Repeated Impact Method and Devices to Simulate the Impact Fatigue Property of Drillstring

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Abstract. It is well known that drillstring failures are a pendent problem in drilling engineering, because of the fatigue accumulation caused by the low amplitude-repeated impact. In order to reveal the effect of low amplitude-repeated impact on the failure mechanism of the drillstring, a repeated impact method and instrument have been developed based on the Charpy impact method, by which a series of tests have been performed in the condition of non-corrosive medium and with H2S environment respective. Test results of non-corrosive medium environment indicates that, with the increase of single impact energy, the low amplitude-repeated impact resistance of drillstring decreases significantly; For H2S corrosion environment, the low amplitude-repeated impact resistances with H2S is much lower than that without H2S corrosion, and high strength material such as V-150 drillstring is more sensitive to H2S corrosion media. Furthermore, based on the experiment data, the accumulation fatigue model to predict the service life of the drillstring is developed, which could be used to predict the fatigue life. Research fruits are very vital to select a suitable rotational speed for drilling job and drillstring design.

1. Introduction

Drilling plays an important role in the exploration and exploitation of oil and gas fields all over the world. And drillstring is an important downhole tool in oil drilling operation. Because of the change of formation characteristics, the rotating drillstring will bend in the drilling process alternative, bearing a periodic rotational bending stress[1]. The cyclic load will cause partial damage on the surface of the drillstring, which is not easy to be found. Charpy impact property, which is regarded as the evaluation index of impact load capacity of materials, is commonly used in engineering industry[2]. But in the process of drilling, the material of drillstring will always collide with the borehole wall, which will produce low amplitude-repeated impact load[3]. This kind of load can cause local microcracks, which mainly occur in the parts of threaded connection of drillstring and the parts of local superficial damage caused by collision. The local microcracks will expand and cause fracture failure of drillstring. Therefore, even though the drillstring material conforms to the API 5D standard, it still fails constantly in the oilfield, which brings about huge economic losses to the drilling industry.

Repeated impact resistance is different from a shock resistance, and it also differs from fatigue resistance. It reflects most of the works under impact load in the process of actual service situation, and it is the bridge between them[4-5]. Traditional mechanical testing methods can't describe fatigue failure of drillstring material under repeated impact load. As for the petroleum industry, no mechanical
testing method can test the failure of drillstring material caused by repeated impact load in API 5D standard. But for the other area, since the beginning of the 20th century, many scholars have done the repeated impact experiments[6]. In recent years, the theoretical study of low amplitude-repeated impact is expanded gradually by scholars[7]. Although the repeated impact of different materials have been studied, but further systematic and comprehensive experiment has to be developed, especially drillstring material of low amplitude-repeated impact.

As the world's increasing demand for oil and gas resources continues, the number of deep wells and ultra-deep wells grows rapidly, and drilling tool service conditions are more and more severe[8]. Furthermore, hydrogen sulfide(H₂S) often presents in deep wells and ultra-deep wells with complex drilling conditions[9]. It's extremely difficult to develop sour gas reservoir with conventional technology and drilling materials because of the corrosion of H₂S. When the partial pressure of hydrogen sulfide is high, the mechanical properties of the drillstring are obviously decreased. Especially the drillstring material can occur stress-corrosion-cracking and corrosion fatigue fracture with the underground alternating stress[10-12]. The corrosion time in hydrogen sulfide situation is an important factor to destruct drillstring material[13]. Different materials have different sensitivity to H₂S and different rate of crack propagation under external force[14-15]. Loss of drill pipe material often causes serious casualties and property damage. From the existing research situation, people have a rich understanding of the corrosion mechanism of hydrogen sulfide and other media, and put forward valuable conclusions and opinions on corrosion prevention[16-18]. However, the variation law of low amplitude-repeated impact fatigue behavior of drillstring material is not studied deeply under the influence of corrosive medium. Therefore, it is very important for the improvement of the drilling efficiency and drilling safety by studying the variation law of a low amplitude-repeated impact fatigue behavior of the drillstring material under the hydrogen sulfide environment. In this paper, three kinds of commonly used drillstring materials are measured under the low amplitude-repeated impact experiment, and the variation law for low amplitude-repeated impact resistance of typical drillstring material under normal and hydrogen sulfide environment is obtained.

