LOW FREQUENCY-SAFT INSPECTION METHODOLOGY FOR COARSE-GRAINED STEEL RAIL COMPONENTS (MANGANESE STEEL FROGS)

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Abstract: In the rail industry, sections of high strength Manganese steel are employed at critical locations in railroad networks. Ultrasonic inspections of Manganese steel microstructures are difficult to inspect with conventional means, as the propagation medium is highly attenuative, coarse-grained, anisotropic and nonhomogeneous in nature. Current in-service inspection methods are ineffective while pre-service X-ray methods (used for full-volumetric examinations of components prior to shipment) are time-consuming, costly, require special facilities and highly trained personnel for safe operations, and preclude manufacturers from inspecting statistically meaningful numbers of frogs for effective quality assurance. In-service examinations consist of visual inspections only and by the time a defect or flaw is visually detected, the structural integrity of the component may already be compromised, and immediate repair or replacement is required.

A novel ultrasonic inspection technique utilizing low frequency ultrasound (100 to 500 kHz) combined with a synthetic aperture focusing technique (SAFT) for effective reduction of signal clutter and noise, and extraction of important features in the data, has proven to be effective for these coarse grained steel components. Results from proof-of-principal tests in the laboratory demonstrate an effective means to detect and localize reflectors introduced as a function of size and depth from the top of the frog rail. Using non-optimal, commercially available transducers coupled with the low-frequency/SAFT approach, preliminary evaluations were conducted to study the effects of the material microstructure on ultrasonic propagation, sensitivity and resolution in thick section frog components with machined side-drilled holes. Results from this study will be presented and discussed.

Introduction: Ultrasonic nondestructive testing (NDT) has a long and successful history of application to the rail networks used by freight and high-speed rail services. This form of inspection is now routinely performed using special test "cars", such as those developed and operated by Sperry Rail Services and several other vendors. Such systems can work well for the inspection of normal rails. However, problems are encountered when a car passes over the short lengths of Manganese steel rail (known as "frogs" in railroad acumen) used at critical locations in the railroad network. The need for an effective and reliable means for pre-service examination of coarse-grained, thick-section, Manganese (Mn) steel frog components in both the freight and high-speed rail industries is well established. In-service examinations consist of visual inspections only, as conventional inspection methods are ineffective. Typically, by the time a defect or flaw is visually detected, the structural integrity of the component may already be compromised and immediate repair or replacement is required. Periodically, frogs are received inherently flawed from a manufacturer, and put into service, as most rail road operators do not have a means to conduct pre-service examinations once these components are received. The problem generates a more significant impact when the cost of labor for repair and/or replacement is then added to the equation. In some cases, warranty claims cannot be made due to the lack of part identification and uncertainty in the root cause of the failure. Accordingly, there is a need for a pre-service inspection methodology that can provide a rapid, cost-effective and non-intrusive inspection capability for detection of defects, flaws, and other anomalies in frog components that eventually lead to premature initiation of cracks or failures of these components during service.

At present, X-ray methods are used for full-volumetric examinations of small numbers of frog components prior to shipment from manufacturing plants. This method is time-consuming, costly, and requires special facilities and highly trained personnel for safe operations, precluding manufacturers from inspecting statistically meaningful numbers of frogs for effective quality assurance. This leads to an unacceptable rate of failure in the field, often within the first 6 months of service. The work described here illustrates an effective ultrasonic solution to this inspection problem by adapting technology developed for the U.S. Nuclear Regulatory Commission (NRC) for inspecting thick-section, coarse-grained steel, nuclear reactor piping components.

The proof-of-concept effort detailed here employed an innovative approach combining and adapting existing capabilities in ultrasonic methodologies and advanced signal processing techniques to test the effectiveness of an ultrasonic pre-service inspection method using low frequency-SAFT Ultrasonic Testing (UT) inspection techniques for examination of Manganese steel frog components.

