ULTRASONIC MEASUREMENT OF POROSITY IN CASTS AND WELDS

Laszlo Adler and Shaio-Wen Wang
The Ohio State University
Columbus, Ohio 43210

Porosity, i.e. voids and gas bubbles, of casting and welds significantly effect the mechanical properties and acceptability. Porosity may occur in castings via two major mechanisms (ref. 1), (a) gas evolution or capture during solidification and (b) shrinkage during solidification. While nondestructive techniques, such as ultrasonic methods are available and used for the detection and characterization of large (i.e. greater than 1 mm) pores in many alloys, only destructive techniques are currently available to quantitatively characterize smaller pores in cast alloys. This paper describes the development of a quantitative nondestructive method which involves ultrasonic attenuation measurements in frequency domain to determine volume fraction of porosity in aluminum cast. The aluminum alloy A357 casting samples were produced at The Ohio State University Foundry with controlled porosity contents ranging from 0% to 6%. A computer controlled system was used to direct ultrasonic beam to a test sample to different places to conduct ultrasonic attenuation measurements. The plot of attenuation coefficients as a function of frequency was then evaluated based on existing theories to determine volume fraction of porosity and pore size.

SAMPLE PREPARATION

The A357 aluminum alloy used in this study has a composition (weight %) given below (ref. 2).

Si	Fe	Cu	Mn	Mg	Zn	Ti	Be	others	Al
6.5-7.5	.2	.2	.1	.40-.70	.1	.10-.20	.04-.09	.15	balance

This alloy has a melting and freezing range of about 50C (Solidus = 557C and Liquidus = 612C). Various techniques were used to produce A357 aluminum alloy casting to have porosities ranging from 0% to 6% by volume.

In order to produce zero gas content samples which could be used as zero gas content standards, the melting, pouring and solidification were performed in an evacuated chamber at a pressure of about 1 mm mercury. After successfully producing low gas content (i.e. less than 0.2% gas voids by volume) samples via the vacuum casting experiments, castings were made in which varying amounts of gas porosity were introduced throughout variations in the melting environment and mold conditions. The A357 alloy was melted in air in both induction and gas-fired crucible furnaces. For some samples, moisture was deliberately introduced to the melt and/or casting by placing a moist towel on top of the melt, placing moisture on the mold surface, or using a moist brick as the support for the permanent mold and allowing contact between the liquid alloy and the moist brick base.

Samples were then sectioned from each casting at various locations and milled to form a regular parallel pipe. The side dimensions and weight were measured to obtain density for each sample. The volume average porosity based on the density measurements was then calculated using the equation:

$$\text{Porosity \%} = (\rho_{\text{the}} - \rho_{\text{measured}})/100 \tag{1}$$

where the theoretical density of the A357 aluminum alloy was taken as 2.667 g/cc. Two faces of the sample were then polished and photomicrographed. The micrographs provide representative statments of the porosity in the sample (Fig. 1) and also could determine the porosity quantitatively. The areas of pures in the picture was cut and both the removed sections and total section were weighted. Porosity was then determined by

$$\text{Porosity \%} = (\text{weight of pures/weight of total section}) \times 100$$

Only samples which have agreeable porosities outcome from both density and photomicrograph were used in ultrasonic study.

