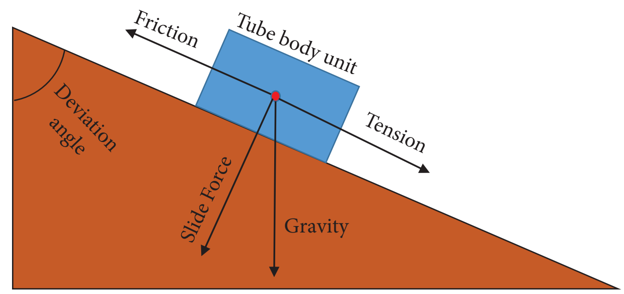

FIGURE 17: Force diagram of the tube body unit.

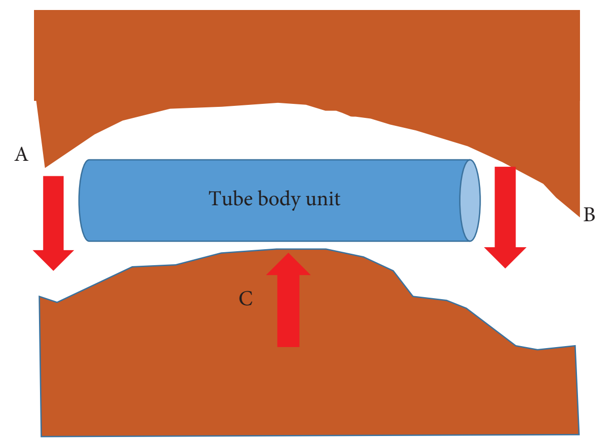

FIGURE 18: Contact force generated by stiffness action.

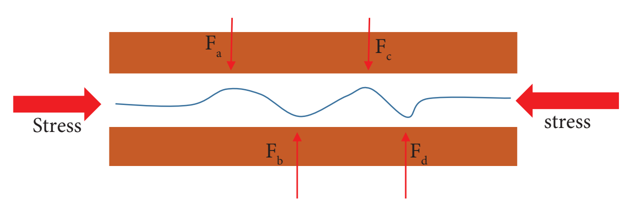

FIGURE 19: Contact diagram caused by buckling.

4.3. Buckling Effect. When the drill string buckling, the drill pipe will contact the borehole wall, as shown in Figure 19. The buckling behavior can increase the contact area between the pipe and the wellbore, thus augmenting the operating friction.

The additional contact forces generated by sinusoidal and helical buckling of the drill string on the borehole wall are calculated as follows:

Sinusoidal buckling:

$$F_c = \frac{rF^2}{8EI}. \tag{5}$$

Helical buckling:

$$F_d = \frac{rF^2}{4EI}, \tag{6}$$

where F_c is the additional contact force after sinusoidal buckling of the string, N; F_d is the additional contact force after helical buckling of the string, N; R is the

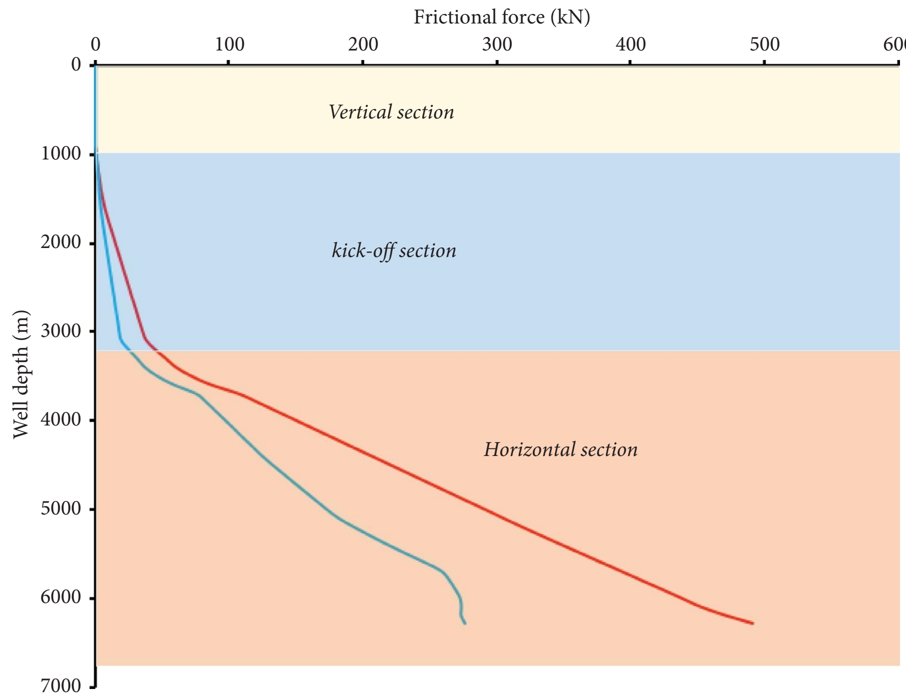

Figure 20: Friction diagrams of two drill pipes.

outer radius of the string, m; F is the axial compression load on the string, N; E is the elastic modulus of the string, Pa; and I is the polar moment of inertia, m^4.