2. Experimental Methods

2.1. Presentation of low amplitude-repeated impact experiment method

Charpy impact energy (\(a_0\)) is often seen as the mechanical properties index of resistance to impact load for the material. Charpy impact energy is obtained by the single impact of the sample under the large enough impact load, but downhole drillstring crack propagation is caused by the low amplitude-repeated impact. So the common Charpy impact experiment can not reflect the actual working conditions underground for the drillstring, and cannot be used to evaluate the characteristics of materials under the low amplitude-repeated impact load. Hence, in order to accurately evaluate the damage mechanism of material under the repeated impact load, a testing device to simulate drillstring for actual downhole conditions developed, and it is based on principles of Charpy impact experiment and depends on the the characteristics of rotary body. The device has the advantages of simple structure, easy maintenance and low cost. The picture of device as shown in Figure 2-1. Furthermore, an experimental specimens with prefabricated notch is designed for the experiment. The notch which
has an angle of 120° on the specimen is a fixed gap of the fastening bolt. We can derive the single impact energy \( E \), and record the number of the impacting \( N \). The product of \( N \) and \( E \) is the cumulative impact energy \( A \) which can characterize the property at the low amplitude-repeated impact. There are the calculation formulas as type (2-1) and (2-2). The pictures of counter and sensor schematic are shown in figure 2-2 and figure 2-3.

\[
E = m(vr)^2 / 2 \quad (2-1)
\]

\[
A = NE \quad (2-2)
\]

2.2. Experimental material

This study used G-105, S-135 drillstring materials which commonly used in deep or ultra deep well, and high strength V-150 drillstring materials, after mechanical processing, wire cutting with prefabricated crack and specifications for specimens of 50mm×10mm×2.5mm, and these samples conform to the requirements of GB and ASTM. The real impact specimen photos as shown in Figure 2-4, which has a 45 degree prefabricated breaking gap and a 120 degree fastening bolt fixed gap, and
notch root radius is 0.25mm. In order to record the crack length, the samples surface was polished.

![Profile and real picture of test blocks](image)

We formulate the corrosion solution based on the standard NACE TM177-96, and this solution will be used in the corrosion immersion test. The formula is 5% NaCl and 0.5% acetic acid dissolved in distilled water, and with saturation of H$_2$S , whose concentration is about 2219–2337mg/L. Corrosion immersion test was performed in a transparent glass vial. Before the experiment, samples need to be cleaned and surface corrosion products need to be removed and dried.

### 3. Results and Discussion

#### 3.1. Relation of single impact energy and low amplitude repeated impact resistance of drillstring material under non-corrosive medium environment

In order to deeply study the relationship between single impact energy and dynamic fatigue performance of drillstring materials, the testing with different single energy is carried out. The testing samples are from G-105, S-135 and V-150 three kinds of drillstring steel body. The cumulative impact energy $A$ presents low amplitude-repeated impact resistance. The experimental results are shown in table 3-1.

| Single impact energy (J) | 2.21 | 2.50 | 3.00 | 3.58 | 3.90 | 4.39 | 4.90 |
|--------------------------|------|------|------|------|------|------|------|
| Cumulative energy of G-105 (J) | 475.2 | 450.2 | 354.3 | 225.5 | 195.0 | 175.6 | 166.6 |
| Cumulative energy of S-135 (J) | 640.9 | 627.5 | 483.1 | 358.2 | 315.9 | 219.5 | 186.2 |
| Cumulative energy of V-150 (J) | 897.3 | 562.5 | 274.2 | 199.4 | 219.1 | 109.6 | 119.5 |