From the standpoint of ultrasonic inspections, cast stainless steel and Manganese steel microstructures are quite similar, as the propagation medium is highly attenuative, coarse-grained, anisotropic and nonhomogeneous in nature. Current in-service rail inspection technology is ineffective and unable to adequately inspect these sections of Manganese steel rail. Manganese steel rail components are fabricated from material that has a large grain size, and it is this factor, which most severely limits current ultrasonic inspection techniques. Previous experience at Battelle with work performed for the U.S. NRC has shown that novel implementations of low frequency ultrasound, combined with an advanced signal processing methodology, can successfully inspect coarse-grained steels. This work has demonstrated high levels of sensitivity and resolution for detection and localization of thermal and mechanical fatigue cracks that compromise the structural integrity of these components. Recent proof-of-principle work conducted at Battelle on Manganese steel frog components provided by Burlington Northern-Santa Fe Railroad (BNSF) and Rail Products and Fabrications, have yielded very favorable results that indicate a solution to the inspection problem using ultrasonic technology. This effort has successfully demonstrated a low frequency ultrasonic inspection protocol that implements the synthetic aperture focusing technique (SAFT), on samples of Manganese steel frog components with various geometric reflectors, side-drill holes and even a laminar discontinuity.

The fundamental problem encountered, when seeking to use ultrasound to inspect sections of cast Manganese steel rail, arises due to the scattering of the ultrasonic energy by the large grains. Similar problems have been previously encountered for thick section cast steel components used in the primary pressure boundary of U.S. nuclear reactors. The approach reported here is based upon ongoing work being conducted for the U.S. NRC as part of a study designed to evaluate and develop ultrasonic in-service inspection techniques for detection of thermal and mechanical fatigue cracks in centrifugally and statically cast stainless steel piping components, which are used within the primary pressure boundary of commercial light-water reactors[1-3]. Figure 1 shows the coarse microstructure of these thick-section reactor piping components.

Manganese steel (Hadfield Steel -- 12% Mn, 1% C) is an anisotropic and nonhomogeneous material. The manufacturing process can result in the formation of a long columnar grain structure, oriented approximately normal to the surface with grain growth oriented along the direction of heat dissipation, forming dendritic features often several centimeters in length. During the solidification of the material, columnar, equiaxed (randomly speckled microstructure), or a mixed structure can result that is dependent upon chemical content and control of the cooling process.

