DEVELOPMENT OF A PREDICTIVE LIFE TOOL FOR TAPERED ROLLER BEARINGS USING MEASURED RESIDUAL STRESS AND RETAINED AUSTENITE DATA

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ABSTRACT

The development of a tool called the Service Load Factor (SLF) for railway tapered roller bearings using residual stress and retained austenite data is presented. Case-carburized tapered roller bearings used in the railroad industry are manufactured with a dual-phase microstructure that consists primarily of tempered martensite and retained austenite. The retained austenite phase is metastable, and will transform to martensite with sufficient thermal or mechanical energy during service. The increase in surface volume because of transformation, and the subsequent increase in compressive residual stress could indicate the onset of certain failure modes, including fatigue spalling. In addition, retained austenite transformation can lead to an increase in bore diameter, which could result in a loss of fit on the axle journal. Several bearing inner races with various service histories were measured with a Siemens X-ray diffractometer using chromium radiation. Results indicated that the transformation of retained austenite and resultant increase in compressive residual stress are interrelated with load and rolling cycles. Results indicate that the SLF is a useful tool that correlates well with current Association of American Railroads (AAR) failure criteria.

INTRODUCTION

Tapered roller bearing performance is a subject of great interest to the railroad industry that makes considerable use of this type of bearing for many of its applications. Freight trains encounter heavy service loads during cargo loading and operation, which require a bearing design that can tolerate these conditions. The performance of the tapered roller bearing is dependent on many microstructural parameters inherent in the steel used to make the bearings. The parameters with the greatest effect on performance include the hardness, steel cleanliness, residual stress, retained austenite content, and texture. All of these parameters are related to each other, and changes to one parameter can sometimes have a dramatic and undesirable effect on another. One of the major factors that has advanced the current knowledge base of bearing performance is the interaction between the amount of retained austenite in the microstructure of the bearing and the residual stress.

The structure of a bearing in the as-produced condition consists of a two-phase structure with a combination of retained austenite and martensite. The martensite phase makes up the body of the structure and forms the matrix of the material. The retained austenite phase exists in quantities on the order of 20% to 25% by volume at the surface, and decreases with depth to the core. During service, a reduction in the amount of retained austenite is observed as the bearing
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progresses through stage 1, shakedown, and into stage 2, steady state [1]. This reduction in retained austenite occurs during the first 50,000 miles (3,921.6 cycles per mile) of service encountered by the bearings that are the subject of this investigation [2]. Once this steady state level is reached, there is little change in the amount of retained austenite unless catastrophic failure occurs. The tapered roller bearings used in this application rarely see the stage 3 condition of martensite decay, because bearings are typically removed for inspection prior to this condition.

Residual stresses at the surface of the tapered roller bearing are an important factor in the prevention of rolling contact fatigue. These types of stresses are present as a direct result of the case-carburized microstructure in these bearings. Upon quenching, during the heat-treatment stage of processing, the phase change from austenite to martensite causes a volume expansion to occur. As a result of this volume change, a compressive residual stress is locked into the surface of the bearing cone, and results in a residual stress in the martensitic phase of approximately 275.8 MPa (40 ksi). The carbon gradient, and resultant Ms temperature variation, from the surface to the core of the cone dictates that the transformation from austenite to martensite will take place non-uniformly. Upon quenching, the core, with its low carbon content, will transform first, causing a volume expansion to occur. The case, or surface region, has greater carbon content and will transform later than the core, as a result of its lower Ms temperature. Because the core has already transformed, it will resist the volume expansion occurring at the surface. This phenomenon forces the now martensitic surface into residual compression, as it is not able to deform completely after the quenching operation. Loads acting on the raceway can cause portions of the retained austenite to transform, which leads to further volume expansion. This volume expansion increases the amount of residual stress at the surface of the cone in a similar method to what is described during quenching. The increase in the magnitude of residual stress also serves to prevent further transformation from occurring in the austenite phase, thereby prolonging the steady state condition [1].