We mapping the curve of low amplitude-repeated impact resistance under different single impact energy according to the above data, and the curve as shown in figure 3-1,3-2,3-3.
Fig. 3-1 Relation of single impact energy and cumulative thrust energy of G-105

Fig. 3-2 Relation of single impact energy and cumulative thrust energy of S-135
It can be seen from the figures, G-105, S-135 and V-150 three kinds of drillstring materials’ cumulative energy decreases sharply with the increase of single impact energy. And the cumulative impact energy has a exponential relationship with single impact energy, which is similar to the fatigue "S-N" curve. The results show that the low amplitude-repeated impact resistance of drillstring material decreases obviously with the increase of single impact energy. Therefore, the single impact energy, that is, the rotation speed of the drillstring in the working process has a great influence on the low amplitude-repeated impact resistance. In the actual drilling operation, reasonable drillstring rotation speed should be selected to avoid the early failure of drill string.

The relationship between the low amplitude-repeated impact and the material strength index is established as type (3-1).

\[ A = 1092.2 e^{0.5376\sigma} E^{(-0.3495\sigma^2 + 0.9365\sigma - 2.19)} \]  

(3-1)

3.2. Presentation of low amplitude-repeated impact energy conversion efficiency

Under the condition of low amplitude-repeated impact, the initial damage of the structure will increase slowly. The cumulative impact energy is different under the different single impact energy.

By comparing the Charpy impact energy and the repeated impact cumulative energy, we use the Charpy impact energy to divide by the repeated impact cumulative energy, and the percentage of the ratio is obtained under different single impact energy. We define the energy conversion efficiency is above percentage, which as shown in table 3-2.

Table 3-2 The percentage of Charpy impact energy divided by the repeated impact cumulative energy

| Single impact energy \(E\) \((J)\) | 2.21 | 2.50 | 3.02 | 3.56 | 3.94 | 4.35 | 4.98 |
|-----------------------------------|------|------|------|------|------|------|------|
| The Charpy impact energy of G-105 is 21.66J |
| G-105 cumulative energy \((J)\) | 475.1 | 450.2 | 354.3 | 225.5 | 195.2 | 175.6 | 166.6 |
| Percentage \((\%)\) | 4.56 | 4.81 | 6.11 | 9.60 | 11.11 | 12.33 | 13.00 |
The Charpy impact energy of G-105 is 20.25J

| Repeated impact | cumulative energy (J) | Percentage (%) |
|------------------|-----------------------|----------------|
| S-135            | 640.9  627.5  483.1  358.2  315.9  219.5  186.2 | 3.16  3.23  4.19  5.65  6.41  9.23  10.88 |

The Charpy impact energy of G-105 is 18.86J

| Repeated impact | cumulative energy (J) | Percentage (%) |
|------------------|-----------------------|----------------|
| V-150            | 897.3  562.5  274.2  239.4  219.1  139.6  119.5 | 2.10  3.35  6.88  7.88  8.61  13.51  15.78 |

It can be seen from the chart, the Charpy impact energy of drillstring material is less than the low amplitude-repeated impact cumulative energy. It is obvious that just some of the energy of repeated impact load on the specimen do good to crack initiation and propagation process. With the increase of single impact energy, the energy for the crack initiation and crack propagation is higher. Moreover, the impact sensitivity of high strength V-150 drillstring material is obviously improved with the increase of single impact energy. However, in the case of lower impact energy(such as 2.21J), the sensitivity of high grade steel V-150 is significantly lower than that of low grade steel G-105. The sequences of sensitivity is V-150 > S-135 > G-105. Therefore, in the condition of low speed drilling operation, the selection for high grade steel drillstring could have longer service life.

3.3. Effect trend of H$_2$S on repeated impact resistances of drillstring

Set the rotation speed to 150 r/min, and the low amplitude-repeated impact experiments for different immersion time of G-105, S-135 and V-150 respectively are made, then the accumulated impact energy is obtained. Based on the experimental data, the variation curves of the cumulative impact energy of the drillstring materials with different corrosion time are obtained, and the curves as shown in figure 3-4,3-5,3-6.
Fig. 3-5 Effect of H$_2$S immersion time on cumulative thrust energy of S-135

It can be seen from the above three diagrams that the low amplitude-repeated impact resistance of the three kinds of drillstring materials with H$_2$S environment is much lower than that without H$_2$S, and the longer corrosion time causes the low amplitude-repeated impact resistance to decrease rapidly.

