EVALUATION OF HEAT TREATED STAINLESS STEEL SAMPLES
BY SPLIT-SPECTRUM PROCESSING TECHNIQUE

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Abstract

In ultrasonic examination where the grain size is much smaller than the sound wavelength (Rayleigh scattering) multiple scattering effects can be ignored. However, for a large grain environment in which the sound wavelength is on the order of the grain size (Stochastic scattering) multiple scattering can no longer be neglected and may reduce the effectiveness of the ultrasonic inspection. Here we present experimental data for heat treated stainless steel samples of various grain sizes. From the available experimental parameters, the stainless steel samples were determined to fall in the Rayleigh and Stochastic scattering regions. In these experiments a signal processing technique referred to as split-spectrum processing was used which improves detection of flaws in large grained materials. The examination of these samples showed the split-spectrum processing to achieve effective grain noise suppression. However, the performance of the algorithm indicates dependence on the grain size, which in general, deteriorates as the grain size increases.

Introduction

In many industrial applications utilizing ultrasonic inspection, grain echoes become a crucial factor in defect detection. Large grain echoes are often observed in ultrasonic examination due to external factors that result in grain growth such as in the heat affected zones of welds[1]. It is therefore important to determine the range of grain sizes for which an ultrasonic system is effective.

In earlier work[2,3], the split-spectrum processing technique was introduced which enhances the flaw-to-grain echo ratio and improves the visibility of flaw echoes masked by grain echoes. The principle is based on partitioning a wideband received spectrum to obtain decorrelated grain boundary echoes which are subsequently processed to enhance flaw visibility. In this paper the effectiveness of split-spectrum processing is evaluated for a range of grain sizes falling in the Rayleigh and Stochastic scattering regions. In order to accomplish this, samples were prepared using type 303 austenitic stainless steel rods to obtain grain sizes similar to the range exhibited by heat affected zones in welds. The basis for choosing stainless steel for these experiments is its wide use in industrial applications which involve critical welds such as in nuclear containment vessels. pipings, etc.

Signal Processing Technique

The split-spectrum technique utilizes a concept similar to the frequency diversity principle used in radar for obtaining decorrelated clutter returns by changing the frequency content of the transmitted signal[4]. The returned echoes are subsequently processed typically by square-law detectors to improve target visibility in clutter. In the split-spectrum technique a novel approach was introduced which obtains the frequency diverse signal set from a wideband echo signal by digital filtering, thus eliminating the need for individual transmission of each frequency band. The block diagram of this technique is shown in Fig. 1.

The split-spectrum technique obtains the amplitude spectrum of the echo signal by an FFT routine, divides the spectrum into the desired number of bands by means of digital filtering, and finally inverse Fourier transforms each band to obtain the frequency diverse signal set. Filtering is accomplished by Gaussian shaped windows having selectable bandwidth b and fixed frequency spacing Δf. The center frequencies of the resulting signals range within the half-power bandwidth of the transducer. These signals are then normalized with respect to amplitude, giving zero-mean outputs with maximum magnitude of unity. The resulting set of decorrelated signals are then processed to enhance flaw visibility.

Several techniques have been used for processing these signals, including conventional averaging (linear and non-linear) algorithms and a novel minimization algorithm as indicated in Fig. 1. In the minimization algorithm, processing involves the selection of the minimum amplitude at each range (data point) from among the set of m squared frequency diverse signals. The mathematical form of both the averaging and the minimization algorithms is given in Fig. 1. Previous experimental data on titanium and stainless steel samples has shown that in general the minimization algorithm achieves significant enhancement in flaw visibility in contrast to the limited improvement observed for the averaging algorithms[2,3]. Therefore, in the work presented here, minimization algorithm has been used for signal processing, exclusively.

