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Status of CSS NDE in Nuclear Power Plants

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ABSTRACT

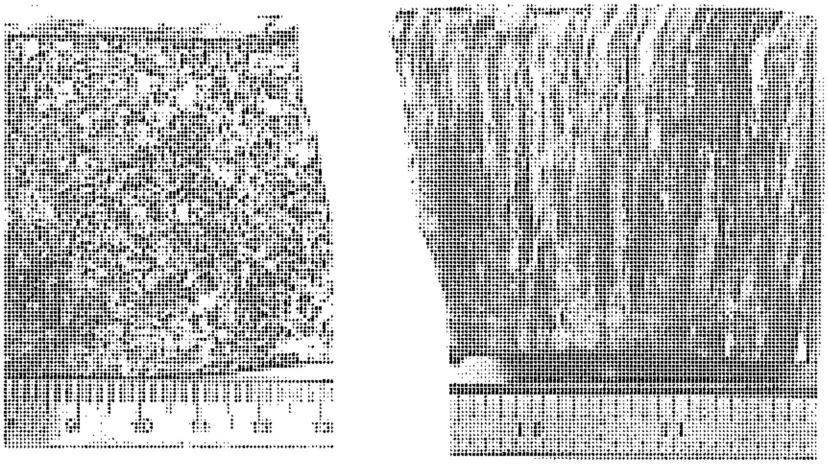
Volumetric examination of (static or centrifugal) cast stainless steel (CSS) weld (parent metal + weld metal) is primarily performed by ultrasonic nondestructive testing method. However, varieties of grain structure of weld metal (mainly columnar-dendritic) and certain parent metals (these can have any type) can make the ultrasonic nondestructive examination impractical. In particular, coarse grains and their orientations make the flaw detection and location unpredictable. Nevertheless, no other nondestructive testing method has yet been demonstrated better than ultrasonics. Grain structures of metal affect ultrasonic wave propagation by the interactions of the propagating waves at the grain boundaries altering wave velocities (phase and group), signal amplitude, beam direction, beam width (diversion and conversion), beam scattering and attenuation. This problem is an important issue in the examination of CSS piping welds in nuclear power plant. This paper summarizes both experimental and theoretical work reported in the past which has helped to identify the reasons behind the difficulties of ultrasonic examination of CSS piping weld, and suggests an integrated procedure for increasing the examination effectiveness.

INTRODUCTION

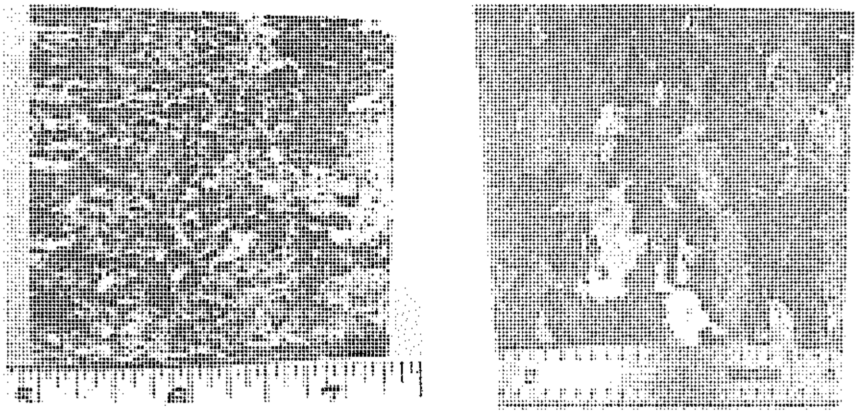
Flaw detection and location within the columnar-dendritic coarse grains of SS weld metal is difficult. However, the varieties of coarse grain structure of certain CSS parent metals (Figure 1) further complicate the ultrasonic examination because the ultrasonic waves have to propagate through the coarse grained CSS parent metal before they reach the weld metal (Figure 2). CSS can have various grain structures such as equiaxed fine grains, randomly oriented coarse grains, columnar-dendritic grains, or a mixture of different grains within the same structure. The flaw detection and location difficulties of CSS weld stem from the severe attenuation caused by the coarse grains and the elastic anisotropy caused by the oriented grains. Ultrasonic wave parameters such as phase velocity, energy velocity, signal amplitude, beam direction, beam width (diversion and conversion), beam scattering and attenuation vary significantly among the different grain structures, and such variations are strongly dependent upon beam incidence angle (elastic anisotropy). Consequently, conventional defect location analysis, where propagating wave velocity is assumed to be constant, cannot be performed accurately. Large (coarse) grains of the material cause severe beam distortion, beam skewing, grain boundary scattering, energy absorption, and mode conversion; all act to decrease the signal-to-noise ratio (SNR). Defect detection is therefore difficult. A lack of knowledge of the grain effects can therefore result in serious errors in ultrasonic examination.

