The vibratory stress relief of a marine shafting of 35# bar steel

M.C. Sun, Y.H. Sun, R.K. Wang*

Department of Materials Science and Technology 921, Harbin Institute of Technology, Box 433, Harbin 150001, PR China

Received 27 March 2003; accepted 28 March 2003

Abstract

The marine shafting is made from a 35# bar steel. The 35# bar steel is named based on PR China national standard GB 699-88, “Quality carbon structure steel technical requirements,” the 35# bar steel corresponds to 060A35, B.S. The bar steel was hot rolled, piled and air cooled; hot rolling, cooling and microstructure transformation formed macro residual stress in the bar steel. There is high macro residual stress in the 35# (060A35, B.S.) bar steel. Worker shaped the bar steel into marine shafting with lathe. During machining, the macro residual stress releases and thus causes considerable deformation of the marine shafting.

The vibratory stress relief is introduced to the bar steel that was shaped into marine shafting. The vibratory stress relief of the bar steel of the marine shafting was carried out. The tensile properties of the bar steel were measured before and after vibration. While the bar steel was vibrating, six different location axial surface vibratory stresses were measured with dynamic strain gauge; the axial surface vibratory stresses distributive curve is obtained. The macro residual stress was measured with X-ray stressmeter before and after vibration. The macro residual stress decreased notably by about 48%. The tensile properties changed slightly. The vibratory wave is a standing wave.

The vibratory stress relief is valid for macro residual stress relieving of the bar steel of the marine shafting. The mechanism of the macro residual stress relieving by vibration on the bar steel of marine shafting is discussed. The “double-dynamic mechanism” is introduced to explain the course of macro residual stress relieving in the test.

© 2003 Elsevier B.V. All rights reserved.

Keywords: Vibratory stress relief; Marine shafting; 35# Bar steel

1. Introduction

Many researchers reported the benefits, limitation and application of the vibratory stress relieving [1–5]. This paper presents the results of the test of the vibratory stress relieving of the bar steel of marine shafting. The marine shafting is made from a 35# (060A35, B.S.) bar steel. The bar steel was hot rolled, piled and air cooled. There is high macro residual stress in the bar steel, about 197.0 MPa. During machining the macro residual stress releases and thus causes considerable deformation of the marine shafting. Annealing is the old method of macro residual stress relieving. The cost of old method is high, the expensive annealing furnace is worth US$30,000.00, the energy charge of electricity is 900 kWh, the work hours is 10 h, the tensile properties are damaged, the mechanical properties need restructuring with harding and tempering, and the macro residual stress reappears in active service [6].

The vibratory stress relief process of the bar steel is as follows: A stimulator vibrates the bar steel, adjusting the frequency of the stimulator to the frequency of the bar steel, the resonance of the bar steel takes place, the highest vibratory stress appears in the bar steel, the highest vibratory stress adds to macro residual stress in the bar steel, the plastic deformation in location results in the adding stresses, this plastic deformation relieves the macro residual stress. The vibratory stress relief of the bar steel of marine shafting demands a stimulator, its price is 10% of the price of annealing furnace, the energy charge is 1% of energy charge of annealing, the work hours is half an hour, the mechanical properties are not damaged, and the macro residual stress does not reappear in active service. The vibratory stress relief of marine shafting does not contaminate the environment [7–10].

In China, many researchers consider that the macro residual stress peak value can be decreased, and macro residual stress background value cannot be decreased in the test of the vibratory stress relief. In their processes, the macro residual stress decreased, but not notably, by about
20%, especially in the vibratory stress relieving of casting iron blanks of machine beds, and this result hinders the vibratory stress relief from popularization in China [6]. In our test of the vibratory stress relief of marine shafting, not only the macro residual stress peak value can be decreased but also the macro residual stress background value. The macro residual stress relieving value is proportional to the local plastic deformation value, the local plastic deformation value is proportional to the number of slid dislocations that led to the local plastic deformation, and the number of the slid dislocations is proportional to the activity of the dislocations and the macro residual stress in the bar steel. The activity of dislocations is associated with the level of vibratory stress. So the level of the macro residual stress relief is associated with the level of vibratory stress. The main aim is to increase the vibratory stress in the bar steel of the marine shafting [7–9]. When the vibratory stress relief of the bar steel is carried out, a stimulator vibrates the bar steel, resonance of the bar steel takes place, and the vibratory stress in the bar steel is associated with the structural stiffness, the stimulator power, all power loss in the vibratory system and so on. Vibratory stress in the bar steel of the marine shafting is associated with the structural stiffness. The smaller the structural stiffness of the bar steel of the marine shafting is, the higher vibratory stress is. The larger the stimulator power is, the higher the vibratory stress is. The lower the all power loss in the vibratory system is, the higher the vibratory stress is. The present research was undertaken to study the vibratory stress relief of the bar steel of the marine shafting.

