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Effect of Microvoids, Oxide Inclusions, and Sulphide Inclusions on the Fatigue Strength of Wheel Steels

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Summary

The Transportation Technology Center, Inc. (TTCI) is currently conducting research to improve life and shell resistance of wheels under heavy haul conditions, and, most importantly, to identify and develop shelling resistant steels for heavy haul applications. It has been demonstrated that microdefects have a strong influence on mechanical properties. In present research conducted in collaboration with BNSF Railway (BNSF), the effect of internal wheel defects, such as voids and inclusions on fatigue resistance of wheels, was determined. Results indicate that inclusions and voids can reduce the endurance limit of wheels up to 25 percent. The Murakami equation results show that microdefects considerably reduce wheel performance and are presumably the major reason for shelling and potentially the initiator of vertical split rims. Both failure modes are one of the major causes for derailments.

The microcleanliness analysis was conducted by BNSF at their facilities using their own microcleanliness standard.

It is concluded that:

- The endurance limit of wheel steels can be considerably reduced by the presence of microdefects, such as voids and inclusions.
- Shelling can be initiated in the vicinity of inclusions or voids on wheels and can represent a major reason for vertical split rims.
- Reduction in the endurance limit, measured in the analyzed wheels, varied from 7 to 10 percent.
- The effect of defects on the endurance limit is proportional to their size. Based on the results of microcleanliness, the smallest defects (usually sulphide inclusions) reduce the endurance limit of wheels by approximately 7 percent. Larger defects, such as voids, can lower the endurance limit up to 20 percent. Therefore, defects, independent of their size, are detrimental to the fatigue life performance of wheels.
- Cleaner steels can considerably improve the performance life of wheels.

There is strong evidence to indicate that shelling is more commonly found on wheels with high levels of inclusions or voids. The analysis of the microcleanliness of the steel used for wheels is therefore of crucial interest. For this reason BNSF has developed a microcleanliness standard to determine the size of defects. BNSF provided TTCI with the results of a microcleanliness analysis of 113 wheels that were either removed from revenue service because of shelling, or had failed in service. A few examples of the provided microcleanliness data was obtained from new wheels. This *Technology Digest* shows a quantification in the reduction of fatigue strength, using the Murikami equation.

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INTRODUCTION AND OBJECTIVE

To extend the service life of heavy haul wheels, several manufacturers have developed premium wheel steels (i.e., microalloyed). Premium wheels may last longer than the regular Association of American Railroads (AAR) Class C wheels under heavy haul applications and are anticipated to be more resistant to shelling and spalling formation. One major concern of railroads is shelling, which considerably reduces wheel life and can result in catastrophic failures such as vertical split rims.

Defects (voids and non-metallic inclusions) can be interpreted as microstructural discontinuities with stress concentration effects that are detrimental to mechanical properties. The stress concentration effect is a function of the size and geometry of the defect; in this *Technology Digest* (TD), the effect of defect size on the endurance limit is investigated.

Failure under fatigue, cyclic loading conditions, can be divided in two stages: (1) crack initiation and (2) crack propagation. It is well known that crack initiation of a defect free material will take between 80 to 90 percent of the fatigue failure life and the other 10 to 20 percent is attributed to crack propagation. Consequently, if defects are discontinuities in the microstructure, they can be considered as initiated cracks that will start their propagating stage or undergo a shorter initiation stage reducing the fatigue life of service components.

In the past, wheel manufacturers successfully tested premium wheels in revenue service in North America finding that these wheels have better wear performance than regular AAR Class C wheels. However, at the time that these premium wheels were tested, cost was a major limitation for implementation.

Today, a major goal of the Strategic Research Initiatives (SRI) Program is to develop and improve performance of wheel steels for heavy haul application.

The subject of this TD is to quantify the reduction of fatigue strength due to measured microvoids, oxide inclusions, and sulphide inclusions of wheel steels. The effects of microscopic discontinuities on reducing the fatigue strength of steels are well known.