SOLIDIFICATION MODES OF WELD

The solidification mode and the resulting solidification substructure (i.e., grain patterns) are influenced primarily by the concentration of solutes present in the alloy and the extent of constitutional supercooling. Note that the region within which the actual temperature is lower than the effective liquidus temperature is said to experience constitutional supercooling[1]. Figure 3, adapted from the work by Tiller et al.[2], summarizes the effects of the growth rate (R), temperature gradient (G), and the solute concentration (C_0) on the solidification mode. In general, the extent of constitutional supercooling is inversely proportional to $\frac{G}{\sqrt{R}}$. The choice of process, the process variables used in making the weld, and the thermal characteristics of the base metal control G while R is controlled by the welding velocity and the direction of growth relative to the welding direction. Note that this schematic diagram is subdivided into five separate areas, each corresponding to a different solidification mode. In general, the solidification mode becomes more dendritic and less desirable, as one moves upward toward higher solute contents, and to the left toward more extensive constitutional supercooling. In general, the value of the parameter, $\frac{G}{\sqrt{R}}$, increases as the intensity of the heat source is increased, thus reducing the extent of constitutional supersooling in a material of a given composition, C_0, and resulting in a more desirable microstructure (planar growth). Conversely, choice of processes and process variables which cause shallow temperature gradients increase the constitutional supercooling and produce less desirable microstructures (dendritic growth). Although the diagram in Figure 3 is only schematic, it can be used in conjunction with metallographic examination of the solidification structure of a series of test welds as an aid in optimizing fabrication procedures.



(a) Equiaxed Fine Grain (b) Columnar Dendritic Grain



(c) Mixed Coarse Grain (d) Large (Coarse) Grain

Figure 1: Grain structures of cast stainless steel (CSS).

WELDING BY MAGNETIC STIRRING

It was reported earlier that some reseachers (Arakawa, et.al. in IHI, Japan) were successful to prevent the columnar-dendritic grain formation and to refine the grain sizes by *magnetic stirring* during the welding process[3]. The dendritic grain prevention and the grain refinement in this technique is obtained by stirring the molten pool with Lorenz force induced by the interaction of welding current and alternative magnetic field applied from the outside magnetic coil (See Figure 4(a)). Figure 4(b) compares the microstructures of conventional and magnetic stirred weldings. It was reported that this technique has indeed prevented the columnar-dendritic grain formation (reduced the anisotropy) and refined the grain sizes (increased SNR)

