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MULTIPLE FREQUENCY ULTRASONIC DETECTION OF SUBSURFACE NEAR-RACE INCLUSIONS FOR IMPROVED FATIGUE LIFE PERFORMANCE

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ABSTRACT
The importance of steel cleanliness for the performance of tapered roller bearings has been clearly established and has led to on-going improvements in steel production methods. The presence of non-metallic impurities within the steel can result in hard/brittle inclusions that may serve as initiation sites for damage due to sub-surface rolling contact fatigue (RCF) if the inclusions lie within the near-race of the bearing components due to the high mechanical stress present. Current inspection standards define steel cleanliness with respect to bulk inclusion morphology, which limits inspection to a small area that may or may not be representative of the entire steel heat. In this presentation, ultrasonic surface wave methods are described for detecting subsurface inclusions directly on finished bearing inner and outer rings. We expand on our previous work to exploit the different inspection depths that can be achieved with different measurement frequencies. The impact of the different inspection depths is quantified through simulated service life testing with heavy axle loading conditions. For this study, bearing components were first subjected to ultrasonic surface wave testing at three different frequencies to identify near-race inclusions. The simulated service life testing was then used to assess the onset and propagation of RCF failure. RCF spall initiations correlated highly with the positions identified by the ultrasonic inspections suggesting that this approach has a predictive potential. However, additional research is needed to establish the specific criteria needed for such predictions with respect to the inclusion location along the race, the depth from the race surface, the inclusion morphology and the inclusion mechanical properties. This work is anticipated to improve the understanding of RCF damage initiation which will lead a higher level of safety for railroad operations.

INTRODUCTION
With the increase in service loads of railcars aimed to improve the efficiency of the transport industry, the desired performance of railway tapered roller bearing increases continuously. One of the most important aspects related to the performance is bearing steel cleanliness, which has been clearly established [1-4]. Bearing steel cleanliness has led to on-going improvements in steel production methods both in design and quality control, such as new standards to measure the non-metallic impurity content in a particular heat of a steel supplier [3-5]. The presence of non-metallic impurities within the steel can result in hard/brittle inclusions that may serve as initiation sites for damage due to sub-surface rolling contact fatigue (RCF) if the inclusions lie within the near-race of the bearing components due to the high mechanical stress present [3,4, 6]. The critical region of bearing components has been estimated as several hundred micrometers.

Current inspection standards for inspection in the critical region of rail components include methods based on bulk inclusion morphology, BS-EN 12080 [7], bulk material ultrasonic scanning, and so on. Even if the exact chemical composition of the inclusion is known, the existing inspection standards with respect to bulk inclusion morphology are limited to a small inspection area that may or may not be representative of the entire steel heat. In BS-EN 12080, an ultrasonic longitudinal wave is generated with an incident normal transducer configuration and the reduced echo reflected from the back surface of the sample is monitored. The size of the drilled flat bottomed hole (FBH) on the surface of standard ranges from 0.5 mm to 1 mm in both diameter and depth, which is much larger than the depth of the critical region such that it is reasonable to question if important inclusions are missed. Bulk material ultrasonic scanning is an efficient method to estimate the quality and cleanliness of steels but it fails to guarantee steel cleanliness in the critical region as identified in the BS-EN 12080. Furthermore, a finite element study using the Hertzian contact stress modeling approach showed that the critical region was approximately 200 μm away from the contact surface of bearing components [6]. Alternatives to inspection within this calculated depth are needed to provide more information about potential impurities. In this article, ultrasonic surface wave inspection methods are applied to achieve this goal for detecting subsurface inclusions directly on finished bearing inner and outer rings. The increased inspection depths are obtained through different measurement frequencies.

SURFACE WAVES AT MULTIPLE FREQUENCIES

Surface waves are generated when the incidence angle of the transmitted sound wave is slightly larger than the second critical angle of the sound wave for the material under inspection. A surface wave is a combination of material displacements of both longitudinal and transverse type. The most significant feature of a surface wave is that it propagates along the free surface and attenuates through a depth of approximately one acoustic wavelength [7]. For a steel sample, a 15 MHz surface wave can penetrate around 200 μm below the surface, while 10 and 7.5 MHz surface waves have corresponding inspection depths of 300 and 400 μm, respectively. This concept is shown schematically in Figure 1. It is clear that the inspection volume of a lower center frequency is larger.

