COMPUTER AIDED ULTRASONIC POROSITY ASSESSMENT FOR CAST ALUMINUM ALLOY

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INTRODUCTION

Successful determination of the volume fraction and pore size of porosity in cast aluminum by ultrasonic attenuation spectroscopy has previously been reported [1]. Cast aluminum samples having a dilute distribution of pores ranging from 1% to 5% volume fraction and an average pore radius from 50 μm to 500 μm were considered.

Initial results were obtained from samples having smooth, flat surfaces, under ideal testing environments. Such factors, e.g., rough (as-cast) surface, alignment, and the measuring limitations of the spectroscopy system, were investigated in order to increase the applicability of the porosity assessment technique. These factors which affect the porosity assessment technique were identified as to whether they caused an under- or overestimation of porosity. Correction routines were devised to improve those porosity results which were underestimated due to the above factors. In most cases it is acceptable to slightly overestimate rather than underestimate porosity.

Combining the ultrasonic assessment technique and the correction routines, a computer aided assessment program was developed. Following sample placement and transducer alignment by the operator, the program will measure the sample attenuation, calculate the volume fraction and pore size, and apply the correction routines when necessary. Constant instructions are given to the operator during each step of execution by the program. Minimal interaction between the operator and computer is required which makes this assessment program ideal for production NDE.

The remainder of this paper is divided into three parts. First, a brief description of the ultrasonic porosity assessment technique is given. Second, the factors which affect the accurate calculation of porosity and the correction routines used to improve these results will be described. Finally, a flowchart and explanation of the assessment program will be presented.

ULTRASONIC POROSITY ASSESSMENT

The theoretical model used for the ultrasonic assessment technique considers the measured ultrasonic attenuation of the cast aluminum sample

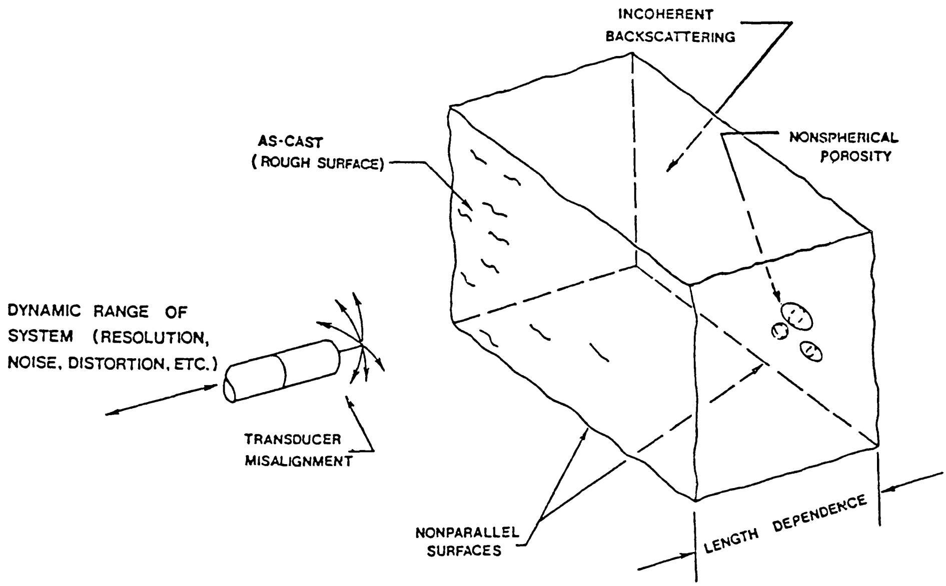

Figure 1. Experimental set up and the factors which affect the porosity assessment technique.

as that produced by single spherical scatterers. Each cast aluminum sample was aligned normal to a broadband immersion transducer and insonified with an effective frequency ranging from 2 MHz to 20 MHz. The experimental set up is shown by Figure 1.

The total measured attenuation losses, L, from the porous sample were determined by comparing the received front surface frequency spectrum, A_f, to the backwall echo frequency spectrum, A_b, using Equation 1.

$$L = \mathrm{Ln}\,\frac{A_f}{A_b} = L_{IMP} + L_{DIFF} + L_{GRAIN} + L_{SURF} + L_P \qquad (1)$$

Attenuation losses from impedance mismatch, L_{IMP}, and diffraction, L_{DIFF}, caused by the liquid-solid interfaces and beam spread of the transducer, respectively, were calculated from known parameters and eliminated. Because of the effective operating frequency range and the material, the attenuation losses from grain scattering, L_{GRAIN}, were neglected. Correction for attenuation losses due to rough surface, L_{SURF}, will be described in the next section and will be neglected here. From Eq. 1, the only remaining term is the attenuation losses from the porosity, L_P, which relates the porosity induced attenuation to the ultrasonically measured attenuation.