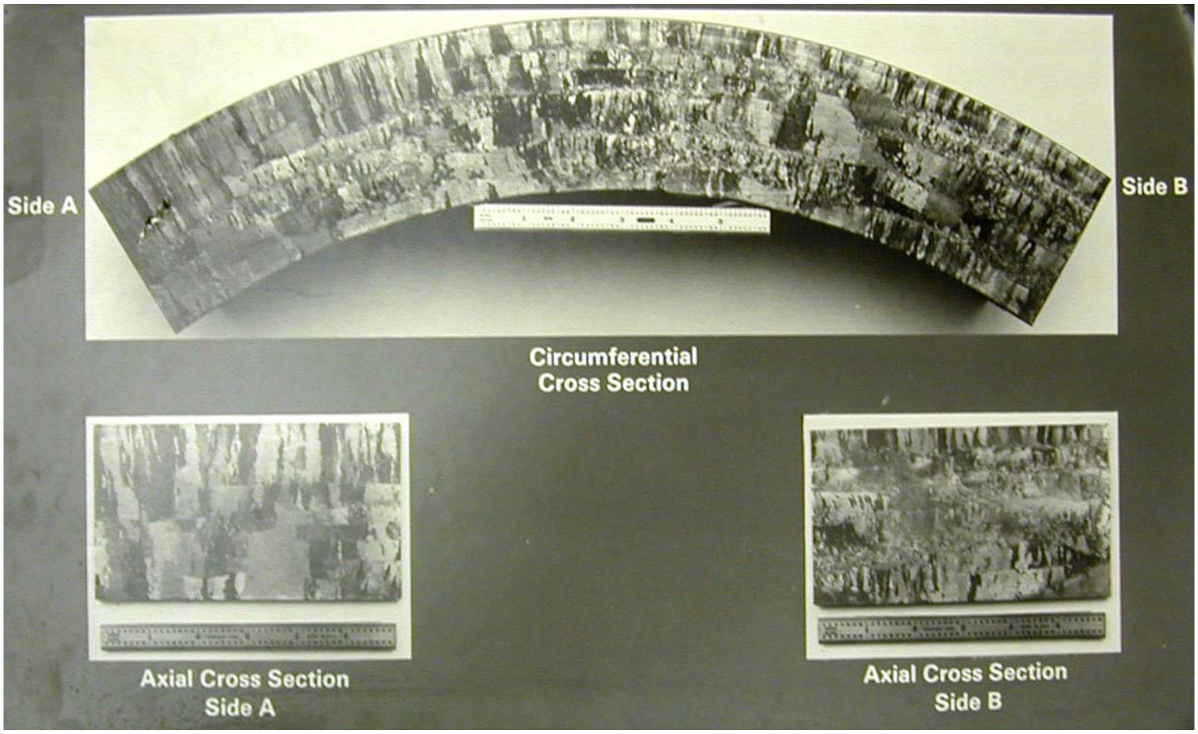

Figure 1. Circumferential and Axial Cross Sections of Thick-Section, Centrifugally Cast Stainless Steel Pipe, Illustrating a Mixed Columnar-Equiaxed Macrostructure with Multiple Layers and Nonuniform Mixing of Grains

The large size of the Mn steel anisotropic grains (typically ¼" diameter), relative to the acoustic pulse wavelength (typically ¼" diameter at 1 MHz), strongly affects the propagation of ultrasound by causing severe attenuation, changes in velocity, scattering of ultrasonic energy, and refraction and reflection of the sound beam at the grain boundaries. These phenomena can result in defects being missed, incorrectly reported, specific volumes of material not being examined, or all of these conditions. When coherent reflection and scattering of the sound beam occur at grain boundaries, ultrasonic indications occur which are difficult to distinguish from flaw signals. When inspecting coarse-grained materials, where the signal-to-noise ratio is relatively low, ultrasonic examinations can be confusing, unpredictable, and unreliable. Hence, novel approaches are required.

Results: There is a significant degree of variability in these microstructures from lot to lot and more importantly, between manufacturers of these components. Of primary concern to roadmasters and track welders are the QA/QC processes that currently exist for Manganese steel frogs at various manufacturing plants. Quite often, newly purchased frogs will exhibit significant internal sand inclusions that act as crack initiation points for components under impact stresses[4]. A novel ultrasonic inspection technique that implements low frequency ultrasound (250 to 450 kHz) combined with a multi-angle, custom-designed transducer head and coupled with an inspection protocol that incorporates advanced signal processing methods for extracting features in the data, has proven to be effective for these coarse grained steel components. The proposed technique uses a zone-focused, low frequency (250-450 kHz) broadband transducer and inspection scanner coupled with an advanced signal processing protocol for reduction of signal clutter and noise and enhancement of signals from defects and anomalies. Figure 2 illustrates the raw ultrasonic rf waveform (time-series) from a sample frog specimen used in this study.

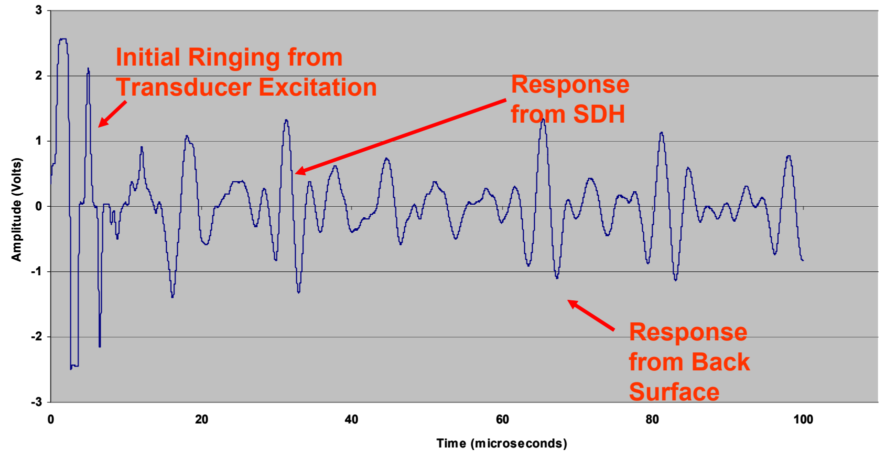

Figure 2. Raw ultrasonic waveform depicting signal response from a 0.25" diameter side-drill hole located 3.2" from the top surface of the frog.