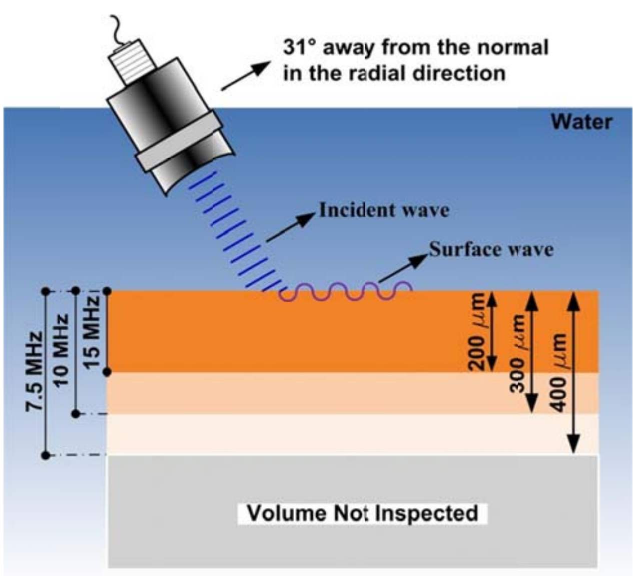

Figure 1: The schematic diagram of an ultrasonic surface wave scan using multiple frequencies on a steel sample.

ULTRASONIC EXPERIMNETAL ORIENTATION

The aim of the ultrasonic surface wave inspection technique is to detect subsurface inclusions at critical regions of the raceways. In this article, a set number of assembly-ready bearing outer rings (cups) were scanned ultrasonically to verify the feasibility of the theoretical assumption. In order to have an accurate understanding of the experimental results, it is necessary to have a uniform set of ultrasonic experimental orientations.

When the cup is oriented with the part identification letters right-side-up, the race above the letters is denoted as the "inboard" race, while the race below the part ID is denoted as the "outboard" race as shown in Figure 2 (a). The two race surfaces are separated by a flat portion as shown in Figure 2 (b). The cup was scanned in a counterclockwise direction for each race. The rotation angle is marked as θ, such that the start point begins just before part identification engraving. Once one race was scanned, the cup was turned over and the other race was scanned. The origin coordinate of z is just above the flat portion, and the end point of the z location is the start of the undercut. Therefore, the z location encompasses only the race. The upward axial direction is the positive z direction in the scanning procedure for both the inboard and outboard races.

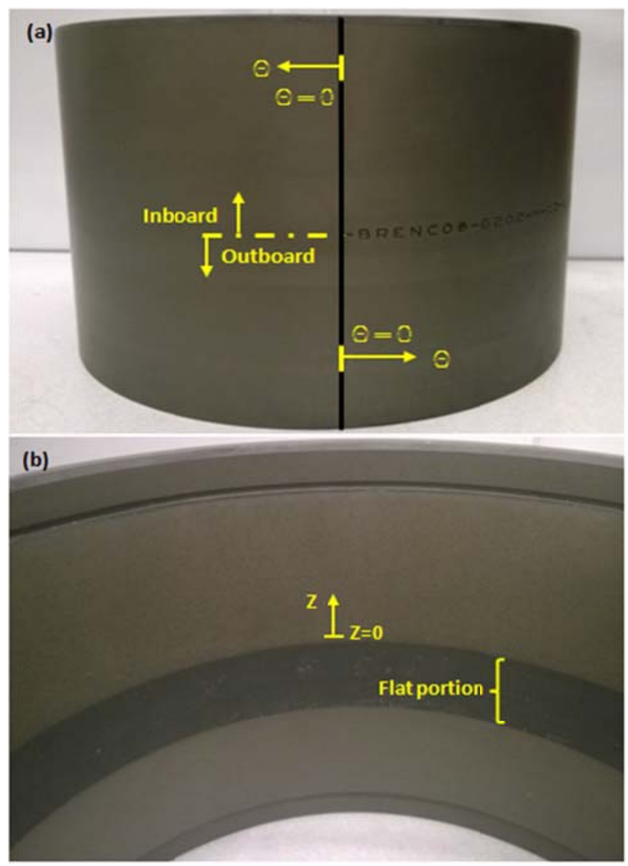

Figure 2: (a) Orientation of the race surfaces (outboard and inboard) and their respective positive θ rotations, (b) Origin coordinate of z and the corresponding positive direction for the both inboard and outboard races.