Sample Preparation

The desired range of grain sizes were obtained by heat treating 2 in. diameter type 303 austenitic stainless steel rods. These samples were heat

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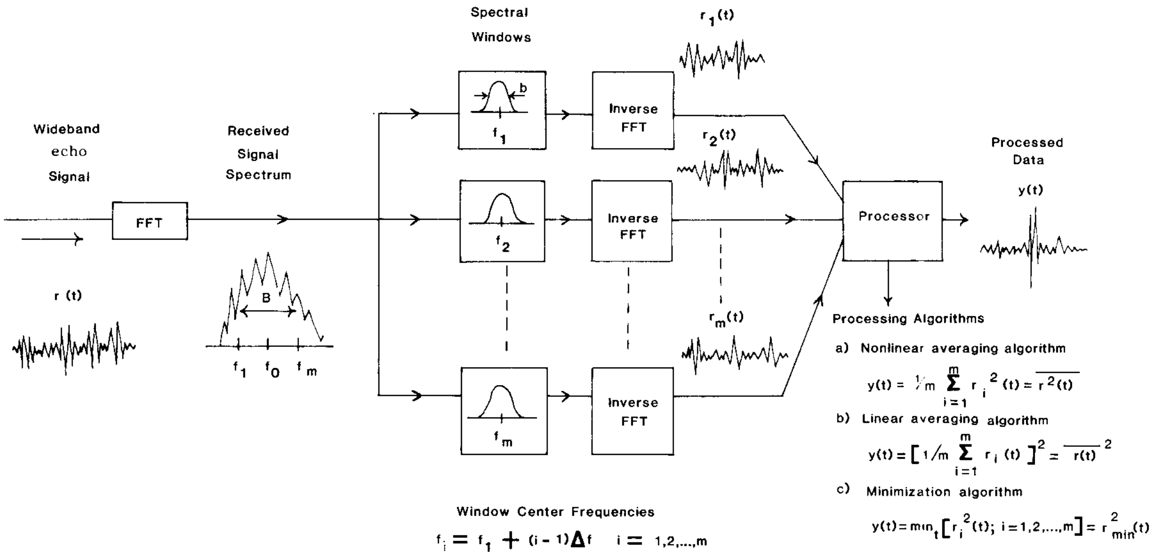

Fig. 1 Split-spectrum processing

treated for approximately one hour at temperatures of 1325°C, 1350°C, 1375°C and 1387°C to achieve a range of grain sizes. In each case the heat treated samples were quenched rapidly in water. The final phase of sample preparation involved the selection and preparation of suitable size flat-bottom holes in the samples. The hole dimensions were selected so that the ultrasonic echo from both the grains and the hole would be approximately the same.

The grain sizes of the heat treated samples were analyzed by the intercept method[5], which resulted in grain-size estimates of 75, 86, 106, and 160μm for the 1325°C, 1350°C, 1375°C and 1387°C samples respectively.

The grain size estimates given here correspond to the average grain boundary spacing rather than the average grain diameter. However, one may approximate the average grain diameter as twice the average grain boundary spacing.[5] Therefore, the selected samples have grain diameters ranging from 150-320μm. For the 5MHz center frequency transducers used (i.e. wavelength ≈ 1mm) the samples fall in the Rayleigh and Stochastic scattering regions. For these two regions Papadakis[6] presents scattering coefficient formulas for both cubic and hexagonal crystals, relating the scattering coefficients to the material properties. These formulas are not repeated here but may be referred to for further consideration.

Experimental Results and Discussion

The heat treated samples were examined using an ultrasonic broad-band transducer with 5 MHz center frequency and the measured signals were processed by the minimization algorithm. Prior to applying the minimization algorithm, outputs corresponding to each frequency band (i.e. frequency diverse signals) are squared to remove the negative values. The squared echo signals and the corresponding processed data for the 1325°C,1350°C,1375°C and 1387°C samples are shown in Figs. 2 to 5 respectively. These results correspond to processing parameters of Δf=100 kHz (i.e. frequency spacing between windows) and window bandwidths of b=300 kHz (i.e. half-power bandwidth) for the 1375°C and b=350 kHz for the remaining samples. The window bandwidths used here were experimentally determined to be the optimal choice for frequency spacing of Δf=100kHz. It should be noted that the performance of the minimization algorithm improves with decreasing Δf, while the flaw enhancement values peak for window bandwidths in the range of 300-400 kHz.[2,3] Although additional flaw enhancement can be obtained for smaller values of Δf (i.e. Δf < 100kHz), it is not significant enough to warrant increased computation time. Therefore, the parameters (i.e. Δf and b) used in Figs. 2-5 approximate those which optimize flaw enhancement obtained by the minimization algorithm.