A porosity induced attenuation coefficient, $\alpha(k)$ (k is the wave vector), was then determined by dividing the porosity induced attenuation by twice the sample thickness shown by Equation 2.

$$\alpha(k) = \frac{L_P}{2d} \qquad (2)$$

The resultant attenuation coefficient was plotted as a function of frequency shown graphically in Figure 2.

The average pore radius, a_p, was then calculated from the "turning point." The "turning point" is characteristic of the wave vector and

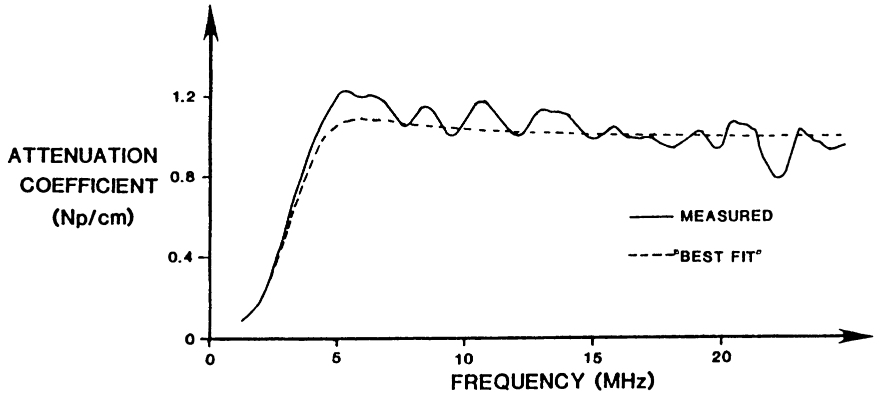

Figure 2. Attenuation coefficient curve for Sample BC-1, with $c = 3.0\%$ and $a_p = 260$ µm.

average pore radius, i.e., where $ka_p = 1.05$, and where the $\alpha(k)/f$ as a function of frequency attains a maximum. Therefore, precise determination of the "turning point" is made by dividing $\alpha(k)$ by the frequency and plotting these values as a function of frequency. The volume fraction of porosity c, was calculated using the value of the attenuation coefficient at the turning point and the average pore size previously calculated, where $c = 1.22[\alpha(k)a_p]$ [1].

FACTORS AFFECTING POROSITY ASSESSMENT

From Fig. 1 it can be seen that a variety of factors affect the porosity assessment technique. Factors, such as the dynamic range of the spectroscopy system, transducer and sample alignment, rough (as-cast) surfaces, and incoherent backscattering effects, are described in this section along with correction routines.

System Dynamic Range

The dynamic range of the ultrasonic spectroscopy system is the operating range in which the instrumentation and sample parameters yield the most accurate porosity results. As shown in Figure 3, the dynamic range for this particular experimental set up was 40 dB. From Fig. 3, it can be seen that the technique is limited to samples having an average pore size ranging from 50 µm to 500 µm because of the particular operating frequency range. The "length dependence" of the sample must also be considered. Samples having high volume fractions or large pore sizes will have to be cut in order to be within the dynamic range of the measuring equipment. It was found that the dynamic range of the system could be increased by ≃ 10 dB using spatial averaging, i.e., incrementing the transducer around the point of interest on the sample and averaging the received signals [2].

Transducer and Sample Alignment

Transducer and sample alignment is probably the most critical factor of all because it is the only function in which the operator is involved. The experimental set up employs an immersion transducer aligned normal to the cast sample's surface. Normally, the maximum front surface response is used as an indicator that the transducer is properly aligned. This may be inadequate, especially for large samples or for samples requiring

