Study on ultrasonic second bottom echo method to examine granularity grades for 20Cr1Mo1V(Nb)TiB fasteners

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Abstract: Based on the scattering attenuation principle to ultrasonic wave, the detection technique was studied for granularity grades of 20Cr1Mo1V(Nb)TiB fasteners including class I (granularity grade 1~2), class II (granularity grade 3~4) and class III (granularity grade 5) by using an A-type ultrasonic pulse reflecting method. Results show that, the effect of different granularity grades on the ultrasonic scattering attenuation is significant, and the scattering attenuation in every fastener to ultrasonic wave increases with the increase of the probe frequency. In the same frequencies and When the first bottom echo height is 80% of the full scale, the average second bottom echo height of class I is about 7.6-28.1% lower than that of class III, its average second bottom echo amplitude is about 10.6-15.8dB higher than that of class III; the average second bottom echo height of class II is about 6.7-9.4% lower than that of class III, its average second bottom echo amplitude is about 4-5.6dB lower than that of class III. When the probe frequencies are 5MHz and 10MHz, the attenuation of coarse grain (class I and class II) in fasteners to ultrasonic wave is more evident. This technique provided a new way to identify the granularity grades for 20Cr1Mo1V(Nb)TiB fasteners efficiently, conveniently, accurately and surface non-destructively.

Keywords: Ultrasonic second bottom echo method; 20Cr1Mo1V(Nb)TiB; fastener; granularity grade

1 introduction

The high-temperature fasteners of steam turbine are very important metal supervisory components for coal-fired power plants, and they are widely used in the parts which need to fasten or seal, like the joint face of cylinder, governing valve, main stop valve and so on. But in recent years, coarse grains (hereinafter referred to as coarse grain) were frequently found in fastener in execute the thermal power unit overhaul metal inspection and early inspection of the infrastructure equipment. The coarse grains may lead to lower mechanical properties, especially dramatically reduce the impact toughness. And a lot of brittle fracture accident happened due to fasteners’ coarse grain, which has become a serious threat to safety of running machine and personal safety. The accident especially in fasteners made of 20Cr1Mo1V(Nb)TiB is the most
serious\textsuperscript{[1]}. For this, DL/T439-2006 "the technical guide for high-temperature bolt of fossil-fired power plant" from our country explicitly prescribed: for fasteners made of 20Cr1Mo1V(Nb)TiB, it should be scrapped for granularity grade 1~2; The original design made of 20Cr1Mo1V(Nb)TiB and introduced large units using this kind of fasteners, granularity grade should be 5. Therefore, it is of great significance to appraisal granularity grade for this kind of fasteners material, promptly find out coarse grain fasteners for replacement, and ensure its safety of running machine and personal safety is of great significance.

At present, the metal materials’ grain size detection methods are mainly metallographic method, ultrasonic velocity method, ultrasonic attenuation method and eddy current conductance method\textsuperscript{[2-6]}. Except metallographic method which has matured, the other methods are still in development stage, the research results are not yet applied. In China, power industry in accordance with common DL/T439-2006 standard, inspect a certain proportion of fasteners sample using metallographic method, but using this method to evaluate materials’ granularity grade, we can only get the granularity grade of the observation surface\textsuperscript{[7]} and it can not only damage materials’ surface, but also inspection cycle is long, the cost is high, and with a random inspection parts, the test result is one-sided. So it can't represent grain level of whole fastener, will naturally cause leak test for coarse grain fasteners, cause hidden trouble to the safety and stable running of the unit. Therefore, the electric power industry urgently need a new method which can census coarse grain fasteners by 100% proportion with rapid, efficient, accurate and lossless surface. Use of ultrasonic to realize grain size detection, has the characteristics of being nondestructive, and the results reflect the average grain size of the ultrasonic wave propagation paths. It is more reasonable than metallographic method to detect the grain size in a single plane. Based on this objective, this paper for the first time develops a new method of using ultrasonic to test granularity grade of steam turbine high-temperature fasteners at home.