Background

Murakami and Endo have derived a model that relates the effects of voids and inclusions based on their specific cross section and the nominal hardness of the material (wheels) on the fatigue endurance limit.¹ This model uses measured quantities of microvoids, oxide inclusions, and sulphide inclusions for both new and used wheels. One of the main reasons to investigate the effect of discontinuities on microstructures is the fatigue sensitivity to failure. Figure 1 shows an example of a failed wheel in revenue service.

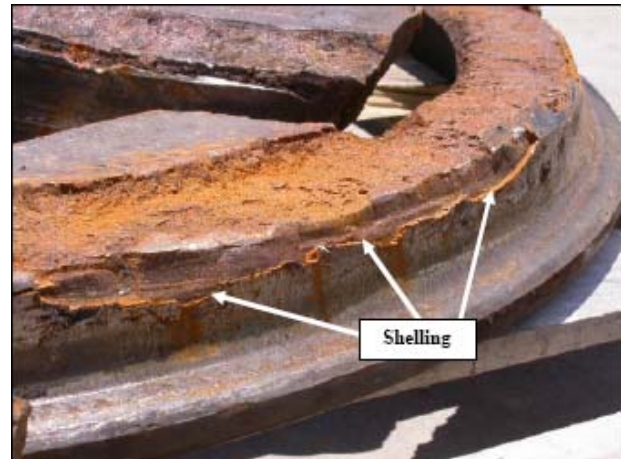
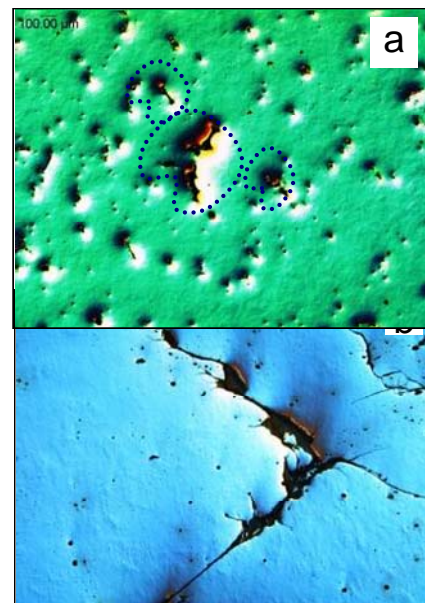


Figure 1. Shelled Wheel Showing a Vertical Split Rim (picture by G. Dahlman, BNSF)

EXPERIMENTAL WORK

Samples for the microcleanliness analysis were prepared following standard grinding and polishing procedures. Image analysis was performed using the Clemex Vision system in accordance with the American Society for Testing and Materials Standard (ASTM E-1245). On a gray scale of 0 to 255 (black to white), voids are in the range of 0 to 39, oxides 40 to 109, and sulfides 110 to 179. Based on contrast, the image analysis system differentiates between the type of defects (i.e., inclusion and void). It is important to mention that the contrast for scratches, in some cases, is similar to sulfide inclusions, which makes it hard to differentiate on the image analysis or system. For this reason, only scratch-free samples were analyzed. Table 1 shows the chemical composition of the Class C steel. Figures 2a and 2b show examples of microstructure with inclusions and voids.



Figures 2a and 2b. (2a) Inclusions and Voids (circled) (50x magnification) and (2b) Their Effects on Crack Propagation on the Class C Steel Wheels Microstructure (100x magnification)

Table 1. Maximum Permissible Content of the Various Elements for the Class C Wheel Steel

Elem.	C	Mn	P	S	Si	Ni	Cr	Mo	Cu
Wt. %	0.8	0.9	.03	.02	1	.25	.25	.06	.35

The area and number of voids, oxide inclusions, and sulphide inclusions were measured on 113 new and used wheels. Data was gathered by sectioning six metallographic specimens from each wheel, such specimens are indicative of the last third of the heat. The specimens were then polished for examination. The total area evaluated for each sample was not less than 1/4 square inch. All inclusions greater than approximately 1 x 10⁻⁶ inch were included. The area of each discontinuity and the number of discontinuities were measured using a quantitative, video-based system. The following limits of the BNSF microcleanliness specifications were used to evaluate all wheel samples:

- Average area percent: the six samples shall not average more than 0.100 percent oxides and voids.
- Maximum area percent per field: the maximum area percent per field shall not be more than 0.200 percent oxides and voids or 0.200 percent sulfides.

