Research on Axle Press-fit Phased Array Ultrasonic Inspection Technology

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Abstract
The crack detection methods are widely used in wheel-set maintenance, especially by ultrasonic and magnetic particle testing. Wheel, gear, and break disk are pressed or shrunk on the axle, and defects at axle press-fit parts can only be used by ultrasonic method by accessing from axle body or end face. This press or shrink processing has significant influence on the in-service axle defect detection comparing with open defect on the axle. Parts of ultrasonic signal would go into wheel hub, and decrease the total signal power. The condition at press-fit interface makes ultrasonic reflection more strong and as a result makes the signal to noise ratio lower. With long time in service, both sides of press-fit have corrosion fatigue make the ultrasonic back reflection varies from one axle to another. In this paper, a series of experiments have been complemented to compare the difference of ultrasonic defect detection between bare axle and axle with press-fit part. By using wavelet denoising algorithm, the defects detecting SNR is obviously increased, and some results are shown as an example.

Keywords: ultrasonic, axle, press-fit, phased array, inspection

1. Introduction

Usually, high quality medium carbon steel is used for forging into different diameter of cylinder to make the railway axles. Because of suffering dynamic load, axles are the key parts of railway transportation. As the complex state under press and certain shocks, the in-service axle can be damaged due to fatigue, bending, torsion or tensile stress, and the fatigue fracture is one of the main forms[1]. Common defects on axles mainly come from material, machining and assembly processing.

To prevent and reduce fatigue cracks at axle press-fit parts, the important methods are: (1) Designing of axle material and strength; (2) Optimizing of press or shrink process and the quality control researches; (3) Non-destructive testing methods on axle, such as magnetic particle testing and ultrasonic testing.

Regularly inspection of the axle is to detect potential defects effectively, so as to avoid axle broken accidents. In this paper, Type RD3 axle is chosen as a test block to research on axle press-fit defects detection ability. Ultrasonic inspection technology is to be used to detect artificial crack defects on the RD3 axle, so as to know the detection ability difference before and after press or shrink process, and analyze the
cause of the differences. Through this study, finally the corresponding relationship between axle actual defect size and ultrasonic testing results can be established, so as to effectively guide on-site maintenance.

2. Ultrasonic testing method on axle

2.1 Axle press or shrink process

Press or shrink process is one of the most important steps in making wheel-set. At present, there are three main kinds of processes: cold press, greasing press and hot shrink, and cold press is most common one, as shown in Table 1.

(1) Hot shrink process flow

The wheel surface cleaning→ Take it into heating box after natural drying→ Put wheel into axle when temperature rise to 230℃~240℃ and after staying it warm for 180 minutes ~ 240 minutes→ After natural cooling, test the distance between the two wheels→ After qualified, store it at room temperature for 24h~48h, do anti-pressure test in accordance with requirements[2].

(2) Greasing press process flow

Greasing press refers to that when the wheel is to be pressed, high pressure oil is poured into the interface between axle wheel seat part and wheel hub bore hole, and the oil pressure is above their interface stress.

The oil film separates the axle wheel seat part and wheel hub bore hole, and it significantly reduces the friction resistance and the stress is not higher than 196kN in the end. It will not scratch axle wheel seat part and wheel hub bore hole surface after disassembled the wheel. It allows to be pressed again with the original wheel and oil[3].

(3) Cold press process flow

Coating oil in axle wheel seat part and wheel hub bore hole→ Put the wheel and axle on press machine→ Input parameters→ Press the right axle→ Press the left axle→ Measure wheel-set assemble dimensions manually.

The advantage of cold press is convenient, but there are still some disadvantages. If the wheel and axle is not to be pressed well, the wheel and axle becomes flexible and change the wheel-set dimensions. It is easy to strain axle to form fatigue source. And it even leads to derailment accidents, and threats wheel-set safety directly.