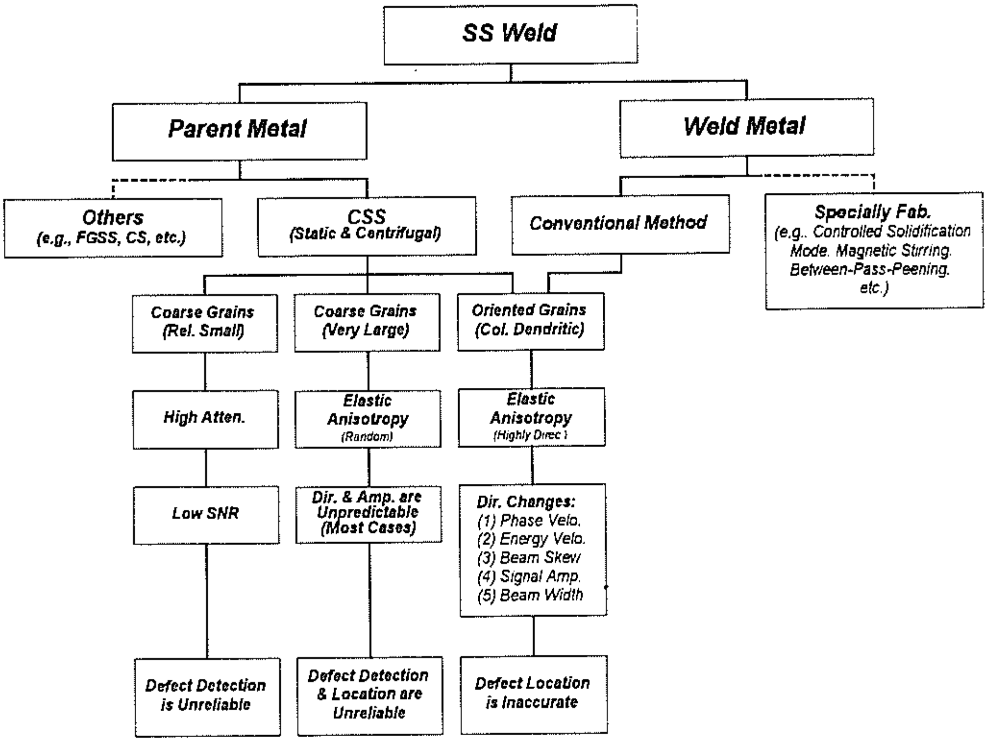


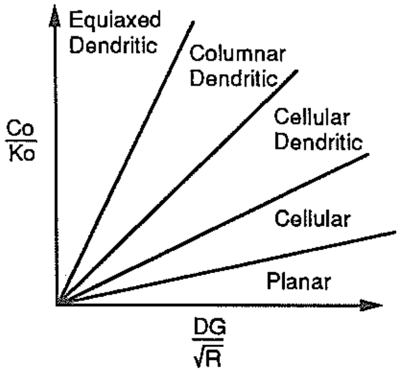
Figure 2: Problems in ultrasonic examination of cast stainless steel (CSS) weld.

WELDING BY BETWEEN-PASS-PEENING

In cooling and solidification of weld deposits, the start of solidification (nucleation) occurs usually from the adjacent solid base metal or previously deposited weld deposits. Thus, the orientation of the dendritic branch pattern tends to follow the orientation of the adjacent solid metal. In many metals and alloys, this pattern can be continued all the way across a multi-layer weld deposit. However, by employing severe between-pass-peening, the undesirable continuous growth orientation pattern may be broken up[4]. Figure 5 shows the breakup of dendritic grain structure by recrystallization due to between-pass-peening of each weld layer.

INSIDE SURFACE EXAMINATION

Since most of the piping weld defects (e.g., IGSCC, fatigue cracks, etc.) initiate from the inside surface of the weld (i.e., weld root side), if one can access the inside surface of the



Notes:
Co – Nominal Solute Content
Ko – Distribution Coefficient
D – Diffusion Coefficient of Liquid
G – Temperature Gradient in Liquid
R – Growth Rate at Solid Liquid Interface