2. Experimental

The marine shafting is made from a 35# (060A35, B.S.) bar steel. The bar steel was hot rolled, piled and air cooled. Its composition is shown in Table 1. Its microstructure is shown in Fig. 1, the composition is specified in PR China national standard GB 699-88, “Quality carbon structure steel technical requirement.” Its tensile properties are shown in Table 2. Two tensile test specimens were cut from subsurface of the bar steel, axis direction. The tensile test was carried out according to the PR China national standard GB 228-87, “Metallic material tensile testing.” Table 3. The testing points location of the macro residual stress before vibration is shown in Table 3. The testing points location of the macro residual stress before vibration is shown in Fig. 2. The bar steel was craned and hung with a chain, a wave node was tested and selected to be the hung point of the bar steel. Six measured points were selected arbitrarily. The measured points interval space is 0.20 m. The dynamic strain gauge measured the dynamic vibratory stress in the bar steel (six points). The oscilloscope displayed the dynamic stress. The controller controlled the stimulator. The stimulator was fixed to the bar steel, the stimulator vibrates the bar steel, adjusting the frequency of the stimulator to the frequency of the bar steel, the reso-

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight percentage</td>
<td>0.32 – 0.40</td>
<td>0.17 – 0.37</td>
<td>0.50 – 0.80</td>
<td>≤ 0.035</td>
<td>≤ 0.035</td>
<td>≤ 0.25</td>
<td>≤ 0.25</td>
<td>≤ 0.23</td>
<td>Other</td>
</tr>
</tbody>
</table>

Table 1

The composition of the 35# (060A35, B.S.) bar steel

<table>
<thead>
<tr>
<th>Yield strength, MPa</th>
<th>Tensile strength, MPa</th>
<th>Reduction of area, Z%</th>
<th>Elongation, A5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>325</td>
<td>670</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>320</td>
<td>670</td>
<td>40</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2

The tensile properties of the bar steel before vibration

<table>
<thead>
<tr>
<th>Testing point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro residual stress (MPa)</td>
<td>-148.0</td>
<td>-197.0</td>
<td>-148.0</td>
<td>-165.0</td>
</tr>
</tbody>
</table>

Table 3

The macro residual stress before vibration

<table>
<thead>
<tr>
<th>Yield strength, MPa</th>
<th>Tensile strength, MPa</th>
<th>Reduction of area, Z%</th>
<th>Elongation, A5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>310</td>
<td>620</td>
<td>43</td>
<td>26</td>
</tr>
<tr>
<td>315</td>
<td>630</td>
<td>42</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 4

The tensile properties after vibration

<table>
<thead>
<tr>
<th>Testing point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual stress (MPa)</td>
<td>-74</td>
<td>-99</td>
<td>-88</td>
<td>-87</td>
</tr>
</tbody>
</table>
nance of the bar steel took place, the resonance frequency is 46.4 Hz. The controller adjusted the frequency and displayed the frequency. When the macro residual stress was relieved, the resonance frequency changed slightly; fine adjustment of the frequency of the stimulator is necessary. The vibratory time was 1 min. One addition was fixed to the end of the bar steel, and was vibrated once again, in order to move the vibratory wave position; the above proceeding was carried out at the next harmonic sequence once again, the frequency is 94.4 Hz. The bar steel turned 30° and was vibrated in sequence. The above proceeding averaged the vibratory stress in the bar steels.

The bar steel tensile properties and macro residual stresses were tested before and after vibration, the macro residual stress was tested with an X-ray stressmeter. The above method is valid for the vibratory stress relief of the bar steel of the marine shafting.

3. Results and discussion

3.1. Experiment results

After vibration, the tensile properties are shown in Table 4. The tensile properties changed slightly. The macro residual stress after vibration is shown in Table 5, the test point locations for the stress measurement after stress relief were the same as those before the stress relief process, macro residual direction is the axis direction, the macro residual stress decreased notably by about 48% (average). The tested points method is the same as before vibration. When the resonance of the bar steel took place, the vibratory wave of the bar steel is a standing wave. When the frequency was adjusted from low frequency to high frequency, there are several overtones. The wave crests and wave nodes are clear. The wave pattern looks like a symmetric arc.

The harmonic sequence changes; the position of wave crests, wave nodes and wavelengths changed. This is used

Fig. 1. The microstructure of the bar steel, the microstructure is ferrite and pearlite, and the etchant is 3% nitric acid alcohol solution.

Fig. 2. The test flow chart of the vibratory stress relief of the bar steel of the marine shafting.