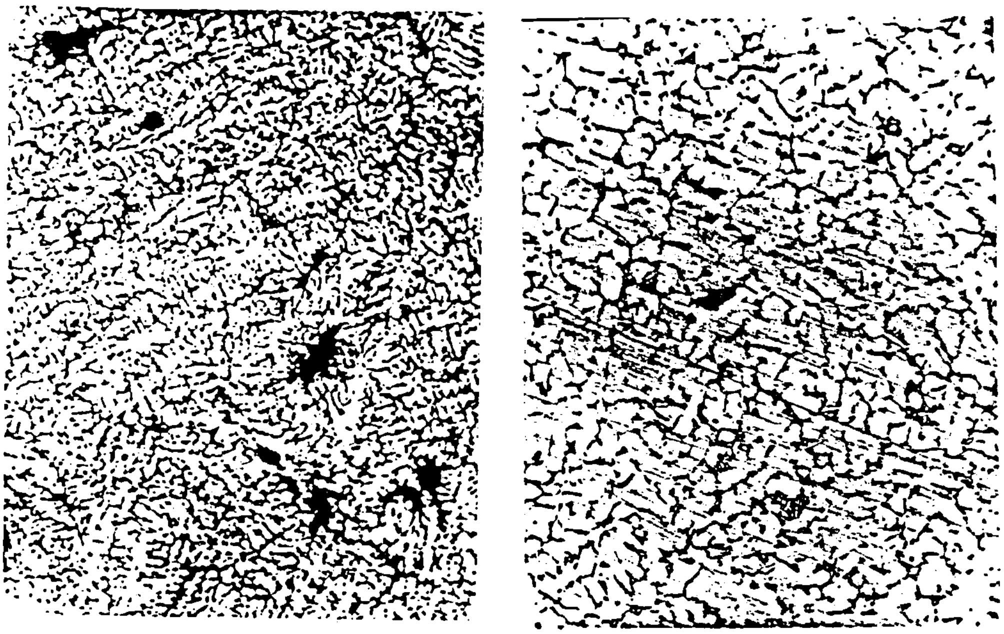

FIG. 1. Metallography: Cast Al

THEORETICAL CONSIDERATIONS

A theoretical approach to use ultrasonic scattering in porous materials has recently been formulized by Gubernatis and Domany (ref. 3) and by Rose (ref. 4). They calculate the attenuation coefficient of elastic waves due to scattering from pores. The assumption is that the pores are far apart that no multiple scattering will take place. The attenuation coefficient is calculated as a function of frequency for various concentrations of pores.

In the Rayleigh region where the wavelength (λ) is much larger than the pore size (a), the attenuation (α) is proportional to the third power of the frequency while in the diffusive region (λ<<a), i.e. for high frequencies the attenuation coefficient is independent of the frequency. There is, however, a connecting region at $k_o a \approx 1$, where k is the wave number, is a turning point. At that point the attenuation coefficient $\alpha \approx k_o CK$. C is the volume fraction of porosity and k is dependent on the elastic constants of the host materials.

The behavior of the predicted frequency dependent attenuation curve is shown on Fig. 2. In the next section, the experimental system and procedures will be described to obtain such frequency dependent attenuation curves in aluminum cast materials.

EXPERIMENTAL SYSTEM AND PROCEDURE

The aluminum cast materials were machined to rectangular blocks on inch thick and a surface area much larger than the diameter of the transducer. The aluminum cast block is submerged in a water bath. A broadband transducer is placed in its desired position in the water bath by rotation around two perpendicular axes situated in a horizontal plane.

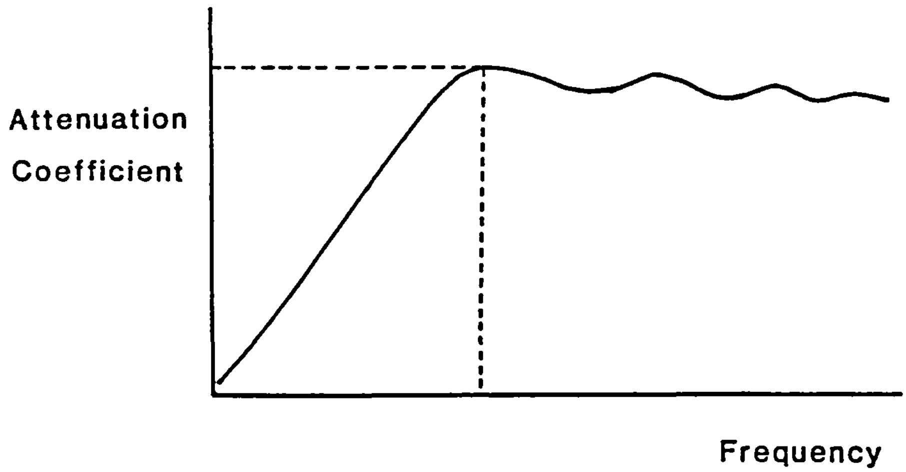

Fig. 2. Theoretical plot of attenuation as a function of frequency for inhomogeneous material.