The examination protocol is based upon the premise that sufficient differences exist between the characteristics of coherently scattered ultrasonic energy from grain boundaries and geometrical reflectors and those scattered signals from surface breaking thermal and mechanical fatigue cracks in coarse-grained steels. Battelle's empirical approach relies on technical experience that shows acoustic impedance variations at the grain boundaries can be minimized by using lower frequencies (longer wavelengths), and the degree of coherent energy scattered from these grain boundaries should be inconsistent as a function of frequency, insonification angle, scan direction, and the amplitude of returning signals. The low frequency-SAFT approach, as used in the nuclear industry for the detection of fatigue cracking in piping and other thick section components, is directed toward detecting the corner-trap response from a surface-breaking crack as a function of time, spatial position, and amplitude. In this application, directly scattered coherent energy was used for detection purposes. If the frequency is low enough, the examination is less sensitive to the effects of the microstructure and the probability of detection increases for fatigue cracks. The tradeoff is resolution. However, with the addition of SAFT signal processing, the examination can be performed at low frequencies while still maintaining the capability to detect relatively small anomalies or features in coarse-grained steel components. Therefore, by utilizing multiple examination frequencies and incident angles, and inspecting from opposing orientations, the low frequency-SAFT technique employs a data fusion approach for detection, localization and sizing of cracks and inclusions in coarse-grained material.

The low-frequency/long-wavelength approach is coupled with a SAFT-UT post processing algorithm. Originally developed for use in reducing RADAR clutter, "Synthetic aperture focusing" refers to a process in which the focal properties of a large-aperture focused transducer are synthetically generated from data collected over a large area using a small transducer with a divergent sound field. The processing required to focus this collection of data has been called beam forming, coherent summation (spatial temporal matched filters), or synthetic aperture processing. The resultant image is a full-volume focused characterization of the inspected area with enhanced resolution and improved signal-to-noise ratio[5,6]. SAFT-UT technology is able to provide significant enhancements to the inspection of austenitic welds and other anisotropic, coarse grained materials. The resolution of an imaging system is limited by the effective aperture area; that is, the area over which data can be generated, collected, and processed. SAFT is an imaging method which was developed to overcome some of the limitations imposed by large physical apertures, and has been successfully applied in the field of ultrasonic testing. Relying on the physics of ultrasonic wave propagation, SAFT is a very robust technique.

Using either a pulse-echo or pitch-catch configuration for typical data collection throughout this work, the transducer was positioned on the surface of the specimens, and RF ultrasonic data were collected. As the transducer was scanned over the surface of the specimens, the A-scan record (RF waveform) was amplified, filtered, and digitized for each position of the transducer. Each introduced flaw produced a collection of echoes in the A-scan records. The unprocessed or RF data sets were then post-processed using the SAFT algorithm, invoking a variety of full beam angle values (between 6º and 24º) in order to evaluate and optimize the temporal/spatial averaging enhancement. If the reflector is an elementary single point reflector, then the collection of echoes will form a hyperbolic surface within the data-set volume. The shape of the hyperboloid is determined by the depth of the introduced flaws in the specimens and the velocity of sound in the specimens. This relationship between echo location in the series of A-scans and the actual location of the introduced flaws within the specimens makes it possible to reconstruct a high-resolution, high signal-to-noise ratio image from the acquired raw data.

If the scanning and surface geometries are well known, it is possible to accurately predict the shape of the locus of echoes for each point within the test object. The process of coherent summation for each image point involves shifting a locus of A-scans, within a regional aperture, by predicted time delays and summing the shifted A-scans. This process may also be viewed as performing a temporal/spatial matched filter operation for each point within the volume to be imaged. Each element is then averaged by the number of points that were summed to produce the final processed value. If the particular location correlates with the elementary point response hyperboloid, then the values summed will be in phase and produce a high-amplitude result. If the location does not correlate with the predicted response, then destructive interference will take place and the spatial average will result in a low amplitude value; thus, reducing the noise level to a very small value. SAFT processing is also effective at removing constant-time signals that are not near the front surface, and sub-volume selection during data analysis readily removes any residual near-surface signals.