2 Basic principle

When ultrasound spread in the media, along with the increase of distance, ultrasonic energy gradually decrease. This phenomenon is called ultrasonic attenuation, and it includes the diffusion of acoustic beam and the scattering of grain and the medium absorption. Among them scattering attenuation is closely related to material’s coarse grains. When grains of the materials are coarse, scattering attenuation becomes serious, and scattering of ultrasonic along the complex path spread to the probe. In this phenomenon, on the one hand, it can cause spurious echo on the screen, make the signal-to-noise ratio decrease obviously, noise will annihilate defect wave when serious. On the other hand, due to the coarse grains of material, the organization is nonuniform and anisotropic sometimes, they make ultrasonic scattering attenuation serious, resulting in significantly reduced ultrasonic ability to penetrate, causing reduced echo height. Therefore, it becomes possible for use of ultrasonic echo signal differences to identify granularity grade\textsuperscript{[1]}.  

3 Test method and process
3.1 Test interference factors and ruling out

When ultrasonic detection system is determined, the actual measurement of ultrasonic attenuation A should include the attenuation of material itself M (scattering and absorption) and the spread loss of sound beam L and the loss of reflection R and the loss of coupling C, namely \( A = M + L + R + C \). Diffusion loss depends mainly on probe diameter and sample size and wavelength of acoustic wave in the medium. So in the same test conditions, the spread loss of different samples were caused by the sample size shape; And the reflection loss and the coupling loss are caused by the various factors including sample surface bumpy, waveform conversion loss and the sound energy absorption by probe and the coupling materials\(^4\).

In order to minimize the effect on the authenticity of the test results by aforementioned factors, the following measures were adopted in the test: (1) The geometry size of the sample have good consistency, material and specifications are 20Cr1Mo1V(Nb)TiB and M56 × 250 mm. (2) To reduce the effect of human factors on the test result, test process were all executed by the technician who has obtained the national nondestructive testing qualification. (3) To facilitate full contact of probe and the measured sample, sample end has been gone through metallographic polishing treatment. At the same time, special ultrasonic couplant was used in order to reduce the reflection loss and the coupling loss to the greatest degree.

The stability of the test system and the consistency of the test condition were ensured through the implementation of the above measures. Because the difference value of L and R and C is very small, we can ignore its influence on the test result. So the measured ultrasonic attenuation A can be viewed as the attenuation M of material itself, and directly using the measurement of ultrasonic attenuation quantity, then comparing attenuation of different granularity grade of fasteners, consequently granularity grade of the fasteners can be identified.

3.2 Test method and process

A-type ultrasonic pulse reflecting method was used in this study, Germany USM35 model was used as ultrasonic instruments, the special ultrasonic couplant was used as the coupling agent, three types of normal probe 2.5 P20Z and 5P20Z and 10 P20Z were selected. The test procedures are as follows:

(1) To prepare test samples, the 42 collected sample fasteners of the maintenance, were mechanically processed into unity of the specifications of the M56×250 mm, detection surface was executed metallographic surface polishing treatment (as shown in figure 1 below).
(2) Based on DL/T439-2006 "the technical guide for high-temperature bolt of fossil-fired power plant" the sample’s granularity grade was detected by metallographic group method, and divided into class I (granularity grade 1,2), class II (granularity grade 3,4) and class III (granularity grade 5), including 16 fasteners of class I, 14 fasteners of class II, 12 fasteners of class III (part of the fasteners’ analysis of metallographic organization in figure 2).

Fig. 1 Fastener samples for test

Fig. 2 Metallurgical structure of part of fasteners
(3) According to requirements of "the technical guide of ultrasonic inspection for high-temperature tight bolts" (DL/T 694-1999), we used the LS-1 standard test blocks to determine the sensitivity by adjusting the first bottom echo height to 80% of full scale as the benchmark sensitivity.

(4) Executing ultrasonic inspection test, recording, sorting, analyzing the test data, and drawing the conclusion.

