IMPROVING ULTRASONIC INSPECTION OF AUSTENITIC STEELS:
A COMBINED THEORETICAL AND EXPERIMENTAL APPROACH

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INTRODUCTION

The ultrasonic inspection of austenitic castings and welds is often complicated by their material structures. These steels are characterized by large grains, sometimes comparable in size with typical ultrasonic wavelengths. Such coarse macrostructure can lead to high ultrasonic attenuation, significant grain noise and to anisotropic properties [1]. Furthermore, austenitic welds may solidify as large columnar grains, with orientations which are slowly varying throughout the weld. These materials are then inhomogeneous as well as anisotropic.

The problems of inspecting these structures are well known: anisotropy leads to preferred propagation directions and to unexpected defect reflection behavior. The presence of large grains of varying orientations gives rise to high attenuation from scattering at grain boundaries. The problem is further complicated by inhomogeneity, this leading to curved propagation paths.

Figure 1 shows a macrograph of an austenitic weld, showing examples of three material types. On the left hand side of the figure, the grains are large but randomly oriented. On average, therefore, this material behaves isotropically, but with high attenuation arising from scatter between grains. This type of material is known as "equiaxed". The material on the right hand side of the weld region is columnar: the grains all have similar orientations, leading to a macroscopically anisotropic but homogeneous material, again with high attenuation. The central weld region shows a varying grain structure throughout the material, this pattern dependent on the weld manufacturing conditions. This region is also highly attenuating, because of the large grains, and is inhomogeneous because of the variation of material properties.

Some of these problems associated with the ultrasonic inspection of austenitic steels have been studied at UKAEA, Harwell Laboratory in a joint theoretical and experimental program. The aim of this work has been to improve the understanding of the relationship between a steel's macrostructure and its ultrasonic propagation characteristics. Experimental studies have taken advantage of the favorable propagation behavior of low frequency waves within these materials, such as relatively low attenuation and lower beam path bending [2]. This has
led to the development of a drive waveform synthesizer capable of generating short, low frequency pulses, to overcome many of the problems traditionally associated with producing such pulses, and signal processing algorithms to optimize inspection parameters after data has been collected. Theoretical work has included the development of a ray tracing model capable of giving frequency dependent predictions, and the development of finite-difference models for handling anisotropy and inhomogeneity. This paper reviews some of this work.

WAVE PROPAGATION

Frequency Dependent Ray Tracing

Ray tracing theory is of use for predicting ultrasonic energy paths, travel times and wavefronts in anisotropic materials. At Harwell we have developed a 3-dimensional ray tracing model, known as RAYTRAIM [3], capable of studying ultrasonic propagation behavior in anisotropic and inhomogeneous materials. An inhomogeneous material is effectively regarded as finely layered, with slight changes in material properties across adjacent layers. A ray is stepped through this material, with the model calculating the gradually changing ray properties which accompany the changing material properties. This leads to curved ray paths, amplitude losses and changing wavefront shapes. This model has been used extensively to study the propagation of ultrasonic energy in various weld geometries [3]. The model gives good indications of the relative inspectabilities of different weld types and component geometries.

This ray tracing theory is valid in the limit of high frequency and gives predictions which are independent of frequency. It is valid when the ultrasonic wavelength, λ, is small compared with the grain size. In practice ultrasonic inspection of austenitic steels is often carried out at low frequencies (1 or 2 MHz), for which the conventional ray tracing limit is not applicable. To overcome this problem, we have modified the ray tracing model such that the material properties used as input to the model are now dependent on the ultrasonic frequency [4]. This is intended to represent the differing sensitivity to material variations of rays of different frequencies. The modified model describes the material variations within inhomogeneous regions by defining elastic constants at grid points throughout the region. These elastic constants are obtained, for example, by studying macrographs of weld structures together with knowledge of the relevant single crystal elastic constants. This grid describing the variation of material properties is then processed to smooth out material variations to an extent dependent on the ultrasonic wavelength (i.e. frequency). This gives “effective material properties”.
Some results from this model are shown in Figure 2, where the predictions of compression ray paths and amplitudes are shown for a single V weld, for frequencies of 10 MHz, 3 MHz and 1 MHz. Also shown on the figure are the phasefronts associated with the ray paths. As the frequency is reduced, the ray paths become less distorted, as do the wavefronts. This agrees well with knowledge of the favorable propagation behavior of lower frequencies within austenitic steels.

**Finite Difference Modeling**

The use of finite difference techniques to study the propagation of elastic waves, and interaction with defects, in isotropic materials is well known (see reference 5 for further literature). The same principles may be applied to wave propagation in anisotropic and inhomogeneous materials, where the material properties may now differ at each grid point. At Harwell we have developed such a finite difference model and used it to study the propagation of ultrasonic waves in weld materials. The model gives frequency dependent predictions of wave propagation behavior.