The hole echoes shown in Figs. 2 to 5 resulted in signals of similar size to the grain echoes. The processed data in each case shows enhancement in the visibility of the targets. In addition, for the 1325°C sample the processing recovered the back surface echo, which originally appeared smaller than the neighboring grain echoes as seen in Fig. 2. A similar situation is seen for the 1375°C sample in Fig. 4 where the hole echo is smaller than the largest grain echo and yet easily recovered. These results indicate the capability of the minimization algorithm in distinguishing the echo

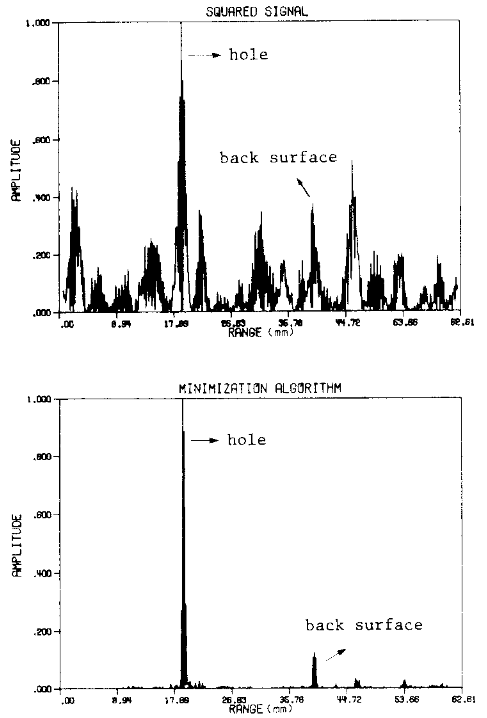

Fig. 2 Squared echo signal and processed data for stainless steel sample heat treated at 1325°C.

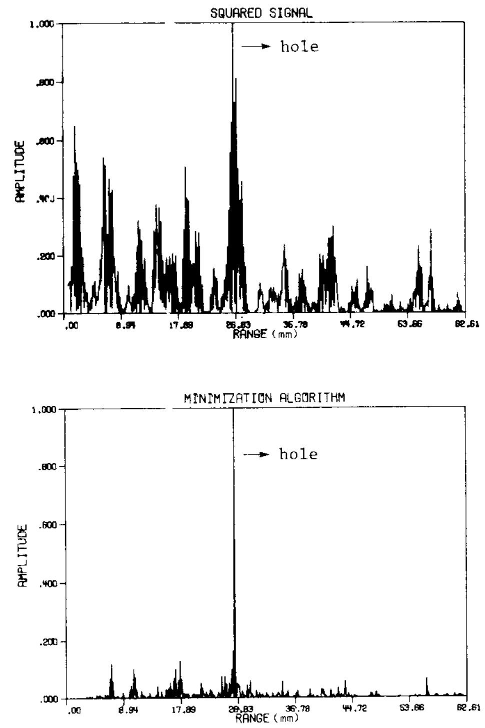

Fig. 3 Squared echo signal and processed data for stainless steel sample heat treated at 1350°C.

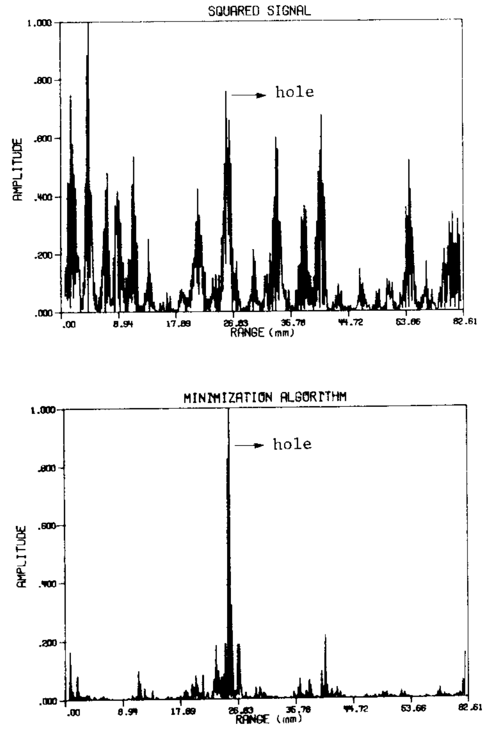

Fig. 4 Squared echo signal and processed data for stainless steel sample heat treated at 1375°C.