All of the previously mentioned microstructural changes discussed affect the cone bore diameter. During service, the diameter of the cone grows in response to the change in residual stress at the surface of the component. This phenomenon is simply result of a stress balance occurring between the surface, which is in a state of residual compression, and the core, which balances the overall stress state by being in residual tension. Initially, there is a large increase in cone bore growth up to approximately 50,000 miles that is consistent with the retained austenite data discussed above. Once this point is reached, less retained austenite is being converted, and the residual stress is holding at a constant value. This transition region is the beginning of the steady state phase of these bearings in service [2].

**EXPERIMENTAL**

Measurement of retained austenite in steel components is a standard and well-developed technique, which is outlined in SAE SP-453 [3]. In this study, four peaks were used to determine the amount of retained austenite. Those peaks are the austenite (200) and (220), and the martensite (200) and (211). The integrated intensity of the measured peaks is proportional to volume, and therefore the volume ratio of martensite to retained austenite, $V_m/V_\gamma$, can be replaced with the ratio of integrated intensities for both the martensite and retained austenite phases.
However, these integrated intensities must be multiplied times a constant, $R_{x}^{hkl}$, which is specific for each material and $(hkl)$ reflection and is given in Eq. (1) [4].

$$R_{x}^{hkl} = \frac{1}{V^2} \left| FF \right| pLPe^{-2m}$$  \hspace{1cm} (1)

The constant, $R_{x}^{hkl}$ of Eq. (1) contains the volume of the unit cell, $V$, the structure factor, $|FF|$, the multiplicity factor, $p$, the Lorentz polarization factor, $LP$, and the temperature factor, $e^{-2m}$. Making these substitutions results in Eq. (2), which is the solution for the volume of retained austenite when four diffraction peaks are used, where $R_t$ is the ratio of the sum of the $R_{x}^{hkl}$ constants for each peak measured.

$$V_{\gamma} = \frac{1}{I + R_t^2 \left( \frac{I_200^m + I_{211}^m}{I_{200}^T + I_{220}^T} \right)}$$  \hspace{1cm} (2)

X-ray diffraction techniques used to determine the residual stress in a crystalline material are well established [4,5]. When a single crystal is placed under load, be it compressive or tensile, the interplanar spacing, $d$, will either increase or decrease as a result of the elastic strain of the crystal. This change in interplanar spacing as a result of the uniform macrostrain manifests itself in Bragg’s law as a change in the Bragg diffraction angle. This relationship is described in Eq. (3).

$$\Delta d = \frac{\lambda}{2 \sin(\Delta \theta)}$$  \hspace{1cm} (3)

The residual stress is calculated by Eq. (4), with approximations made for the strain free lattice spacing, $d_\zeta$. To accurately determine the stress using this equation, a technique called the multiple measurement method, or $\sin^2 \psi$ technique, is used. This technique involves making a perpendicular measurement, $d_\zeta$, and considering this the zero stress value. Lattice spacings are then determined for several $\psi$ tilts and a linear regression is fitted to these data. The stress in the sample surface is then calculated from the slope of this line.

$$\sigma_\psi = \frac{E}{(1 + \nu)} \frac{1}{\sin^2 \psi} \left( \frac{d_\psi - d_\perp}{d_\perp} \right)$$  \hspace{1cm} (4)

In Eq. (4), the elastic constants used are not the bulk values, but the values for the crystallographic planes in which the strain is being measured. Because of elastic anisotropy, the elastic constants for any $(hkl)$ direction can vary significantly from the bulk mechanical value, which is an average determined from a randomly orientated polycrystal.

In this study, a Siemens type F X-ray diffractometer with chromium radiation operated at 35kV and 15mA was used to conduct the measurements. The goniometer in this setup utilized a custom fixture that accepts an in-tact bearing cone as shown in Figure 1. Retained austenite data was taken over an angular range of 72° to 158°, with a 0.02° step and a 5 s counting time in order to capture data for the four measured peaks. Residual stress data was collected for the martensitic (211) peak over an angular range of 150° to 158°, with a 0.02° step and a 10 s counting time. Psi tilts were conducted at angles of 26.69°, 44.64°, and 50.3°.
RESULTS AND DISCUSSION

Preliminary work in this study was used to assess the condition of bearing races in several conditions. As-produced measurements were used to establish baseline properties of the components. Then, several bearings from laboratory bench testing and various field service conditions were examined. As mentioned previously, as-produced values for a typical tapered roller bearing cone are 20% to 25% retained austenite, and a residual compressive stress in the martensitic phase of -42,500 psi. These data were compared to several components that were captured from laboratory testing in which bearings had been tested through 250,000 miles as part of a routine benchmark test. In addition, bearings returned from railroad service in various states of service life were examined for comparison and to establish an approximate failure criterion. The baseline results for these components are shown in Table I.