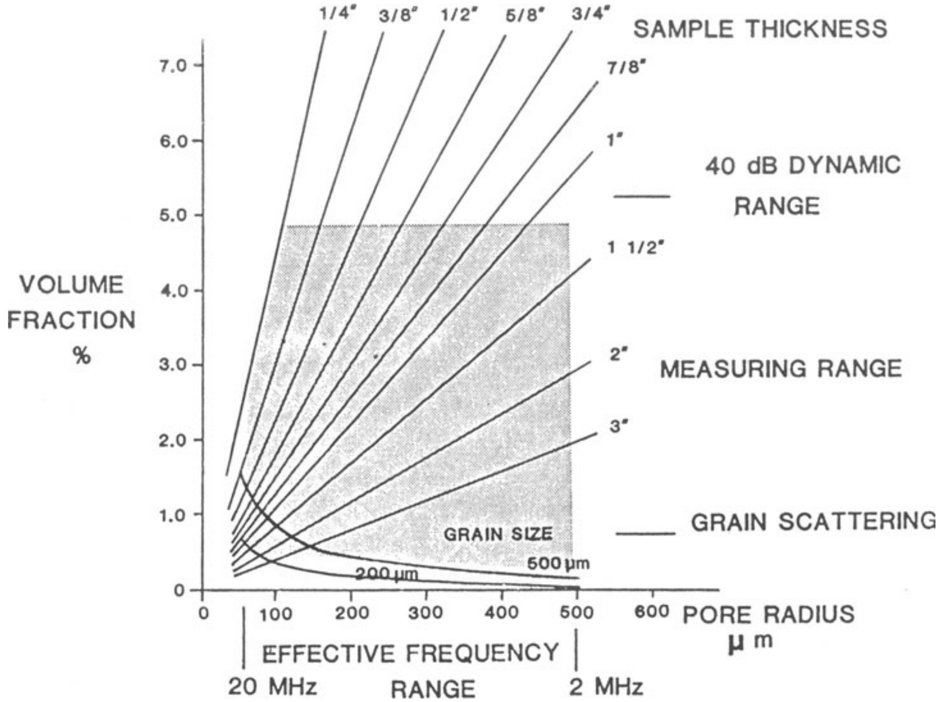

Figure 3. Dynamic range for the ultrasonic assessment system.

spatial averaging. In this case the entire sample and transducer must be aligned normal to each other. Samples having nonparallel surfaces can be detected by noting the change in position of the backwall echo signal as the surface of the sample is scanned.

Rough (As-Cast) Surface

The effects of the rough (as-cast) surface is to substantially reduce the front surface reflection spectrum with a small reduction in the backwall echo spectrum [3]. This reduces the porosity induced attenuation, and consequently, underestimates the calculated porosity by as much as 30%. One possible solution is to machine the surface smooth, however, this may not be feasible, especially for large castings. Two correction routines were developed in order to avoid machining. First, the rough surface spectrum can be replaced by a reference spectrum obtained from a smooth flat sample using the same transducer. This method causes a slight overestimation of the porosity. Second, instead of completely replacing the front rough surface spectrum by a reference spectrum, a modified rough surface spectrum is used. The modified rough surface spectrum is an average of the reference spectrum and the rough surface spectrum in which the reference spectrum is given twice as much weight as the rough surface spectrum.

Incoherent Spatial Noise

The transducer used for porosity assessment has a finite beam area and is somewhat sensitive to the incoherent scattered field, i.e., a small part of the scattered energy will appear in the detected signal together with the attenuated coherent signal. This effect is also dependent on the sample width and porosity located near the backwall of the sample.

The dynamic range of the system is exceeded by the effects of incoherent noise because of the increased measured attenuation. Comparing time periods immediately preceding and following the backwall echo to the backwall echo will indicate if the dynamic range is exceeded since the incoherent terms have the same statistical properties over these periods as during the backwall echo. Use of spatial averaging, described earlier, can be used to increase the reliability of the ultrasonic results by effectively rejecting the incoherent signal components [2].

COMPUTER AIDED POROSITY ASSESSMENT

The flowchart for the computer aided porosity assessment program is shown on Figure 4. The program combines the ultrasonic porosity assessment technique and the correction routines to accurately measure porosity induced attenuation and calculate the volume fraction and pore size of porosity in cast aluminum.