4 Experimental results and analysis

To reduce the influence of accidental test data of individual sample on the authenticity of the overall test results, and the ultrasonic data of all kinds of fasteners has taken the arithmetic mean. The test data as shown in table 1.

<table>
<thead>
<tr>
<th>probe type</th>
<th>granularity grade</th>
<th>the average of second bottom echo height (%)</th>
<th>the average of second bottom echo amplitude (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5P20Z</td>
<td>class I</td>
<td>8.3</td>
<td>46.2</td>
</tr>
<tr>
<td></td>
<td>class II</td>
<td>16.5</td>
<td>39.2</td>
</tr>
<tr>
<td></td>
<td>class III</td>
<td>23.2</td>
<td>35.7</td>
</tr>
<tr>
<td>5P20Z</td>
<td>class I</td>
<td>6.4</td>
<td>40.3</td>
</tr>
<tr>
<td></td>
<td>class II</td>
<td>22.2</td>
<td>30.7</td>
</tr>
<tr>
<td></td>
<td>class III</td>
<td>29.8</td>
<td>27.8</td>
</tr>
<tr>
<td>10P20Z</td>
<td>class I</td>
<td>4.2</td>
<td>51.9</td>
</tr>
<tr>
<td></td>
<td>class II</td>
<td>21.9</td>
<td>41.7</td>
</tr>
<tr>
<td></td>
<td>class III</td>
<td>30.3</td>
<td>36.1</td>
</tr>
</tbody>
</table>

4.1 the influence of granularity grade on the attenuation of ultrasonic second bottom echo

![Fig.4](image-url) The average value contrast fig of ultrasonic second bottom echo height of various fasteners
As can be seen from the graph, no matter which model of detector for the ultrasonic probe are used, ultrasonic scattering attenuation phenomenon is significant due to coarse grain, and wave amplitude average increase by the increasing of grain size, while wave amplitude average of second bottom echo amplitude decreases by the increasing of grain size. And ultrasonic attenuation is most obvious in class I. This is because the ultrasound was weakened through the coarse grains and it is influenced by many factors, but mainly influenced by the inhomogeneity of the material, such as: grain boundaries of polycrystalline material, the interface of different phase component, foreign material and so on, which cause the most significant waves scattering caused by many tiny interface which have different acoustic impedance, and thus lead to the sound pressure or sound energy attenuated.

Table.2 Experimental data table of various fasteners with ultrasonic second bottom echo

<table>
<thead>
<tr>
<th>probe type</th>
<th>the comparison between granularity grade (%)</th>
<th>the average difference of second bottom echo height (dB)</th>
<th>the average difference of second bottom echo amplitude (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5P20Z</td>
<td>class I, III</td>
<td>14.9</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>class II, III</td>
<td>6.7</td>
<td>4</td>
</tr>
<tr>
<td>5P20Z</td>
<td>class I, III</td>
<td>23.4</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>class II, III</td>
<td>7.6</td>
<td>4.9</td>
</tr>
<tr>
<td>10P20Z</td>
<td>class I, III</td>
<td>28.1</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>class II, III</td>
<td>9.4</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Table 2 compares the test data for all kinds of fasteners’ ultrasound second bottom echo. compared
with class I and class III of fasteners, the average second bottom echo height of class I is about 7.6 ~ 28.1% lower than that of class III, its average second bottom echo amplitude is about 10.6 ~ 15.8dB higher than that of class III; compared with class II and class III of fasteners, the average second bottom echo height of class II is about 6.7 ~ 9.4% lower than that of class III, its average second bottom echo amplitude is about 10.6 ~ 15.8dB higher than that of class III.