Because retained austenite data and residual stress data have a symbiotic relationship, a tool was developed that took these data into account and was termed the SLF (Service Load Factor). The formula takes the ratio of absolute residual stress (ksi) and retained austenite data, and then normalizes the result to an as-produced value (42.5 ÷ 22.5 = 1.88). The result is a scale that begins at a value of 1.0 and increases as the service becomes more severe as shown in Table I. Based on experience, a failure criterion is also assigned at an SLF value of 7.5. This value is based on known performance data that indicates a severe decline in life when the residual stress and retain austenite reaches these levels, indicating stage 3 behavior. Also note that the severe overload bearing returned from the field is well beyond this value.

Application of the SLF

To show the application of the SLF as it relates to examining the health of service components, a bearing was captured that had seen approximately one million service miles. Baseline
measurements were conducted on both the outboard and inboard cones for residual stress and retained austenite data, and subsequent calculation of the SLF.

<table>
<thead>
<tr>
<th>Component</th>
<th>Average retained austenite (%)</th>
<th>Martensitic residual stress (ksi)*</th>
<th>SLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>New product 0 miles</td>
<td>22.5</td>
<td>42.5</td>
<td>1.00</td>
</tr>
<tr>
<td>Typical bench test 250,000 miles</td>
<td>18</td>
<td>80</td>
<td>2.36</td>
</tr>
<tr>
<td>Typical field test 450,000 miles</td>
<td>18</td>
<td>84</td>
<td>2.48</td>
</tr>
<tr>
<td>Failure criterion 140 ksi/10% RA</td>
<td>10</td>
<td>140</td>
<td>7.50</td>
</tr>
<tr>
<td>Severe overload</td>
<td>7</td>
<td>160</td>
<td>12.15</td>
</tr>
</tbody>
</table>

* Absolute values

Visually, the outboard cone had several defects that would allow this component to be placed back in service after reconditioning. A decision was made to run the bearing in a laboratory bench test for an additional 200,000 miles and then reassess. After completion of the additional mileage, visually, the outboard cone had progressed into a condemnable condition based on guidelines from the 2003 AAR Field Service Manual. Also, the calculated SLF at this level of service was also above the designated failure criterion. These data and pictures taken of the components before and after the additional service are shown in Table II and Figure 2. Note that the value of the SLF for the inboard cone did not change significantly. This is further confirmation of the steady-state relationship between retained austenite and residual stress in stage 2. In comparison, note how significantly the SLF changed for the outboard in the same number of cycles. Clearly, this component is in stage 3, and if unchecked, could cause a potentially hazardous failure.

<table>
<thead>
<tr>
<th>Baseline result, 1 million miles</th>
<th>SLF</th>
<th>After 200,000 miles of additional service</th>
<th>SLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 OB*</td>
<td>6.56</td>
<td>66 OB</td>
<td>10.67</td>
</tr>
<tr>
<td>66 IB</td>
<td>3.23</td>
<td>66 IB</td>
<td>3.45</td>
</tr>
</tbody>
</table>

* Average values

Figure 2. Left: outboard cone from Table II in the baseline condition; right: outboard cone after subsequent laboratory testing for 200,000 miles.
CONCLUSION

A tool has been developed which correlates measured retained austenite and residual stress data to failure progression in bearings. The calculated values for the SLF agree with current AAR regulations concerning condemnable bearings. In order to make this tool applicable for the industry, further work needs to be conducted in order to evaluate service histories for various rail service conditions. Potential applications for this method are for root cause failure analysis, and use in bearing reconditioning facilities to assess the health and longevity of bearings that could potentially be placed back in service. A limitation of this method is that not every bearing produced is the same, and initial conditions can vary within groups of product and between manufacturers. Further study is needed to determine the applicability of this tool for other populations of bearings.

REFERENCES