Fig. 3. The vibratory stress crest values of six-point distribution along the axis direction (six points).
to average the vibratory stress in the bar steel. The vibratory stress crest values of six points in the bar steel distribution along the axis direction are shown in Fig. 3, six measured points were selected arbitrarily, the measured points interval space is 0.20 m, the dynamic vibratory stress direction is the axis direction, the resonance frequency is 46.4 Hz, the $x$ axis indicates the measurement point locations, and the $y$ axis indicates the peak of dynamic vibratory stress of each measurement point locations. The above six-point dynamic vibratory stress measurement was carried out after the end of the vibratory stress relieving process, or the dynamic vibratory stress was mixed with the changing macro residual stress.

When we removed the stimulator from the bar steel, we unexpectedly saw an interesting phenomenon, an extra harvest of the test is that the split washers relieved stress and became flat from warpage, and the split washers were used to fix the stimulator with the screws in vibration.

4. Discussion

Adjusting the frequency of the stimulator to the frequency of the bar steel, the resonance of the bar steel took place, the stimulator transported a sine wave, it acted with the reflected wave of the bar steel, and they created a standing wave. The frequency was adjusted from low frequency to high frequency, there are $n$-harmonic waves, and their frequency is the natural frequency of the bar steel.

The vibratory stress peak values of each point increase from wave node to wave crest, as shown in Fig. 3. It is the same as a beam simply supported at each end (each wave node).

The tensile properties changed slightly as shown in Table 2 and Table 4. It indicated that the cycle-dependent softening did not take place.

The macro residual stress decreased notably, as shown in Table 3 and Table 5; after the vibratory stress relief process, the distortion decreased and thus caused considerable deformation of the marine shafting during later machining. The swing error in the middle of marine shafting is in the 0.00–0.60 mm range, if not vibrating, the swing error in the middle of the marine shafting is in between 0.60 and 3.00 mm. The macro residual stress decreased by 80 MPa, by about 48%.

The macro residual stress relieving results from plastic deformation of the local part of the bar steel. The local part plastic deformation results from slip of dislocations. There are many dislocations in the bar steel, as shown in Fig. 4. When the local part plastic deformation took place, the Frank–Read source generated a number of dislocation loops in pileups. Without application of the shear stress, the Frank–Read source is shut down [11]. The interaction stresses of the dislocation loops make the Frank–Read source and the initial dislocation loops easy to slip. Front and back shear stresses produced by vibration made the Frank–Read source multiplication and antimultiplication time and again, the dislocations were stimulated, any change would not originate in the process, and the vibratory stress in the bar steel only played the role of activation dislocation. The macro residual stress only played the role of pushing forward the above activation dislocation oriented slip, which lead to oriented plastic deformation. It was this oriented plastic deformation that relieved the macro residual stress itself. The above macro residual stress and vibratory stress in the bar steel are called “double-dynamic.” The above explanation is called “double-dynamic mechanism.”

The macro residual stress in the bar steel always changed from high to low; this phenomenon is easy to explain with “double-dynamic mechanism.”

The split washers relieved the stress and became flat from warpage, which verified that the macro residual stress background value could be decreased in vibratory stress relief test of marine shafting.

There are double zero-stress points in a structure. One is thermal zero-stress point; the other is structural zero-stress point. When the structure is annealed, the macro residual stress decreases to thermal zero-stress point. When the structure is vibrated, the macro residual stress decreases to structural zero-stress point. The macro residual stress of annealed structure reappears in active service. The macro residual stress of vibrated structure does not reappear in active service. The reason is that the vibrated stress is the same as the active service stress of the structure.

The structural stiffness is too big, the vibratory stress is too small, and the result of vibratory stress relief is not good. This is why many researchers consider that the macro residual stress peak value can be decreased and the macro residual stress background value cannot be decreased in the test of vibratory stress relief. It is very difficult for the big stiffness to relieve its macro residual stress with the vibratory stress relief; we have to use the other method.
5. Conclusion

The main conclusions from this work are as follows:

1. The tensile properties of the bar steel changed slightly before and after vibration, yield strength decreased by 3.1%, tensile strength decreased by 7.5%, reduction of area in increased 7%, and elongation increased by 8.3%.

2. The macro residual stress decreased notably by about 48%. The macro residual stress background value can be decreased in the vibration.

3. When the frequency was adjusted from low frequency to high frequency, there are several overtones, so there are n-harmonic waves; their frequency is the natural frequency of the bar steel. The vibratory wave of the bar steel is a standing wave; wave crest and wave nodes are clear. The standing wave pattern is a symmetric arc.

4. The points vibratory stress is distributed as shown in Fig. 3.

References