However, in a word, the contact force between the drill pipe and borehole wall is related to the lateral force F_a caused by gravity, the F_b caused by stiffness, and F_c and F_d caused by buckling. Under the same conditions, the F_a and F_b produced by the titanium alloy drill pipe are much smaller than that produced by the steel pipe, although the titanium alloy drill pipe is prone to buckling resulting in additional lateral forces F_c, but the buckling occurs only in very few segments. Therefore, the contact force generated by titanium alloy drill pipes is much smaller than that of steel, and it can be expressed as follows [28–30]:

$$F_{aT} + F_{bT} + F_{cT} + F_{dT} < F_{aS} + F_{bS}, \tag{7}$$

where F_{aT} and F_{aS} respectively represent the contact force caused by gravity of the titanium alloy drill pipe and steel drill pipe, N; F_{bT} and F_{bS} respectively represent the contact force of titanium alloy drill pipe and steel drill pipe caused by stiffness and tensile action, N; and F_{cT} and F_{dT} respectively represent the contact force caused by sinusoid and spiral buckling of titanium alloy drill pipe, N. The relationship among multiple factors such as gravity, stiffness, and buckling was not superposed but a competitive and synergistic relationship. Meanwhile, the work friction is caused by pipe string contact with borehole; the friction of the two types of drill pipe during drilling is shown in Figure 20.

As shown in Figure 20, in the straight section, the drill pipe is not in contact with the shaft wall, and the friction is almost zero. As the depth of the well increases, the friction between the two types of drill pipe increases. When the horizontal section is reached, the friction difference between steel and titanium alloy drill pipes becomes larger and larger; the deeper the well is, the greater the friction difference between the two is, the more obvious the drag reduction effect of titanium alloy drill pipes is.

4.4. Economic Evaluation. The price of titanium alloy drill pipes will vary depending on the origin and size. From a single drill pipe point of view, a titanium drill pipe costs 15 times as much as steel. But from the overall effect, first of all, the use of titanium alloy drill pipe can reduce rig load by more than 40%, so as to reduce the selection of rig specifications and reduce construction energy consumption. Second, the fatigue life of a titanium alloy drill pipe in a corrosive environment is more than 10 times that of conventional drill pipes, which dramatically improves the safety and service life of drilling tools. It is especially suitable for drilling operations in complex well conditions such as ultradeep and short radius wells. Third, the titanium drill pipe assembly reduces operating torque and friction, further improving mechanical speed. In addition, the nonmagnetic characteristics of titanium alloy also provide a convenient condition for the normal use of some logging equipment. To sum up, although the titanium drill pipe is more expensive in the short term, it is more suitable for drilling complex wells in the long term, taking into account the maintenance and replacement of steel drill pipes and the additional rig costs. The manpower, consumables, and other costs saved in the later stage of titanium alloy drill pipes far exceed their purchase cost. If a steel drill pipe is used, the following measures can be used to reduce operational drag: First, optimizing the drill pipe assembly and using different size drill pipe assemblies in the horizontal section can effectively reduce the contact and friction between the drill string and the borehole wall; Second, when drilling with steel pipe, use a lubricated low-friction drilling fluid system to reduce friction during drilling; Finally, optimization of drilling design (including well structure, well trajectory, and building slope) is one of the effective methods to solve the high friction of steel drill pipe operation.

5. Conclusions

In this paper, the extrusion and tensile experiments of titanium alloy drill pipes were carried out. Based on the test results, the mechanical behavior of titanium alloy drill pipes in downhole was studied and compared with steel drill pipes. Meanwhile, the mechanism of reducing drag of titanium alloy pipes was briefly analyzed using the various indicators. The key conclusions are as follows:

First, the extrusion test shows that the maximum compressive load of titanium alloy drill pipe is 70 kN and has excellent plasticity; a tensile test indicates that titanium alloy drill pipe's yield strength reaches 882.96 MPa, tensile strength reaches 955.94 MPa, and elongation is 13.37%, which is similar to those of the S135 drill pipe. The test proved that the titanium alloy drill pipes could meet the requirements of complex well trajectory completely.

Second, titanium drill pipe buckling is more easy than steel drill pipes. However, the friction of titanium pipes is about 60% of that of steel pipes. The longer the working interval, the more pronounced the drag reduction effect of the titanium alloy drill pipe is.

Third, the contact force between the drill pipe and borehole wall is mainly related to gravity and stiffness of drill pipe, buckling has little influence on contact force. The relationship among multiple factors such as gravity, stiffness, and buckling was not superposed but a competitive and synergistic relationship. This is an important reason why the contact force of the titanium alloy is smaller than that of steel pipe despite buckling.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest with respect to publication of this paper.

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