The Murakami Equation was used to determine the reduction in the endurance limit of an alloy subjected to cyclic load fatigue.

$$\sigma_{el} = \frac{C*(H_V + 120)}{\sqrt{(Area_{Max})^{1/6}}}$$

where: σ_{el} = fatigue endurance limit (MPa)*

H_V is the Vickers hardness

$Area_{Max}$ = area of the largest inclusion/void†

The Murakami equation is not applicable for discontinuities greater than 0.04 inch. Note that the equation uses the maximum area of the largest inclusion. The data used herein is for the average area of the defect, and therefore, the calculated endurance limits will be larger than if the area of the largest defect had been used. Further, it is assumed that the wheels with the largest average discontinuity will also have the largest maximum size. The 1.41 coefficient value used in the Murakami equation was determined based on fatigue data previously published in the literature and the information provided in Reference 2. Lonsdale and Dedmon have reported a fatigue endurance limit of 68,000 pounds per square inch (psi) for AAR Class C steel with a tensile strength of 164,500 psi.² Tensile strength may be converted to Brinell hardness number (BHN) by dividing by 4,893. This results in 357 BHN (377 Hv).

Substituting the previous values for endurance limit, hardness, and the average area of oxide inclusion diameter gives a calculated coefficient C of 0.55.

Finally, the specified hardness of AAR Class C wheel steels can vary from 321 to 363 BHN (340 to 383 Hv). Therefore, on the basis of hardness alone, the endurance limit may vary between 59,300 and 64,900 psi.

RESULTS AND DISCUSSION

Table 2 shows the data for the new and used wheels.

Table 2. Calculated Endurance Limits for Voids, Oxides, and Sulfides in New and Used Wheels

		Voids	Oxides	Sulphides
Average	Average Area, mm ²	0.0038	0.0017	0.0022
	Calculated Endurance Limit, ksi	60.5	64.6	63.3
Worst	Area of Worst Wheel, mm ²	0.0133	0.0036	0.0050
	Calculated Endurance Limit, ksi	54.5	60.6	59.1
Best	Area of Best Wheel, mm ²	0.0010	0.0012	0.0003
	Calculated Endurance Limit, ksi	67.5	66.6	75.4
Ratio	Worst/Average Endurance Limit, Percent	90	90	93
	Worst/Best Endurance Limit, Percent	81	91	78

The endurance limits for new and worn wheel data assumes that all wheels were 381 BHN (361 Hv), which is the average of the specified hardness range of AAR Class C wheels.

The calculated endurance limits for wheels with the greatest average area of voids, oxides, and inclusions are less than expected for wheels of the softest specified hardness. Figures 3, 4, and 5 show the calculated endurance limits versus average inclusion area.

Figures 3, 4, and 5 also show that void areas tend to be clustered between 2.32 x 10⁻⁶ and 6.98 x 10⁻⁶ inch. Similarly, the oxide areas tend to cluster between 2.32 x 10⁻⁶ and 3.88 x 10⁻⁶ inch. The sulfides tend to a tighter cluster, 1.17 x 10⁻⁶ to 2.79 x 10⁻⁶ inch, but have a greater number of outliers at higher average areas.