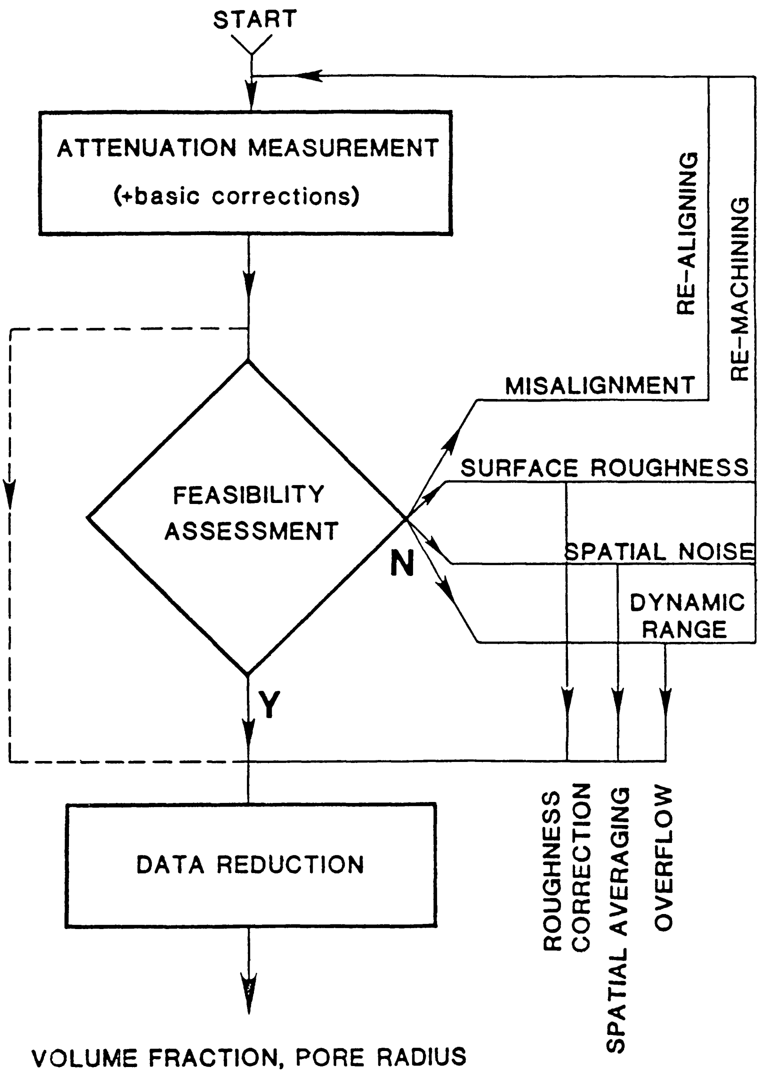

Figure 4. Flowchart of the computer aided porosity system.

Prior to executing the assessment program, a transducer library is established. Each transducer selected for porosity assessment is cataloged by number, frequency, and a reference spectrum of the transducer obtained from a smooth flat surface. The program uses the transducer library during the execution of the program to compare the reduction in signal amplitude that occurs when the front surface is misaligned or due to surface roughness.

Initially the operator aligns the sample and transducer. The program then instructs the operator to select the proper instrumentation settings. Once the instrumentation is properly adjusted, the front surface echo is gated, a FFT (Fast Fourier Transform) applied, and the front surface spectrum obtained. The program compares the received front surface spectrum to the reference signal. If a significant difference between the two signals is noted the operator will be prompted to realign the sample. For samples having a rough surface the options given for correcting this effect will be listed by the computer and the operator must make a choice. Either the received surface spectrum, a modified front surface spectrum, or the reference spectrum will be stored. The program will continue to the next step.

Again, the program prompts the operator to readjust the instrumentation so that the backwall echo spectrum can be processed. The program will then gate, apply an FFT, and store the backwall echo spectrum. If no visible backwall echo is apparent, the dynamic range of the system is exceeded.

From Eqs. 1 and 2, the program calculates the attenuation coefficient as a function of frequency. If the attenuation coefficient exceeds the dynamic range of the system, the program will prompt the operator with two options. First, the operator can choose to "quit." The program will proceed to calculate estimated values for the pore size and volume fraction of porosity and then "stop." Second, if the operator elects to continue, the program will spatial average, and then recalculate the attenuation coefficient. Failure at this point to calculate an acceptable attenuation coefficient may require that the sample be cut by the operator and remeasured.

The program calculates the average pore size in the same manner as described in the first section. The volume fraction is then computed so as to achieve a "best fit" between the measured and theoretical curves using Equation 3.

$$\alpha(k) = \frac{4}{3}\left(\frac{C}{a_p}\right)\Gamma(ka_p) \tag{3}$$

The calculated value for the reduced cross section of the scatterers, $\Gamma(ka_p)$, where $ka_p = 1.05$ was substituted into Eq. 3 [1]. The results obtained from the porosity assessment program are shown graphically in Fig. 2.

CONCLUSION

A computer aided porosity assessment program has been developed for cast aluminum. The program incorporates an ultrasonic attenuation spectroscopy measuring technique and correction algorithms. By measuring the porosity induced attenuation of the cast material, the program calculates the volume fraction and average pore size of the porosity. Factors which affect the accurate measurement of the porosity induced attenuation are corrected. This technique can be used to evaluate samples having volume fractions less than 5% with an average pore size ranging from 50 μm to 500 μm. The program optimizes the measuring process by using a combination of time and spatial averaging.

ACKNOWLEDGEMENTS

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