Early Inspection of Drill String Fatigue Damage Based on Metal Magnetic Memory Method

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Abstract. The frequent drill fracture accidents during the drilling process severely affected the exploration and development proceedings of gas resources. To solve this problem, this paper applied the metal magnetic memory (MMM) technique to the detection experiment of drill string fatigue damage. 42CrMo steel as representative tool material in drilling was selected to carry out the tensile fatigue test to simulate the fatigue process of drill service. It collected MMM signals on the surface of samples under different cycle times and extracted MMM signal feature parameters. In addition, single tool thread damage detection test and engagement thread fatigue damage detection test during the drilling process were conducted. The results of the tensile fatigue test indicate MMM signal feature parameters can well illustrate the tensile fatigue process of materials and represent their stress concentration degrees of different fatigue stages. Single tool thread damage detection test and drill string engagement thread fatigue damage detection test during the drilling process indicate that MMM technique can effectively detect the stress concentration degrees of tool threads and their distribution, which provide safe and effective testing methods to prevent drill string fracture accidents from happening.

Introduction

The drill string is made up of numerous drill pipes by means of tapered threaded connections. The drill string experience strong fatigue loads during the drilling operations. More than 50% of failures are caused by fatigue[1][2]. The fatigue failure of drilling tools is the result of repeated accumulation of cyclic stress on stress concentrated parts. Under the effect of cyclic alternating compound stress, it’s the prominent stress concentration part where cracks initiate. Then cracks propagate under the influence of further cyclic stress. When they propagate to a certain degree, drilling tools will suddenly break. Connections are the preferential sites of structural failures. It can be expensive and time consuming due to the recovery procedures[3]. Therefore, it is very essential to detect the abnormal stress concentration and micro-cracks in sensitive parts (especially the connections) during the use process of drill tools and take timely steps before cracks propagate in order to effectively prevent drilling tool fatigue damage.

Metal magnetic memory (MMM) method is an effective and non-destructive technique for inspecting stress concentration and early damage, or even preventing the occurrence of abrupt structural failure[4]. Different from traditional magnetic non-destructive method, MMM measures the residual magnetic fields induced by the combined action of mechanical stress and the geomagnetic fields without artificial magnetization on the detected objects. Therefore, MMM is a more preferable method for assessing early damage[5]. By far, lots of
research on MMM have been conducted. Roskosz and Bieniek[6] presented a residual stress evaluation method by comparing the residual stress distributions with the residual magnetic field measurements induced by tensile stress. Furthermore, the universality of the residual stress evaluation method was verified by using plate samples with two geometries[7]. Li et al.[8] developed a test platform to collect, store and process the magnetic field distributions during tensile tests based on leakage flux theory. In fatigue tests, most research of MMM technique is about the range of normal components of MMM signals under different loads; whereas research about tangential components under different cycles is very limited. This paper selected 42CrMo steel, which is a kind of representative drilling tool material, to carry out the tensile fatigue test to simulate the fatigue process of drill service. During the test, the tangential component signals, $H_p(x)$, under different cycles are collected and the gradient peaks of tangential component signals, $K_{max}$, are extracted. Hence the fatigue process was presented by the $H_p(x)$ and $K_{max}$. Combined organizational deformation of the materials, stress concentration and magnetic signals, stress and stress concentration of the materials during the fatigue process can be represented in a new and more specific way, which provides novel thoughts for the fatigue damage and life prediction. Besides, based on the achievement of the indoor test, this paper has done single drilling tool thread damage detection test and drill string engagement thread fatigue damage detection test during the drilling process.

1. Fatigue Test

1.1 Materials and Experiment Method

The specimen is made of 42CrMo steel, of which the yield strength is 980 MPa and the tensile strength is 1080 MPa. Its chemical composition is shown in Table 1. The geometry of the specimen is presented in Fig.1. A small transverse precut artificial notch which is 2mm wide and 1.5mm deep, was carefully cut by a linear cutting machine at the center of the specimen. Four lines were arranged vertical to the notch center at intervals of 90 degree, numbered L1–L4 respectively. Three samples were machined in order to avoid contingency caused by single sample. The effective testing distance was 60mm.