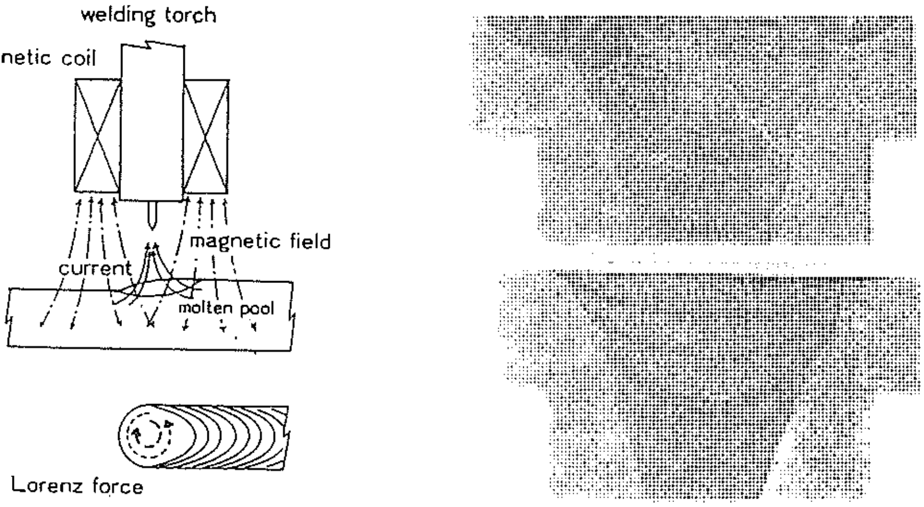
Figure 3: The factors controlling growth mode during solidification (extracted from [2]).

structure, such defects can be reliably inspected from the inside surface of the weld. The inside surface inspection is simple and most reliable because ultrasonic waves travel through neither the weld metal nor the coarse grained CSS parent metals. Ultrasonic surface waves (focused or non-focused) could be effectively used for the examination of such cases. However, if inside surface is unfortunately inaccessible, then, attempts should be made to identify the grains and to compensate the grain effects as discussed in the following paragraphs.

CSS MATERIALS CHARACTERIZATION WORK

The effects of various grain structures on the ultrasonic wave propagation were extensively investigated at the EPRI NDE Center[5]. Ultrasonic wave propagation parameters were measured using specially designed specimens: e.g., angled blocks, polygonal blocks (for SH-wave measurement), and calibration blocks including the wide wedge-shape specimens to obtain 2-D scan images using an automated ultrasonic system. The CSS grain structures investigated were: (1) equiaxed fine grain, (2) randomly oriented coarse grain, (3) columnar-dendritic grain, and (4) mixed grain. For comparison purposes, (5) forged SS and (6) carbon steel were also investigated although no significant variations were expected in these materials (very fine grains). Longitudinal wave, horizontally polarized shear wave, and vertically polarized shear wave modes were utilized in the ultrasonic measurements. The experimental results were then compared with theoretical predications of the wave parameter variations. The measurements made during the experiments included phase velocity, energy velocity, beam skew, signal amplitude, beam width, and frequency influences. Both manual and automatic UT systems were used for the investigation. A parametric analysis for velocity, slowness, and wave surfaces was performed. Using these characteristic surfaces, an ultrasonic ray tracing program was developed. It allows predicting the wave propagation behavior in a given grain structure.

The CSS materials characterization work drew the following conclusions based on both



(a) (b)

Figure 4: (a) Magnetic Stirring Method (b) Comparison of microstructures of conventional and magnetic stirred weldings: Top - Conventional Welding; Bottom - Magnetic Stirred Welding (extracted from [3]).

theoretical and experimental results: (1) Wave propagation parameters such as phase velocity, energy velocity, signal amplitude, beam direction, beam width (diversion and conversion), beam scattering, attenuation, and frequency spectrum vary significantly among the different grain structures of CSS, and such parameters can be utilized for grain structure identification. However, it was not successful to separate the (arbitrarily) mixed grains from the other coarse grains. (2) All three wave modes (longitudinal, vertically and horizontally polarized shear waves) can be utilized for grain structure identification. However, the use of horizontally polarized shear wave requires further investigation for practical use. This study also suggested that, for an actual grain identification in the field, only two backwall echoes, which are acquired by (1) vertical measurement with the pulse/echo method, and (2) angle-beam measurement (between 10^0 - 30^0) with the pitch/catch method, are sufficient to extract the necessary wave parameters to resolve most of the cases (at least, to discriminate (1) equiaxed fine grain, (2) randomly oriented coarse grain, (3) columnar-dendritic grain, and (4) very fine grains (e.g., forged SS or carbon steel). For further details, refer to aforementioned reference (Jeong and Ammirato[5]).