<table>
<thead>
<tr>
<th>Items Modes</th>
<th>Axle broke probability%</th>
<th>Success rate</th>
<th>Precision</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold press</td>
<td>8~12</td>
<td>ab. 90%</td>
<td>0.7~1.5mm</td>
<td>High efficiency</td>
</tr>
<tr>
<td>Greasing press</td>
<td>5~9</td>
<td>ab. 98%</td>
<td>0.5~1mm</td>
<td>Low efficiency</td>
</tr>
<tr>
<td>Hot shrink</td>
<td>0</td>
<td>No requirements</td>
<td>0.2~0.4mm</td>
<td>Low efficiency</td>
</tr>
</tbody>
</table>

Table 1.Comparing of different press process
The cold press process is common in China, however, it is easy to damage axle wheel seat part and wheel hub bore hole and change the stress distribution of this press-fit area. It is the source of forming cracks and stress concentration to reduce the service lifetime of the axle. Moreover, the cold press is interference press-fit, it is easy to cause longitudinal strain. Therefore, the study of the railway axle press-fit defects detection ability through different press-fit process is carried out. It is very important to prevent and reduce axle press-fit parts fatigue defects.

2.2 Failure analysis of axle damage

The axle fracture failure types includes thermal axle broken and cold axle broken. The thermal axle broken has nothing to do with the quality of axle. It is caused by bearing failure. The cold axle broken has something to do with the quality of axle, it is caused by unqualified axle or unqualified external conditions[4].

Under the condition of high speed and high load operation, the axle suffers alternating stress and large torque, especially at press-fit parts. The defect at axle press-fit parts has a very close relationship with press process. If the press-fit stress is not enough, it will accelerate the fatigue crack initiation[6]. However, if the press-fit stress is too large, it will increase the axial static tensile stress and cracks extend rapidly on the axle. The reasons are as follows.

(1) Because of press process, the axle wheel seat fatigue strength is decreased obviously, and it is more likely to produce fatigue damage.

(2) The axle wheel seat part and wheel hub bore hole will slide against each other to produce micro corrosion due to the alternating bending stress. Corrosion will cause one or more forms of destruction. The axle wheel seat part corrosion is inevitable. It has something to do with micro momentum, form of wheel seat, stiffness, and the contact stress and other factors[5]. Micro corrosion will produce many small pit corrosion in the contact area, it is located at the outer side of wheel seat part from 10mm to 35mm and at the inner side of wheel seat from 5mm to 30mm, as shown in Fig.1. The diameter of the small defects could reach 0.2 mm to 0.4 mm to form an axle with small defects.

Fig.1 Corrosion area at axle press-fit interface

2.3 Ultrasonic testing on axle

In the process of running train, the axle wheel seat part suffers press process and alternating of bending stress, it is easy to produce fatigue crack in press-fit part. To
prevent and reduce axle fatigue crack, NDT method is used for axle checks inspection on a regular basis. At present, ultrasonic testing is the only convenient way to detect axle press-fit parts defects without disassembling wheel and bearing from axle.

3. Research on railway axle press-fit defects detection ability

3.1 Research contents

With a good understanding of the wheel-set maintenance process, a RD3 type axle is chosen and artificial defects is designed and machined. One side of the wheel-set is done with cold press process, and the other side is done with hot shrink process. Before and after press-fit, all the artificial defects on the axle are detected by phased array technology. In the end, the test results are contrasted and analyzed between bare axle and press-fit axle, as well as the test results between cold press and hot shrink.

3.2 Test object and equipment

(1) Defects test scheme

The detailed detection parameters are ensured by simulation software, including phased array probe and wedge model (32 elements, 50° angle beam wedge with curved surface coupling on axle), ultrasonic frequency (5MHz), probe position (axle journal and axle body). The sectorial scan with shear wave is achieved by phased array probe. According to the defects size and position, the scanning angle range is set up 25°~70°. The principle of shear wave detection on axle press-fit parts is shown in Fig.2.