The tensile fatigue tests were carried out on PLN-100 hydraulic servo machine. Stress control with the maximum of 20kN, was adopted in the fatigue tests. Loading force was sinusoidal; stress ratio was 0.1, and loading frequency was 3Hz. The $H_p(x)$ was detected every 2000 cycles by stress concentration detector based on the theory of giant magnetoresistance[9][10]. The sample was placed on the level platform after unloading.

<table>
<thead>
<tr>
<th>Steel no.</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
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<td>42CrMo</td>
<td>0.43</td>
<td>0.31</td>
<td>0.67</td>
<td>0.014</td>
<td>0.007</td>
<td>0.89</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Fig. 1. The picture of the sample geometry
1.2 Characteristics of Magnetic Memory Signals

The test results of the three samples were similar. The variation tendency of magnetic signals measured along the four lines (lines L1–L4) was similar. Therefore only the results from the line L1 of sample 1 are shown. For careful analysis of the whole fatigue process, the variation of $H_p(x)$ on the specimen surface under different cycles is divided into four parts shown in 2(a)-2(d). The abscissa is the effective length for measuring, the ordinate is the magnetic field intensity, and different colors represent different cycles.

![Fig. 2](image)

**Fig. 2.** The $H_p(x)$ along the surface of the specimen during the cyclic procedure: (a) before $2 \times 10^3$ cycles; (b) from $2 \times 10^3$ to $4 \times 10^4$ cycles; (c) from $4 \times 10^4$ to $5.4 \times 10^4$ cycles; (d) after $5.4 \times 10^4$ cycles

In order to further analyze the relationship between MMM signals and fatigue damage, the $K_{max}$ under different cycles was extracted ($K_{max}=\max(|K|)$). The quantitative evaluation of MMM is to determine the value of $K$ which is the gradient of magnetic field $H_p(x)$ in the stress concentration zone ($K=\Delta H_p(x)/\Delta L$)[11][12][13]. The $K_{max}$ directly represents the maximum of stress concentration severe degree in the detection area. The value of $K_{max}$ is closely related with whether the workpiece can continue to direct service. Fig.3 shows the variations of $K_{max}$ under different fatigue cycles are similar to the variation of $H_p(x)$. It can be seen from Fig.3 that the variation of $K_{max}$ under different fatigue cycles can be divided into four different stages: the initial stage may be described as the rapid increase of the $K_{max}$ from 0.027v/mm to 0.097v/mm before $2 \times 10^3$ cycles; the second stage is fluctuated from $2 \times 10^3$ to $4 \times 10^4$ cycles and $K_{max}$ is in the fluctuating region of 0.09v/mm
to 0.13v/mm; the third stage is converged from $4 \times 10^4$ to $5.4 \times 10^4$ cycles, when the specimen is at a convergence stage, and the Kmax slightly ranges from 0.12v/mm to 0.13v/mm until the crack initiation; the fourth stage is propagation stage ($\geq 5.4 \times 10^4$ cycles). After entering the fourth stage, the Kmax increases rapidly until the failure of specimen.

The variation of Kmax during the whole fatigue tests can be explained by MMM test theory, ductile material slip crack theory and ferromagnetic principles.

At the initial stage of fatigue tests, the stress energy within the specimen strengthened sharply. Magnetoelastic energy was produced accordingly within the specimen to offset the stress energy. However, the production of magnetoelastic energy was through the variation of magnetic domain wall position and magnetic domain self-magnetization direction, which caused the leakage magnetic field on the material surface. In the end, it was represented by the sharp increase of Kmax at the initial stage. During the material grain sliding motion, there was a process of energy accumulation, which took some time, but the stress energy got released after the sliding motion. Therefore during the stage of mixing and superposition of accumulation and sliding, a mass of grains could result in the slow and regular fluctuation of stress within materials, which explained the state of fluctuation of Kmax at the second stage. Generally, when the fatigue life of the test specimen is over half, the majority of the slip bands will stop motion. Only few persistent slip bands are able to continue expanding, and finally develop into fatigue crack sources. At that time, internal accumulation of energy was only used to facilitate persistent slip bands to expand[14]. That’s why the energy needed decreased remarkably. That explained the third stage of convergence of the Kmax. After the crack initiation, since the cross section of the specimen was narrow, crack propagation ended until the specimen broke within fewer cycle times. During this process, the value of Kmax increased quickly, which corresponded to the fourth stage.