Ultrasonic Spectroscopy System

The ultrasonic spectroscopy system, which is schematically displayed in Fig. 3, is assembled around a PDP II/34A minicomputer. A broadbandwidth ultrasonic pulse is produced by exciting an untuned ceramic transducer with a fast rise-time, high-voltage pulse. Reflected signals are received by the same transducer (pulse-echo configuration). The electrical pulse generated by the received waveform is filtered and amplified.

The time domain signal can either be fed to a conventional spectrum analyzer or be sampled and converted into digital data to be processed by a computer. For processing by the spectrum analyzer, a stepless gate is used to select a portion of the received signal. The receiver output as well as the gated waveform are displayed. The amplitude spectrum of the gated waveform is displayed on a spectrum analyzer.

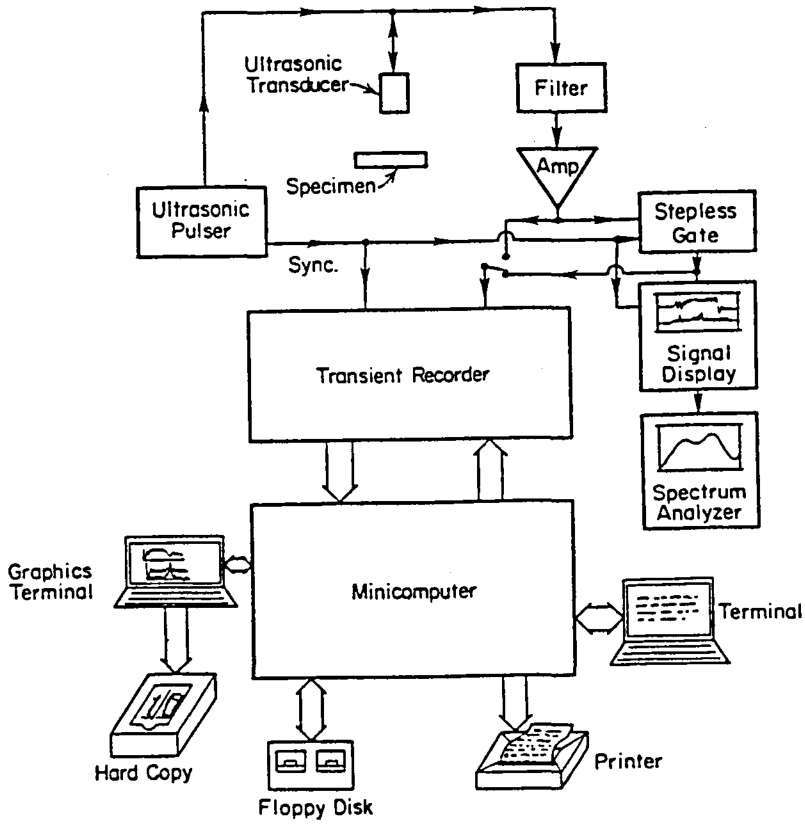

FIG. 3 Schematic diagram of the ultrasonic spectroscopy system.

For conversion to digital data, a high-speed transient recorder is used to store the signal amplitude at discrete times in its digital memory. The computer controls the acquisition of the ultrasonic pulse data and then transfers the digitally represented signal from the recorder to the minicomputer memory. The RF signal data may be permanently recorded on floppy disks. Processing of the ultrasonic signal is performed on the minicomputer and includes the following operations: gating, autocorrelation, averaging, Fourier transform (Fast Fourier Transform procedure), deconvolution and plotting. Plots in the time domain as well as in the frequency domain are displayed on a graphics terminal. Displays may be recorded permanently by utilizing a hard copy unit.