ULTRASONIC EXPERIMENTAL RESULTS

The ultrasonic experimental results are stored as C-scan images, in which the waveform signals are obtained from locations on each sample. Each value in the C-scan image corresponds to the maximum reflection amplitude of the gated signal of the individual waveform. In these experiments, the gate is placed just after the initial scattering from the surface of the sample by the reason of surface roughness and grain scattering.

An example of ultrasonic C-scan image from the surface wave scanning procedure using three center frequencies, i.e., 15, 10, and 7.5 MHz, is shown in Figure 3(a)-(c). In these figures, the range of interest (0-210 degrees) has been reduced from the original C-scan image (0-360 degrees) for clarity. A threshold has been applied to distinguish the inclusion signals from the grain scattering. One inclusion can be observed in Figure 3(a) (15 MHz) while three inclusions found both in Figures 3 (b) (10 MHz) and (c) (7.5 MHz). The inclusion locations and corresponding amplitudes are listed in Table 1. Comparing the images Figure 3 (a), (b), and (c), the same inclusions are identified although slight differences in position and size are recognized due to positioning uncertainty and the difference of inspection frequency. The consistency between these results is a positive indication regarding the presence of the inclusions for the different inspection depths, which can be verified from the amplitude in Table 1.

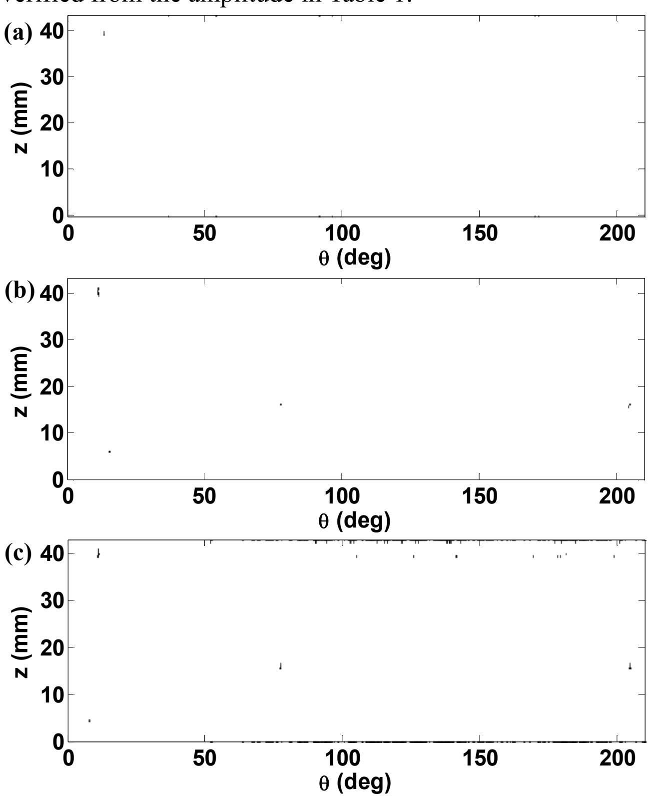

Figure 3: C-Scan images from a cup using three different center frequencies, (a) one inclusion found using 15 MHz, (b) three inclusion found using 10 MHz, (c) three inclusion found using 7.5 MHz.

Table 1: Locations of high amplitude indications from ultrasonic surface wave scanning.