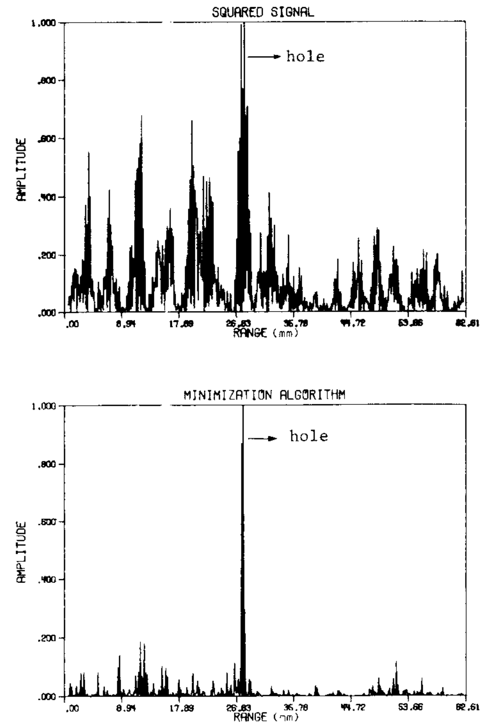

Fig. 5 Squared echo signal and processed data for stainless steel sample heat treated at 1387°C.

corresponding to a larger target reflector from grain echoes even when the target echo appears at or slightly below the grain noise level in the original data.

The enhancement measurement throughout this study was based on the improvement in the ratio of the actual flaw to the largest grain echo, which is defined as

$$F/G|_{enh} = \frac{F/G|_{out}}{F/G|_{in}}$$

where the denominator $F/G|_{in}$ is determined from the squared echo signal and $F/G|_{out}$ is based on the processed output. In some cases this criterion may result in relatively lower enhancement values compared to criteria based on reduction in grain variance or mean value. However, since the echo amplitude contains the most significant information in ultrasonic evaluation, this is an appropriate concept for enhancement measurements.

The $F/G|_{enh}$ data for the heat treated samples is shown in Fig. 6 in terms of window bandwidth b for fixed frequency spacing Δf=100 kHz. The peak enhancement occurs at relatively low b values (i.e. b=300-350 kHz) for each sample. The lower heat treatment sample (1325°C) shows steady decay beyond the maximum value as b is increased. The higher heat treatment samples (1350°C, 1375°C, 1387°C) show some fluctuation in $F/G|_{enh}$ as b is increased beyond the maximum $F/G|_{enh}$ value, which may be a result of increased multiple scattering. However, there seems to be no detectable correlation between grain size and the value of window bandwidth b, where the enhancement reaches maximum as can be seen from the plots in Fig. 6.

Conclusions

In conclusion, the results obtained from the available samples show that the minimization algorithm can enhance flaws in stainless steel samples for a range of grain sizes, similar in size to the grains in the heat affected zones in stainless steel welds. From the available experimental parameters, the stainless steel samples were determined to fall in the Rayleigh and Stochastic scattering regions where significant backscattering occurs. In addition, the experimental results indicate that the performance of the minimization algorithm shows some dependence on grain size, which in general, deteriorates as the grain size increases.

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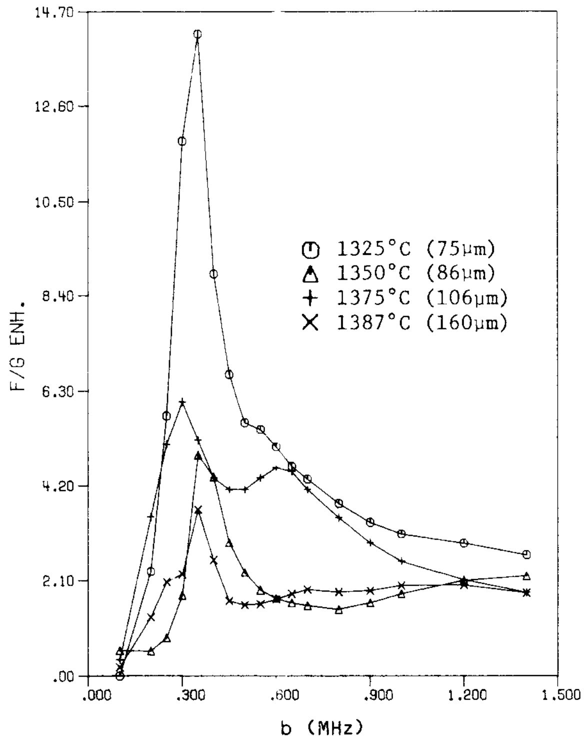

Fig. 6 $F/G|_{enh}$ plots for heat treated stainless steel samples using minimization algorithm.