![Fig. 2 Principle of sectorial scan at axle press-fit parts](image)

(2) Design and machine artificial defects on axle test block

According to the relevant standard, different depth of transverse artificial notches are made on the axle press-fit part, including 9 EDM notches each with 1mm depth, 1.5mm depth and 2mm depths, as shown in Fig.3. Defects are consistent on both sides (Side A and B) of the axle wheel seat, and they are symmetric. The two wheels are strictly pressed and shrink respectively onto the axle to ensure the experimental test results. The side A is done with hot shrink process and side B is done with cold press process.
3）Test equipment

The bare axle and press-fit axle testing platform are shown in Fig. 4. It mainly includes the axle test block, ultrasonic testing data acquisition system, phased array probe and coupling water, etc.

3.3 Bare axle testing and results

Put the probe on axle journal and body, and set up configuration parameters. According to different defects, a lot of testing is done. The defect wave amplitude is set at 80% and the testing gain and SNR of each defect is record and analyzed. One of the same 1 mm depth defects at each side of the axle is inspection and the testing result samples are shown in Fig. 5. The test results on both sides of the bare axle are almost the same.

3.4 Press-fit axle testing and results

With the same configuration parameters and method as bare axle inspection, the test on press-fit axle is carried out. In the end, the test results are compared between bare axle and press-fit axle, and also between cold press and hot shrink process results. One of the same 1 mm depth defects at each side of the axle press-fit part are inspected and the testing result samples are shown in Fig. 6. The press-fit interface wave appears in the same sound path of defect and lowers the SNR.
3.5 Data comparison before and after press-fit

Fig. 6 Test results after hot shrink and cold press process

Fig. 7 Data comparison before and after press-fit

The data of bare axle and press-fit axle on 1mm depth defects inspection comparisons are shown in Fig. 7.

4. Comparison of before and after press-fit

(1) Comparison between bare axle and press-fit axle testing

By testing, the press-fit interface wave is obvious. The defect wave and press-fit interface wave overlaps on the same sound path. Although the gain is almost the same, SNR significantly reduces, especially the small defects such as 1mm depth, the press-fit interface wave seriously disturbs the defect judgment. As shown in Fig. 7, the larger of the test angle, the more obvious of the press-fit interface wave influence is given. As shown in Table. 2, for 1mm depth defects, the average SNR difference of the same defect before and after cold press is about 19.3dB, before and after hot shrink is 16.9dB.

<table>
<thead>
<tr>
<th>Defect depth</th>
<th>Comparing on objects</th>
<th>Maximum difference</th>
<th>Minimum difference</th>
<th>Average difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1mm</td>
<td>before and after cold press</td>
<td>27.4</td>
<td>14.1</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>before and after hot shrink</td>
<td>24.6</td>
<td>10.1</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td>between cold press and hot shrink</td>
<td>2.8</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>1.5mm</td>
<td>before and after cold press</td>
<td>24.9</td>
<td>14.8</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>before and after hot shrink</td>
<td>21.6</td>
<td>10.1</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td>between cold press and hot shrink</td>
<td>3.3</td>
<td>2.1</td>
<td>1.1</td>
</tr>
<tr>
<td>2mm</td>
<td>before and after cold press</td>
<td>23.2</td>
<td>13.0</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>before and after hot shrink</td>
<td>21.6</td>
<td>12.1</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>between cold press and hot shrink</td>
<td>1.6</td>
<td>2.1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

(2) Comparison between cold press and hot shrink testing

The hot shrink image is cleaner than cold press process. Under the same gain, the hot shrink interface wave amplitude is higher than cold press. Comparing the same 1mm defect in both side of axle, the cold press gain is higher and SNR is lower. The hot shrink has lower influence on defect inspection and it tests better. As shown in Table. 2, the average SNR difference of the 1mm depth defect between hot shrink and cold press inspection is about 1.4dB.

(3) Reasons for the differences
As shown in Fig. 8, when detecting the axle interface parts defects, the probe receive not only defect wave, but also interface wave. It also receive wheel hub wave without doubt. The interface wave reduces the test SNR. As defect wave and interface wave are in the same sound path, if the defect is tiny, these two waves will overlap and it is hard to recognize the defect. The hot shrink is with vastly superior, but it is more time consuming.