Attenuation Measurements and Results

To obtain attenuation coefficients as functions of frequency of the given sample, a deconvolution process was used. The spectrum of a normally reflected signal from the back surface of the sample was deconvolved with the spectrum obtained from the front surface. This procedure is shown schematically on Fig. 4. On Fig. 4 a,b,c the front, the back and the deconvolved spectrum is shown respectively. Correction for other losses such as beam spread and interface losses are also incorporated into the program to obtain the attenuation/unit length as a function of frequency.

The experimental results of the averaged ultrasonic attenuation coefficient as a function of frequency were displayed in Fig. 5 for low, medium and high porosity samples. The location of the turning point was then used to determine the mean pore and the porosity contents from the following equations:

Pore size: $a = (V/2\pi)\cdot(1/f_p)$

Porosity: $c = (V/2\pi\cdot K)\cdot(\alpha_p/f_p)$

where V is the longitudinal velocity of each sample, K is a constant which depends on the material used, f_p and α_p are the frequency and the attenuation coefficient corresponding to the location of the turning point. Table 1 shows the calculated results. The pore radii are close to those obtained from photomicrographs. As to the porosity contents, the results from ultrasonic experiments agree well with those from density measurements for low and medium porosity samples. For samples with high porosity such as cast Al 1920, the agreement is off a little bit. This may be caused by a multiple scattering due to the existence of more pores, which contradict the theoretical assumption of individual scattering.

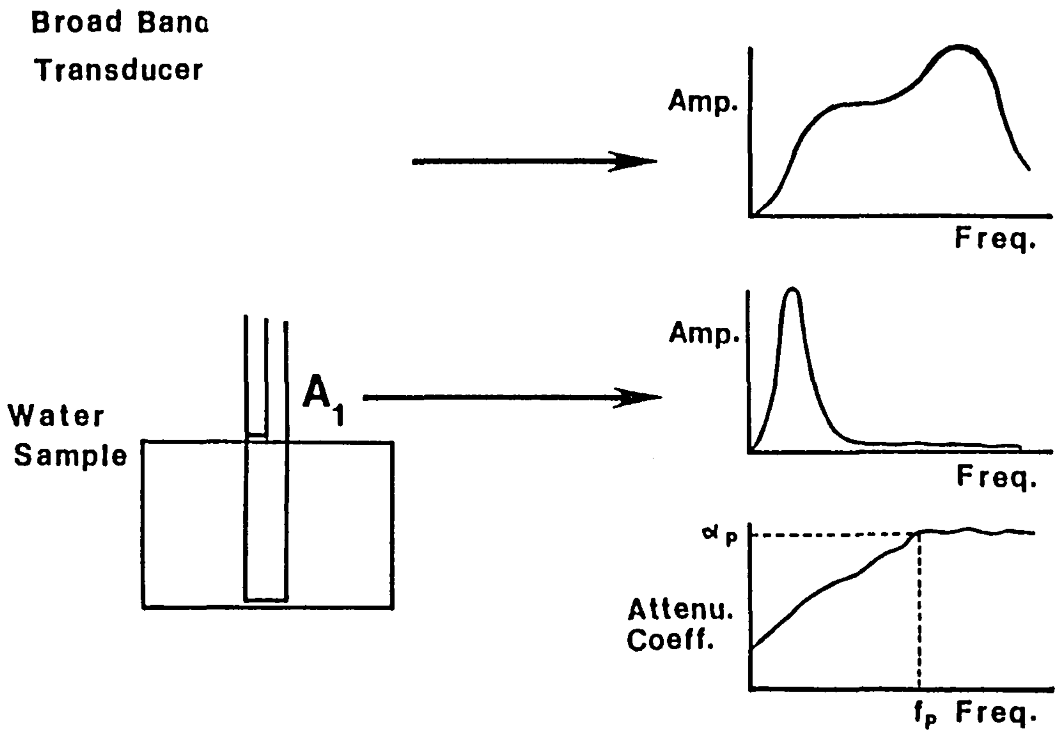

FIG. 4. Ultrasonic Determination of Porosity.