Figure 3 illustrates one of the primary frog specimens used in this study. Raw unprocessed and SAFT post-processed ultrasonic data in the B-scan mode for a portion of this specimen is shown in Figure 4. The

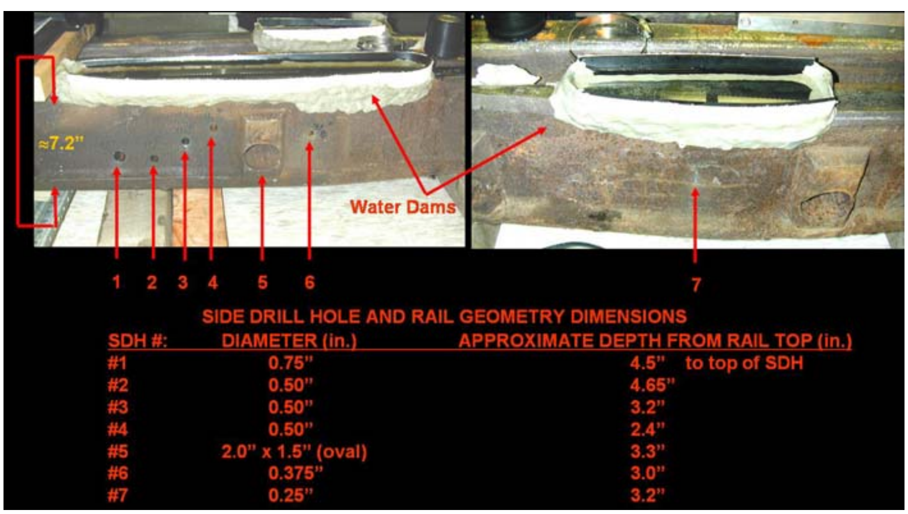

Figure 3. Illustration of Frog specimen with dimensions and positions of machined reflectors.

improvements obtained by using SAFT to process the ultrasonic data prior to analysis are clearly evident.

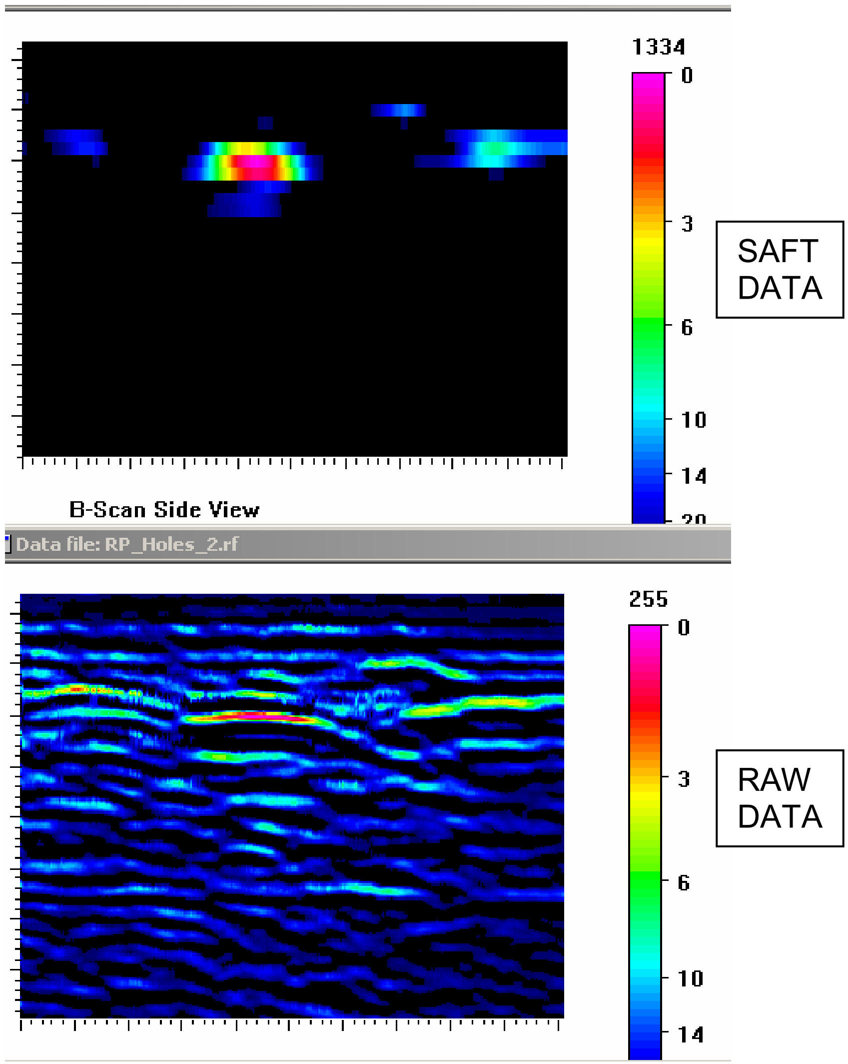

Figure 4. Visual Illustration of Unprocessed Ultrasonic Data Acquired on a Rail Products & Fabrications, Inc., Frog with Machined Reflectors and the same Raw Data after SAFT Processing. Side Views (left) and Top Views (right).