Frequency	Location	θ (Deg)	z (mm)	Amp. (%)
15 MHz	A	79.358	15.675	30.469
	B	13.379	38.745	94.531
	C	206.247	14.689	32.031
10 MHz	A	77.55	16.221	82.813
	B	11.563	39.73	100
	C	204.769	16.227	82.031
7.5 MHz	A	77.609	15.716	100
	B	11.233	39.84	100
	C	204.447	15.717	98.438

The inclusion found using all three frequencies is in the detection range of 15 MHz, and the remaining two appear to be close to the inspection limitation of 10 MHz. For clarity, a schematic diagram of the suspected inclusion locations for this example is shown in Figure 4.

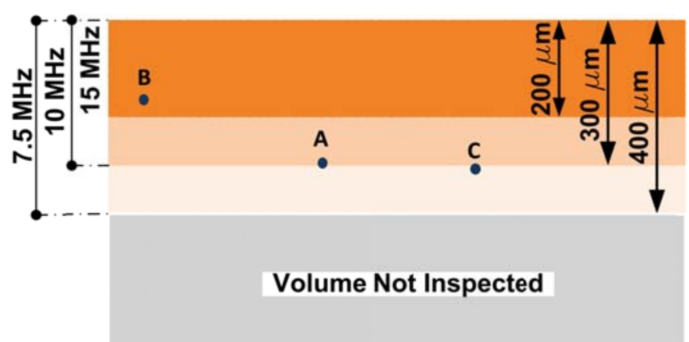

Figure 4: The schematic diagram of presumed locations of inclusions with the relative depths in the sample.

SIMULATED SERVICE LIFE TESTING RESULTS

Four cups with high amplitude subsurface near-race inclusions were selected using this method and subjected to simulated service life testing to verify the damage initiation potential for such inclusions. The simulated service life testing used four complete bearings, which includes four selected cups and eight clean cones whose near-race regions were inspected and found to be free from any detectable inclusions. The assumption behind the testing is that a subsurface near-race inclusion would ultimately cause a spall to appear on the cup surface in the detected area within 250,000 miles of operation.

The spall can be detected by the irregular signatures of bearing operations either from the temperature or vibration [1-2]. Once such signatures are detected, the test is paused such that the bearings can be inspected visually.

The ultrasonic experimental results of one cup in the simulated service life testing are shown in Figure 5. Here, only the result of 15 MHz center frequency is displayed in Figure 5(a) because the locations for these two inclusions on the outboard race are identical for all three center frequencies. However, the only subsurface inclusion found on the inboard race is shown in Figure 5(b), which was identified only from the 7.5 MHz inspection. Furthermore, detailed information about the inclusion locations and corresponding amplitudes are given in Table 2.

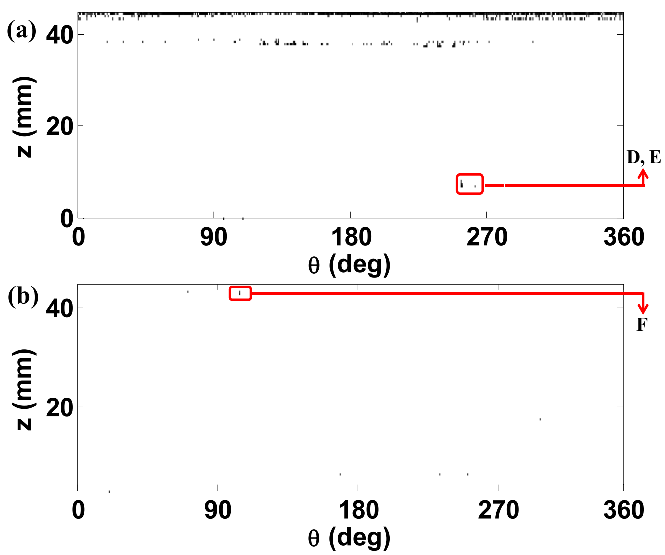

Figure 5: C-Scan image from the cup in the simulated service life testing, (a) two inclusions found using 15 MHz on the outboard race, (b) the only inclusion found using 7.5 MHz on the inboard race.

Table 2: Locations of high amplitude indications from ultrasonic scans for the simulated service life testing.