Table I. Experimental Results of Porosity and Pore Size from Ultrasonic Measurements.

Sample	Attenuation Coefficient (NP/cm)	Frequency (NHz)	K_0(1/cm)	Pore Radius (um)	Porosity Exp.	Porosity Density
Cast Al 013	.39	15	142	70	.24	----
Cast Al 1010	.22	12	114	87	.17	0
Cast A. 1210	.20	8	76	131	.23	.22
Cast Al 1410H	1.02	13	123	80	.74	1.3
Cast Al 1410L	.20	10	95	105	.19	1.3
Cast Al 1510	1.12	9	85	116	1.18	2.18
Cast Al 1810	1.00	10	95	105	.95	.9
Cast Al 1820	1.25	12	114	87	.99	1.05
Cast Al 1830	1.20	11.5	109	91	.99	1.20
Cast Al 1850	1.00	11	104	95	.86	1.08
Cast Al 1920	2.85	8	76	131	3.4	4.6

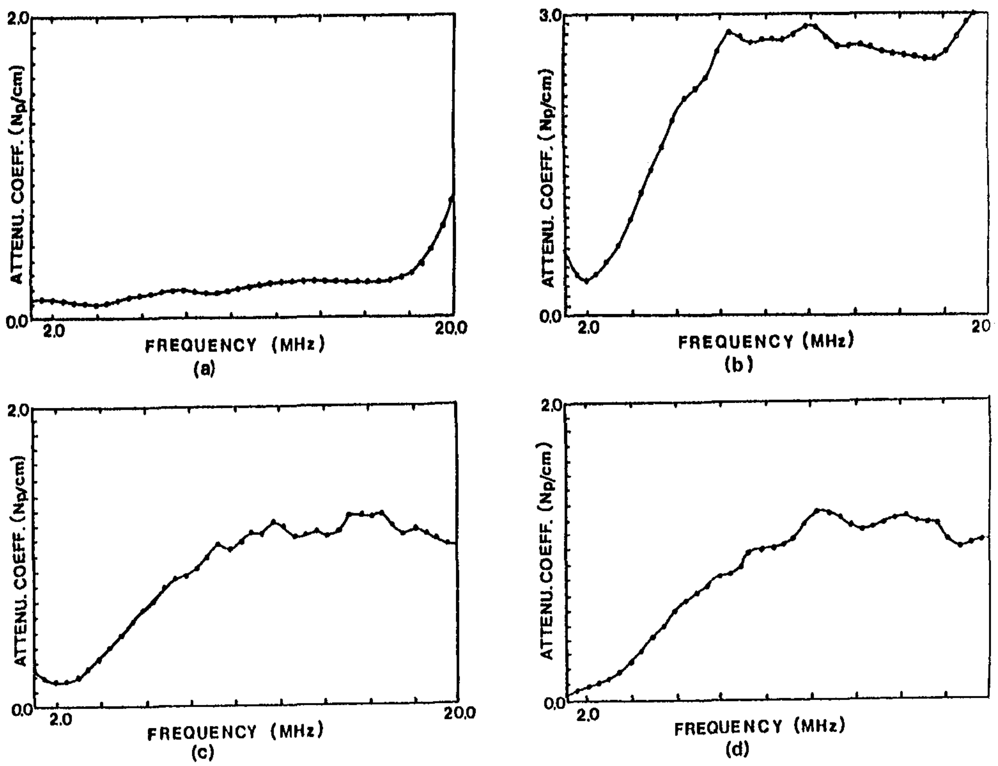

FIG. 5 Attenuation Coefficient as a function of frequency for cast Al Samples: (a) 1010, .2% porosity; (b) 1920, 5% porosity; (c) 1% porosity; (d) 1830. 1% porosity.

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