5 Wavelet algorithm for denoising

5.1 Wavelet threshold method

The press-fit interface wave, electrical noise and speckle noise seriously affect the defect detection ability, and the noise cannot be separated from signal in frequency domain. Wavelet transform is a linear filter, its multi-resolution and time-frequency analysis ability are quite applicable for removing these kinds of noise. So the threshold method is used below to improve SNR.

Through multi-scale analysis and approximation a Signal \( f(t) \) can be represented as:

\[
f(t) = \sum_{k \in \mathbb{Z}} c_k^j \phi_k^j(t) + \sum_{i=1}^{j} \sum_{k \in \mathbb{Z}} d_k^i \psi_k^i(t)
\]  

(1)

Where \( c_k^j \) and \( d_k^j \) are approximation coefficients and detail coefficients of \( j^{th} \) layer, respectively, \( \phi_k^j(t) \) and \( \psi_k^j(t) \) are approximation wavelets and detail wavelets of \( j^{th} \) layer, respectively.

The detail coefficients are sparse, the noises in the wavelet domain transformed in Gaussian distribution. A proper threshold \( T \) should be chosen, the \( d_k^j \) blow \( T \) is considered to be noise coefficients. Hard threshold function\(^6\) is selected to remove them in Eq. (2).

\[
d_k^j = \begin{cases} d_k^j, |d_k^j| \geq T, \\ 0, |d_k^j| < T. \end{cases}
\]  

(2)

Then use VisuShrink threshold\(^7\) to estimate the threshold \( T \) in Eq. (3).

\[
T = \sigma \sqrt{2 \ln n}
\]  

(3)
Where \( \sigma \) is standard deviation of the noise, \( n \) is the number of coefficients. If \( n \) is unknown, it can be estimated using the robust median absolute deviation of the finest scale in Eq. (4).

\[
\sigma = \sum_{i=0}^{n-1} |d_i|/(n \times 0.6745) \tag{4}
\]

5.2 Experimental results

Use hard threshold function and db1 mother wavelet which is similar to the defect wave, decompose each echo beam in 5 layers. Specially, the subsection processing is used in case of that the wave caused by wedge and noise in near path will lead the T becoming too large to remain the defect wave in far path completely. The original beam and denoised beam are presented in Fig.9, and the peak signal to noise ratio (PSNR) in table 3 shows the effectiveness of the denoising method.

![Defect analysis diagram](image)

(a) Beam of 46°

(b) Beam of 55°

Fig.9 Defect analysis diagram

<table>
<thead>
<tr>
<th>Angle</th>
<th>PSNR of original beam(dB)</th>
<th>PSNR of denoised beam(dB)</th>
<th>Increase of PSNR(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>46°</td>
<td>14.0</td>
<td>21.9</td>
<td>7.9</td>
</tr>
<tr>
<td>55°</td>
<td>11.3</td>
<td>15.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Process a cold press S-scan data, the scan angle start from 40°, and the interval is 0.2°. As showed in Fig.10, the wavelet threshold based subsection processing method for axle press-fit defects detection can weaken electrical noise, speckle noise and press-fit interface wave obviously. Meanwhile, the stationary echoes in near and far path are remained too.

5. Summary

(1) The axle press-fit parts suffers many loading stress, it changes the original stress state and results in obvious press-fit interface wave to disturb the defect judgment.

(2) Through the implementation of hot shrink and cold press, a RD$_1$ axle test block is design and machined, and a lot of testing and analysis is done. Through a large number of ultrasonic testing data statistical comparisons, the average SNR difference of the same 1mm depth defect before and after cold press is about 19.2dB, before and after hot shrink is 17.6dB(press-fit is lower), and the average SNR difference of the same defect between hot shrink and cold press inspection is 1.3dB (cold press is lower). According to the results, quantitative evaluation criteria for artificial defects in the axle test block between bare axle and with press-fit can be built up.

(3) By railway axle press-fit defects detection ability researches, the real defect size equivalent can be achieved and this can help the wheel-set maintenance. It will ensure the safety of the axle and increase the service life of the axle.

(4) By using wavelet thresholding algorithm, the SNR of the press-fit part testing is increased obviously. Some other algorithms including anisotropic diffusion etc. technologies will be carried out in the next step.

References