Frequency	Location	θ (Deg)	z (mm)	Amp. (%)
15 MHz	D	253.034	7.205	100
	E	261.746	7.228	79.688
7.5 MHz	F	103.934	42.719	91.406

The initiated spall was found at location F after 51,420 miles of operation, and the area of the spall was 112.709 mm^2. The corresponding deterioration of this spall is shown in Figure 6. After an additional 26,086 miles of operation, the spall grew twenty-five times in size with a comparison between Figure 6(a) and Figure 6(c). The development of the spall observed in the successive teardowns shows the destructive potential of such inclusions to lead ultimately to bearing failure during service life.

The simulated service life test was terminated after 77,506 miles of operation due to the high vibration noise which began to affect the signals from neighboring bearings in the test rig. The final state of the inside of the cup is shown in Figure 7. The two locations of spalls are identical to the positions found from the ultrasonic surface wave inspections.

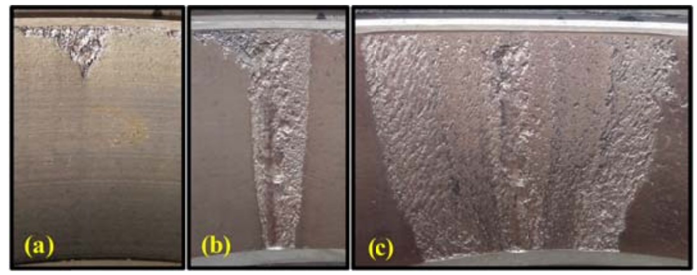

Figure 6: The spall deterioration on an outboard race (cup) at location F, (a) mileage = 51,420 miles, area = 112.709 mm^2, (b) mileage = 63,678 miles, area = 677.418 mm^2, and (c) mileage = 77,506 miles, area = 2850.317 mm^2.

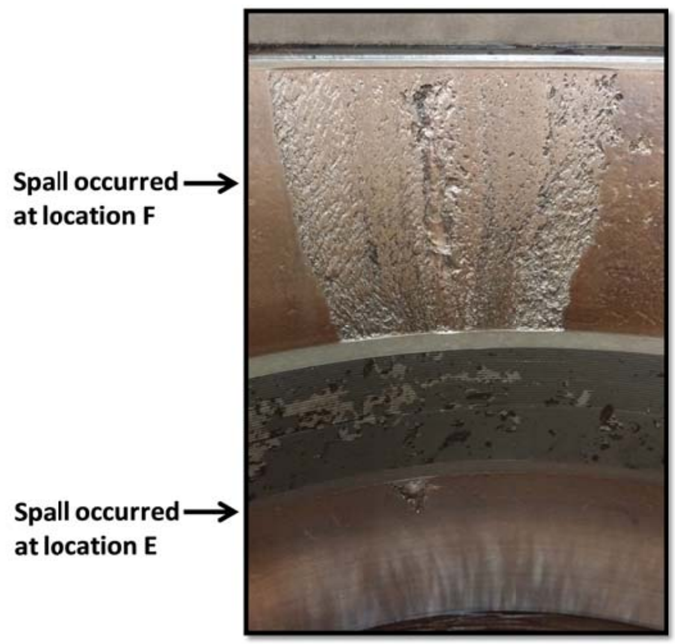

Figure 7: Spalls that developed on the surfaces of the outboard and inboard races (cup) at locations which coincide with the subsurface inclusion sites E and F, respectively.

CONCLUSION

With the verification of simulated service life testing, the ultrasonic surface wave results are identical to the RCF spall initiations, highlighting the predictive potential of this approach. More research is needed to understand why certain inclusions that are detected (location F in Figure 7) lead to a spall while other inclusions (e.g., location D) do not. Such differences are thought to be due to the intrinsic characteristics of the inclusion, which is one of the topics of future work. Therefore, future research will focus on the establishment of specific criteria needed for such predictions with respect to the inclusion location along the race, the depth from the race surface, the inclusion morphology and the inclusion mechanical properties. Although the work here is focused on tapered roller bearings, it is anticipated that this study can improve the understanding of RCF damage initiation for other applications within railroad operation such as wheel-rail contact.

ACKNOWLEDGMENTS

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