The above results show that Kmax exhibits different characteristics at different stages of fatigue damage. From Fig.3, when cycles reach $5.6 \times 10^4$ cycles, Kmax begins to increase quickly from 0.16 v/mm. Specimen develop from the crack initiation to propagation stage, which is a very dangerous state. So Kmax=0.16 v/mm can be a first-line standard to judge whether the stress concentration degree of drill tools made of 42CrMo is at a dangerous state.

![Fig. 3. The Kmax under different cycles](image)

2. Field Test

Most of drill string failures are due to fatigue of the threaded connections. The complex geometry and inherent stress concentrations of drill string act as likely fatigue crack initiation sites[15]. MMM technology was used to detect the external and internal threads of scrapped API 5 inches drill pipes in one west oilfield in China. The type of threads is NC50. In order to
satisfy the need of rapid, comprehensive and accurate detection of the stress concentration state of threads, the entire thread was covered completely by the detection device through uniform distribution of 16 channels, which could achieve complete thread detection in one time.

In Fig. 4(a), the detection result of external threads shows that stress concentration state of about 3 teeth, counted from the thread nearest to shoulder, is poor, and the $K_{\text{max}}$ reaches $0.25v/\text{mm}$. In Fig. 4(b), the detection result of internal threads shows that stress concentration state of the second and third teeth is serious, counted from the farthest thread from shoulder, and the $K_{\text{max}}$ reaches $0.23v/\text{mm}$. As Fig. 4(a) and Fig. 4(b) show, the most serious stress concentration positions in internal and external threads by MMM detection coincide with those obtained by finite element simulation by A.R. Shahani[16] and Mohamed Ferjani[17]. In addition, the positions of higher accident rates of drilling tool threads in the oilfield are consistent with those by MMM detection results.

![Fig. 4. The $K$ of drilling tool threads detection: (a) external threads of pin and (b) internal threads of box](image)

As we all know, realization of real-time monitor of the fatigue damage of the drill string during the drilling process is significant for reducing or even eliminating the drill string fatigue fracture incidents.

Wellhead drill string fatigue damage monitor device, based on MMM theory, was developed. The real-time monitor tests of wellhead drill string fatigue damage were completed. The $K$ of engagement thread which is an accident-prone portion of drill string is presented, as shown in Fig. 5. It is the $K$ of engagement thread in which stress concentration is poor. The $K_{\text{max}}$ of engagement thread is near the shoulder of pin. The stress concentration degree near the shoulder of pin is more serious than that far from shoulder of box. The $K_{\text{max}}$ of whole thread engagement is $0.25v/\text{mm}$. As Fig. 6 shows, in the wellhead drilling string fatigue damage real-time monitor tests, the experimental apparatus achieved integrated monitor of connection, pipes and thickening area, providing technical support to prevent drilling accidents because of drilling string fatigue damage during the drilling process.
3. Conclusions

The giant magnetoresistive sensor, based on GMR effect, has characteristics of small volume, high sensitivity and high reliability[10]. Those characteristics provide convenience for giant magnetoresistive sensor applied to the drill string fatigue damage test. This paper selected 42CrMo steel to carry out the small-size specimen tensile fatigue test. During the test, the $H_p(x)$ under different cycles is collected and the $K_{max}$ is extracted. In addition, single tool thread damage detection test and engagement thread fatigue damage detection test during the drilling process were conducted in one west oilfield of China. The conclusion drawn from the work is as follows:

- The $H_p(x)$ and $K_{max}$ of tensile fatigue test under different cycles can be divided into four different stages: the initial stage, fluctuation stage, convergence stage and propagation stage.
- Fatigue test result shows after $K_{max}$ reaches 0.16v/mm, the $K_{max}$ of sample surfaces increases rapidly with the increase of cycles until the failure of the specimen.
- The detection result of external threads of scrapped drilling tools shows that stress concentration state of 3 teeth is poor, counted from the thread nearest to shoulder. The detection result of internal threads show that stress concentration state of the second and third teeth is serious, counted from the thread farthest from shoulder.
- Wellhead drill string fatigue damage monitor device was developed. The drill string
wellhead real-time monitor tests are completed. The detection results of engagement thread show that the Kmax is near the shoulder of the pin, which is in accord with that of drill string engagement thread in the oilfield.

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