![Fig.6 The difference contrast fig of average value of ultrasonic second bottom echo height](image)

![Fig.7 The difference contrast fig of ultrasonic amplitude average value](image)

Due to the ultrasonic scattering attenuation of the media is related to and its grain size, anisotropy degree and ultrasonic frequency\[8\]. According to the spherical wave attenuation equation...
\[ P_s = \frac{P_o}{\sqrt{X}} e^{-ax} \] and scattering attenuation coefficient \( a = \begin{cases} \frac{e^2 F d}{c_s} f d^2 \lambda & d = \lambda \\ \frac{e^2 F d}{c_s} f d^2 \lambda & d < \lambda \end{cases} \) (In the above formula: \( P_o \) — sound pressure of which the distance from the wave source to 1 unit; \( P_s \) — sound pressure of which the distance from the wave source to \( X \) unit; \( X \) — to the distance of the wave source; \( a \) — medium attenuation coefficient, the unit is NP/mm; \( e \) — natural logarithm’s bottom (\( e = 2.718... \)); \( f \) — acoustic frequency; \( d \) — medium grain diameter; \( \lambda \) — wavelength; \( F \) — anisotropic coefficient; \( c_s, c_3 \) — constant), when ultrasonic wave spreading in the same medium, ultrasonic attenuation has strong dependence to frequency. When \( d < \lambda \), scattering attenuation coefficient becomes direct ratio with \( f^\lambda \) and \( d^\lambda \). Therefore, with the increase of frequency, the degree of scattering attenuation becomes serious, the more sound waves of materials are scattered, the less reflection sound energy will be received by the probe, test results and the theoretical analysis is perfectly fit. But use frequency for 5 MHz, 10 MHz probe to detect fasteners’ grain level, ultrasonic scattering attenuation of the fasteners of class I is more obvious than the fasteners class II and III, which makes it possible to use ultrasonic detection for the granularity grade of fastener made of 20Cr1Mo1V(Nb)TiB.

**4.2 the application of the field detection fasteners’ grain levels**

According to the above analysis, when testing granularity grade for fasteners made of 20Cr1Mo1V(Nb)TiB by using ultrasound in the field, in order to improve the work efficiency, and the fasteners of class III can be used to adjust reference sensitivity, primary the first bottom echo height is adjusted to 80% of the full scale, and gain 10.6~15.8 dB to detect other fasteners’ granularity grade (if the fasteners specifications to be inspected is different with above sample, need to add the flat bottomed hole echo decibel difference flat bottomed hole echo, which was converted according to echo sound pressure of large flat surfaces, its formula is as follows: \( \Delta = 20\lg X_1/X_2 \)), through the observation of ultrasound second bottom echo height and the wave amplitude, and based on the experience, we can accelerate and accurately estimate fasteners’ granularity grade.

(a) class I fastener  (b) class II fastener
Figure 6 is ultrasonic testing signal figure for using 5 P20Z probe to detect in fasteners made of 20 Cr1Mo1V (Nb) TiB. The graph clearly shows, the ultrasonic second bottom wave height difference of I class and II class and III class of fastener is very big, so it is very easy to judge the level of grain. But in the filed test, because of different strength of the personnel’s hand, coupling effect is different, leading to different ultrasonic height, so we should use the inspection experience and prudent judgment, and verify doubt fastener with metallographic organization analysis when necessary, so as to avoid the undetection to coarse grain fasteners and to bring the safe operation to the hidden trouble in thermal power unit.

5 Test results

(1) In the same detection frequency, when primary bottom wave height is 80% of full scale, compared with I class and III class fasteners, I class’s low ultrasound second bottom wave average 7.6 ~ 28.1%, the high average amplitude about 10.6 ~ 15.8 dB; compared with II class and III class of fasteners, II class’s low ultrasound second bottom wave average 6.7 ~ 9.4%, the high average amplitude about 4 ~ 5.6 dB.

(2) For all kinds of fasteners, the ultrasonic scattering attenuation becomes more serious along with the increase of probe frequency, and when the probe frequency are 5 MHz and 10 MHz, the ultrasonic scattering attenuation of I class and II class of fasteners is more obvious than III class of fasteners.

(3) In the use of ultrasound grain level test for fasteners material 20 Cr1Mo1V (Nb) TiB at field test, inspection personnel can use III class of fasteners to adjust reference sensitivity. Through the observation on the screen of the echo signal and based on the inspection experience, we can make an fast and accurate estimate to the grain level of fasteners.

6 references