Figure 3 shows some results from a finite-difference calculation of wave propagation in a K-shaped austenitic weld. The assumed material structure is shown diagrammatically in Figure 3a. The weld is characterized by a rapid change of material properties near the vertical interface, with the grain orientation changing smoothly by 90° over 2 or 3 mm. A 45° compression wave beam is incident onto the weld region as shown in Figure 3b. Snapshots of the compression and shear wave components at later times show evidence of beam skew and some beam splitting, as seen in Figures 3c and 3d. By studying many such results we are able to investigate the effects of frequency on wave propagation behavior and to compare these with ray tracing predictions.
Finite-difference predictions for 45° compression waves in a K weld. a) schematic of weld grain structure; b) contour plots of shear and compression wave amplitudes after 2μs of travel time c) and d) as b) at times of 3μs and 4μs respectively.

Experimental Studies

As part of the experimental program of research into austenitics we have studied the effects of material macrostructure and ultrasonic frequency on wave propagation. In general the lower the frequency, the lower the attenuation and the smaller the beam path deviation, as predicted by the theory. A further effect of material structure on wave propagation is the roughening of wavefronts on passing through highly inhomogeneous materials. This represents a loss of phase coherence as adjacent parts of a beam travel through slightly different regions of material at different velocities. This effect is more marked the higher the frequency. Figure 4 shows the B-scan images resulting from scanning the rear face of coarse-grained block, at center frequencies of 0.5 MHz and 4.5 MHz. Wavefront roughening at the higher frequency is clearly seen. This effect is also predicted by the frequency dependent ray tracing model, and is seen in Figure 2, with the effect becoming less marked the lower the frequency.
INTERACTION WITH DEFECTS

Predicting Pulse-Echo Ray Paths

The bending of ray paths within inhomogeneous materials, and the skewing of beams within anisotropic materials leads to difficulties in predicting inspection paths. For example, simple rules relating probe beam angle to fusion face angle are no longer appropriate for determining ray paths for Pulse-Echo inspection of lack-of-fusion defects. For detection to occur via Pulse-Echo a defect must reflect specularly back along the incident path. This requires the phase vector to be normal to the defect face. For anisotropic materials, because of beam skewing, this is not in general the same as requiring the direction of energy travel to be perpendicular to the defect face.

Ray tracing theory can be of use in this problem, by determining those ray paths for which specular reflection along the path of incidence will occur. Figure 5 shows predicted compression ray paths for a fast reactor double V-weld, using the fusion face as a source of rays with phase vectors at 90° to the face. Reciprocity ensures that the emerging rays are those which would be required to inspect for lack-of-fusion defects along this fusion face. It is clear that the ultrasonic energy is not in general travelling perpendicular to the
Fig. 5. Predicted Pulse-Echo ray paths for lack-of-fusion defects in a double V weld, using ray tracing theory.

fusion face for this condition to be met. The ray tracing and finite-difference models may be used to study other inspection problems of this sort.

Improving Signal to Noise Ratio

Poor signal to noise ratio in austenitic steels arises because of a high level of grain scatter, particularly at higher frequencies. Methods of overcoming this usually include post-processing of collected scan data using digital processing methods or spatial filtering. We have studied some of these methods and have achieved improved resolution in some situations. Many of these approaches make use of the behavior of austenite as a low pass filter, with higher frequencies more severely attenuated.

A different approach has concentrated on ensuring that the waveform input to the material is matched as well as possible to the "transfer function" of the system, that is, as low frequency as possible, taking account of the defect resolution required. However, this is made difficult by the problems of generating short, low frequency pulses: conventional transducer technology yielding pulses of about 1.5 cycles at 5 MHz gives rise to pulses of about 3 cycles at 1 MHz. To help overcome this problem, we have used a digital waveform synthesizer in combination with well damped probes operating at the low frequency edge of their response to generate short pulses of low center frequency (typically 1.5 cycles at frequencies below 1.5 MHz). Results using this synthesizer are generally encouraging. Figure 6 shows time-of-flight diffraction scans of a hot-tear at a depth of 47 mm, both with and without the digital waveform synthesizer. There is considerable enhancement of the signal to noise ratio when the synthesizer is used. This method of improving the inspectability of austenitic steels is undergoing further investigation.
CONCLUSIONS

This paper has reported on some results of a joint experimental and theoretical investigation of the ultrasonic inspection of austenitic steels. Theoretical modeling using ray tracing and finite difference techniques has given valuable insight into the effects of material macrostructure and ultrasonic frequency on inspection. Experimental studies have concentrated on methods of improving signal to noise ratio in these steels and on relating properties such as attenuation to material structure.

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REFERENCES