In order to compare the influence of different corrosion time on the impact resistance of different drillstring materials, the percentage of the low amplitude-repeated impact resistance with different corrosion time of three kinds of materials was calculated, and the chart of comparative analysis as shown in Figure 3-7.
It is obtained from the experimental data that with the immersion time less than 120h, the decrease in cumulative impact average energy of S-135 is lowest, and the cumulative impact average energy of V-150 drops at the most in the all stage of corrosion. But the low amplitude-repeated impact resistance of three kinds of drillstring material decreased constantly with longer immersion time. When the corrosion time is 168h, the average value of cumulative impact energy of G-105 decreased by 53%, and the average value of cumulative impact energy of S-135 decreased by 56.25%, while the average value of cumulative impact energy of V-150 decreased by 59.95%. It can be seen that the low amplitude-repeated impact resistance of high strength material such as V-150 drillstring decreased significantly, which indicates that it is more sensitive to H₂S corrosion environment. Hence, this type drillstring should avoid contacting with hydrogen sulfide corrosion environment for long time. This low amplitude-repeated impact method is better to reflects the influence of H₂S corrosion environment on drillstring material, because it can describe the failure of drillstring in the underground actual service situation.

3.4. Analysis of fractures
The EDS energy spectrum analysis of V-150 fracture surface after the corrosion time of 12h as shown in Figure 3-8 below.
EDS has detected the Na and Cl elements which have been permeated into the fracture surface. It is indicated that H₂S corrosion environment causes the crack of the metal surface, and the Cl⁻ can penetrate into the surface of metal material. Then the passive film is ruptured and will develop pitting corrosion, so it will reduce the mechanical properties of metal materials greatly. The results verify the above conclusion which is mentioned, it means that the low amplitude-repeated impact resistance of drillstring material in H₂S environment is far less than that in non-corrosive medium condition.

4. Establishment of cumulative fatigue model

The low amplitude-repeated impact is different from from the Charpy impact. The low amplitude-repeated impact load is a kind of dynamic load. In this paper, the rupture process is divided into two aspects from the angle of damage accumulation and energy. The impact process of specimen is also divided into two parts. It means that the energy consumption is also divided into two parts. One is that the repeated impact energy causes the specimen to accumulate damage and to initiate crack in prefabricated gap; The other one is that the stress concentration causes the crack propagation at the notch root.

Make the model assumptions as follows:
1) The sample is continuous and uniform, and the density is unchanged after deformation;
2) The chopping block is considered as a rigid body, and the plastic deformation of the specimen is negligible after the collision; The specimen is regarded as an elastic plastic body, which can produce elastic plastic deformation;

3) The impact energy is absorbed completely and the energy loss is negligible;

4) It is linear elastic relation before crack formation at notch root.

The energy of each impact is equivalent to a small rectangular area, the sum of a several small rectangles area is the area of entire curve around, that is the consumed energy \( A_{kn} \) of the crack initiation and expansion, as shown in figure 4-1. The energy absorption value before crack initiation is \( A_{kn} \), and the energy absorption value after crack initiation is \( Q \), so that the energy calculation method of the whole repeated break process is shown (4-1):

\[
A = A_{kn} + Q
\]

Fig. 4-1 Schematic diagram of energy accumulation before crack initiation

The detailed analysis of the two phase energy equivalence method is as follows:

(1) Under the condition of low amplitude-repeated impact, the crack initiation at the notch requires the stress concentration to cause the root of the notch to yield and to produce a certain plastic deformation. The specimen prefabricated notch root absorbs a certain amount of energy when the specimen fixed on the specimen holder impacts the chopping block each time. The picture of specimen holder as shown in Figure 4-2. When the edge of the specimen impacts the chopping block, it can produce a certain elastic deformation. The specimen restores original shape after knocking, but the gap has been damaged. After several times, the damage has been accumulated to a certain extent, and the specimen was no longer return to its original shape, namely it has developed the plastic deformation. At the same time, the crack begins to start from the notch root initiation and begins to expand, the absorbed energy is the energy \( A_{kn} \) in type (4-1), which corresponds to blue small rectangular area in Figure 4-1.
Based on the crack nucleation criterion of Stroh\cite{19,20}, the method of crack nucleation and crack initiation is derived:

\[
A_{kn} = k \frac{(1-\nu^2)\pi^2 S_B}{12a_0E} \mu d \sigma_y^2
\]  
(4-2)

The \( K \) value in the formula (4-2) is a constant with respect to the material.

(2)When the tip of the prefabricated gap is yielding, the stress intensity factor at the crack tip reaches the fracture toughness \( K_{IC} \). And the crack at the notch is produced and expand rapidly. \( K_{IC} \) can be obtained by formula. The energy causes stress concentration and causes the plastic zone. When the notch plastic zone reaches the yield strength of the material and the cumulative damage satisfy the crack initiation condition, the crack starts initiate from the notch root. To define the initial crack opening angle is \( \theta_0 \) (it is 45° of prefabricated gap in this paper), the notch crack opening angle change into \( \theta_0, \theta_1, \theta_2, \theta_3, \ldots, \theta_n \) after the impact load acting on the specimen. The initial crack length is also defined as \( a_0 \). With the expansion of the crack, the crack length becomes into \( a_1, a_2, a_3, \ldots, a_n \).

When the specimen impacts the chopping block, the crack length increases \( \Delta a \), then the crack length becomes into \( a_n \). The \( a_n \) is the initial crack of the next crack expansion. The crack propagation stress can be calculated based on the value of \( K_{IC} \). Also the the total power consumption (\( Q \)) of the crack propagation process can be caculated by using the geometric integration principle of the stress and displacement of each impact.

The extended function of \( K_{IC} \) calculation method is derived based on the crack, crack under plane strain condition for the total power consumption growth expression:
\[ Q = \frac{1}{2} \sum_{i}^{n} \sqrt{\frac{0.17F_{m}^{2}}{0.35g_{i}}} \cdot \Delta a_{n} \]  \hspace{1cm} (4-3)

To put the formula (4-2) and (4-3) into (4-1), then we can get a complete multi break cumulative energy model.

5. Conclusions

Based on the above mentioned research, the following conclusions can be drawn:

1. The method and a device to measure the material property under the low amplitude-repeated impact has been perfected, and the three types of material G-105, S-135 and V-150 drillstring materials have been done under non-corrosive medium conditions and H_{2}S environments. This method is better than the traditional Charpy impact experiment, because it can describe the failure of drillstring in the underground actual service situation.

2. Under non-corrosive medium conditions, change the single impact energy, with the increase of single impact energy, the low amplitude-repeated impact resistance of three types of drillstring materials decreased significantly. According to the energy conversion efficiency curve, it is concluded that G-105 is more prone to failure than the S-135 and V-150 in low amplitude-repeated impact.

3. In the constant single impact energy, the experimental results show that the hydrogen sulfide corrosion has a great influence on the G-105, S-135 and V-150, and the influence of V-150 drillstring steel is the highest obviously. Through the SEM observation of the typical fracture surface, the brittle phase caused by hydrogen sulfide immersion corrosion was found at the fracture surface.

4. The mechanical properties of drillstring material can rely on the traditional analysis testing methods, but the new method to consider the the actual load of the drillstring in the drilling process is the best. Because high tensile strength steel is more sensitive to hydrogen sulfide, low level and wall thickness steel in H_{2}S environment is suggested to use. Moreover, long time working in the corrosive environment is not permitted to avoid drillstring failure.

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