* 1 MPa = 0.145 Ksi

† 1 micron² = 1,550 in²

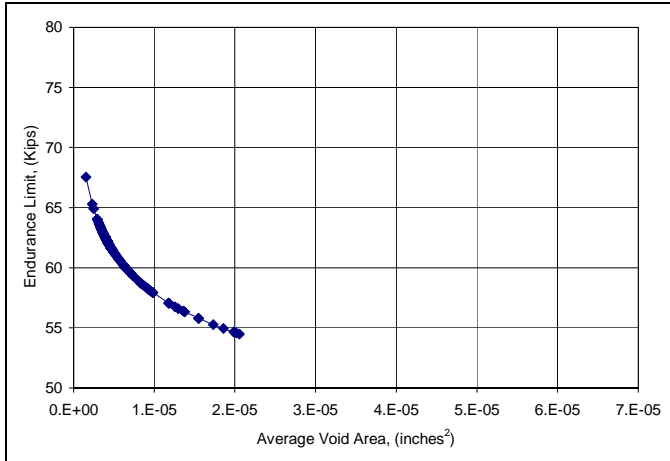


Figure 3. Average Void Area versus Calculated Endurance Limit

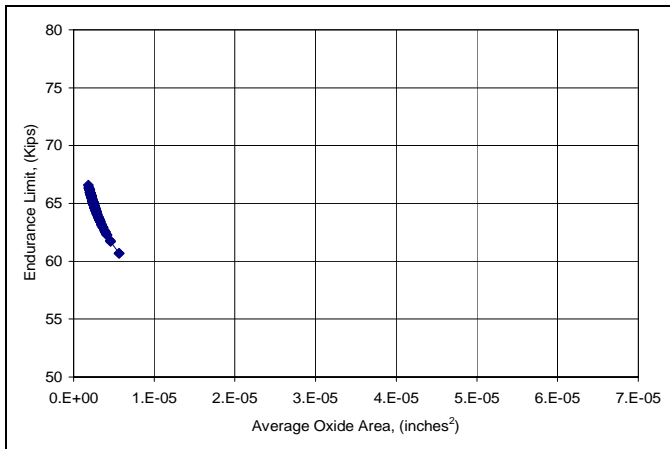


Figure 4. Average Oxide Area versus Calculated Endurance Limit

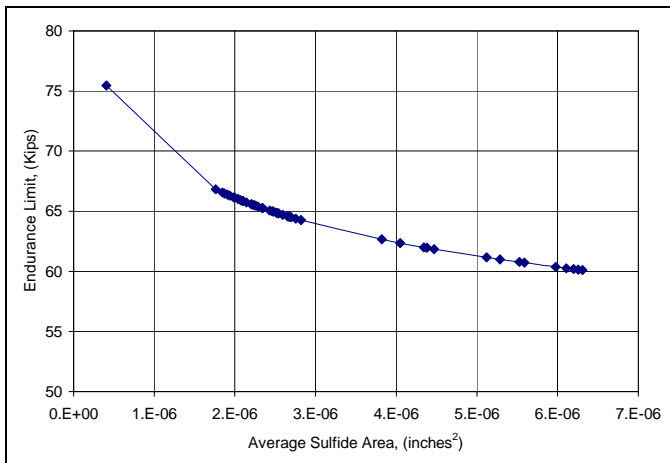


Figure 5. Average Sulphide Area versus Calculated Endurance Limit

CONCLUSIONS

Murakami and Endo have demonstrated that endurance limits of steels are reduced by the maximum area of microdefects.¹ If the average area of voids, oxides, and sulphide inclusions represent the maximum area, then the Murakami equation can be modified to give an estimate of the endurance limit. Based on the defect's (void or non-metallic inclusion) surface area and the results using the Murakami equation, reduction between 7 and 10 percent on endurance limit is expected, which can, in-turn, reduce the fatigue performance of wheels.

The effect of defects on endurance limit is proportional to their size. Based on the results of microcleanliness, the smallest defects (usually sulphide inclusions) reduced the endurance limit of wheels in approximately 7 percent. Larger defects, such as voids, can lower the endurance limit in up to 20 percent. Therefore, defects, independent of their size, are detrimental to the fatigue life performance of wheels. There is a 20 percent lower calculated endurance limit caused from the presence of voids and nonmetallic inclusions, such as sulphides.

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