Discussion: Detection of machined reflectors in Mn steel frogs exhibiting coarse-grained microstructures has been achieved with the low-frequency/SAFT-UT technique. Side drill holes ranging from 0.25” diameter to 2.0” diameter at depths ranging from 2.4” to 4.65” from the top surface of the frog were detected and localized relative to transducer position and outer-surface specimen geometry. That being said, much work still needs to be conducted in order to generate the specifications for a pre-service inspection system for deployment and subsequent use for real-time, ultrasonic nondestructive examination of these types of materials.

It is understood that the pre-service inspection of frog components typically needs to be conducted in a restricted time window (as defined by the manufacturing process or other parameters), and prior to the stage where explosive hardening process is invoked. Therefore, inspection speed, inspection coverage (volumes examined), and a reasonable degree of portability for any inspection methodology must be considered. Accessibility to various surfaces and other environmental factors will also be driving mechanisms for system design and performance characteristics. The inspection length being rather short (approximately 2-3 feet of frog rail being identified as the critical volume for inspection), should allow for a rather rapid inspection. The primary objective for follow-on work is to optimize the methodology for effective and reliable detection through the first 1.5" to 2.0" of material from the top surface of the frog head, as the most severe defects that impact the short-term structural integrity of frogs are found in this region.

The minimum flaw size that can be detected in this material is also an issue that will be addressed in follow-on work. The underlying physics behind the technique is the true limitation of the system's sensitivity and performance, and it is proposed that current standards for X-ray inspection be used to determine the initial detection limits and minimum flaw sizes appropriate for establishing a detection criteria or performance threshold for the inspection methodology. From this proof-of-principle work it appears that the microstructures are finer grained than cast stainless steels used in the nuclear industry, thus, the technique may potentially provide better detection capabilities than those demonstrated on NRC thick-section, cast components with this methodology.

Frog-rail head geometry and/or gross deformation of the gage or field sides of the frog will drive any future design and flexibility characteristics of a prototype sensor head[7]. With ultrasonic testing, efficient and consistent coupling of the sensor head to the material under test is very important. The effects of geometry on the inspection data depend on the size of the ultrasonic sensor package used. If the sensor package is large, geometry variations could preclude access to portions of the frog component, but typically, if the geometrical obstacles are known, the sensor package can be designed to accommodate these variations. At low frequencies, surface roughness and small surface anomalies should be insignificant, unless large holes or pockets in the rail exist. Typical low frequency ultrasonic contact inspections require that the crystal elements are large and this drives the transducer housings to be large as well. If the overall sensor package is large, geometry variations along the rail structure (depending on where the variations typically occur) may pose challenges. Coupling of the sensor package should not pose any technical problems, as rail industry representatives have stated that total immersion of the frog specimen during pre-service examinations is permissible. Future work will focus on utilizing smaller sensors using higher frequencies for volumetric exams covering the first 2" from the topside of the frog-rail head, and using low frequencies (and inherently larger sensors) for examining greater depths into the frog.

Conclusions: Results from proof-of-principal tests in the Laboratory at Battelle were successful, demonstrating in principle an effective means to detect and localize anomalies introduced as a function of size and depth from the top of the frog rail. Using non-optimal, commercially available transducers coupled with the low-frequency/SAFT-UT approach, Battelle staff conducted preliminary evaluations of the effects of the material microstructure on ultrasonic propagation, sensitivity and resolution in thick section frog components with machined side-drilled holes. Although initial signal-to-noise ratios for unprocessed ultrasonic signal responses in this material were low (sometimes 2:1), the synergistic effect of utilizing a low-frequency/long-wavelength approach coupled with advanced SAFT algorithms greatly enhanced the S:N ratio and provided a successful methodology for detection and localization of machined reflectors at varying depths in the sample specimens provided.

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