SUGGESTED INSPECTION PROCEDURE FOR CSS WELD

Figure 6 shows an outline of the general approach to the problem. The procedure

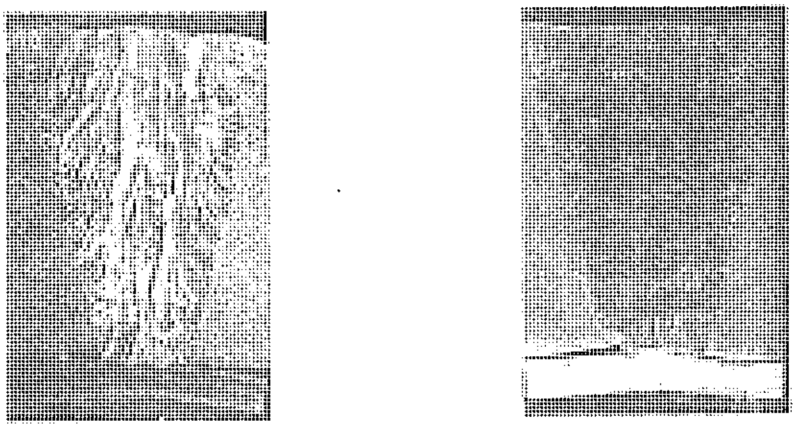


Figure 5: (Left) Continuation of large columnar grain structure across the deposit made with 310 stainless electrode, (Right) Breakup of the dendritic grain structure by recrystallization due to between-pass-peening of each weld layer (extracted from [4]).

emphasizes that one should make the most use of all available information on the testing conditions (e.g., the possibility of inside surface examination) and the component fabrication history (e.g., the weld design and fabrication records) to find out the materials grain structure. Some welds may have been fabricated by special techniques such as controlled solidification environments, magnetic stirring, or between-pass-peening; all can help one to find out the grain pattern of the testing components. Knowing the specific grain types under consideration, one can selecte the most promising inspection procedures including the optimum transducer types, signal processing, anisotropy compensation method, and specific ultrasonic techniques (e.g., phased array, low-frequency surface wave, etc.). If no helpful information is obtained from the weld fabrication records, then, attempts should be made to identify the grain pattern using the CSS materials characterization work as discussed earlier. The CSS materials characterization work suggests the procedure to discriminate the grain patterns as one of the following three: (1) equiaxed fine grains, (2) randomly oriented coarse grains, and (3) columnar-dendritic grains. Specific procedural recommendations for each of the three grain types can be found in the aforementioned reference[5]. In general, signal processing techniques have shown promise for increasing SNR in most CSS materials as demonstrated in several recent field examinations in pressurized water reactor (PWR) plants: *Time Averaging:* When the signal is averaged along the time dimension, short-duration indications (noise spikes, for example) will be reduced, similar to the effect of low-pass filtering. Time averaging smoothes the display and makes it clearer and easier to interpret. *Spatial Averaging:* Spatial averaging consists of adding sets of adjacent waveforms, a method similar to the synthetic aperture focussing technique. The image produced when the transducer is scanned parallel to the flaw is most likely to be useful for improving the SNR for detecting cracks in noisy materials, such as CSS materials. The key feature is that the indication from a crack will persist through several scan increments and will thereby be reinforced through addition. Short-duration indications from grain signals will, on the other hand, be diminished relative to persistent crack indications through the averaging process. *Bandpass Filtering*[6]*:* It is shown that in NDE applications where the received noise is primarily due to Rayleigh scattering (from the grain boundaries) and the flaw echo can be represented by a delta function, flaw visibility can be improved significantly (without the need for sophisticated signal processing algorithms) by merely band-pass filtering (BPF) the lower edge of the received echo spectrum. *Split Spectrum Processing*[7]*:* The principle of this technique is based on partitioning a wide-band received spectrum to obtain decorrelated grain boundary echoes that are subsequently processed (e.g., linear averaging, nonlinear averaging, and minimization algorithms) to enhance visibility (by suppressing the grain boundary Rayleigh scattering).

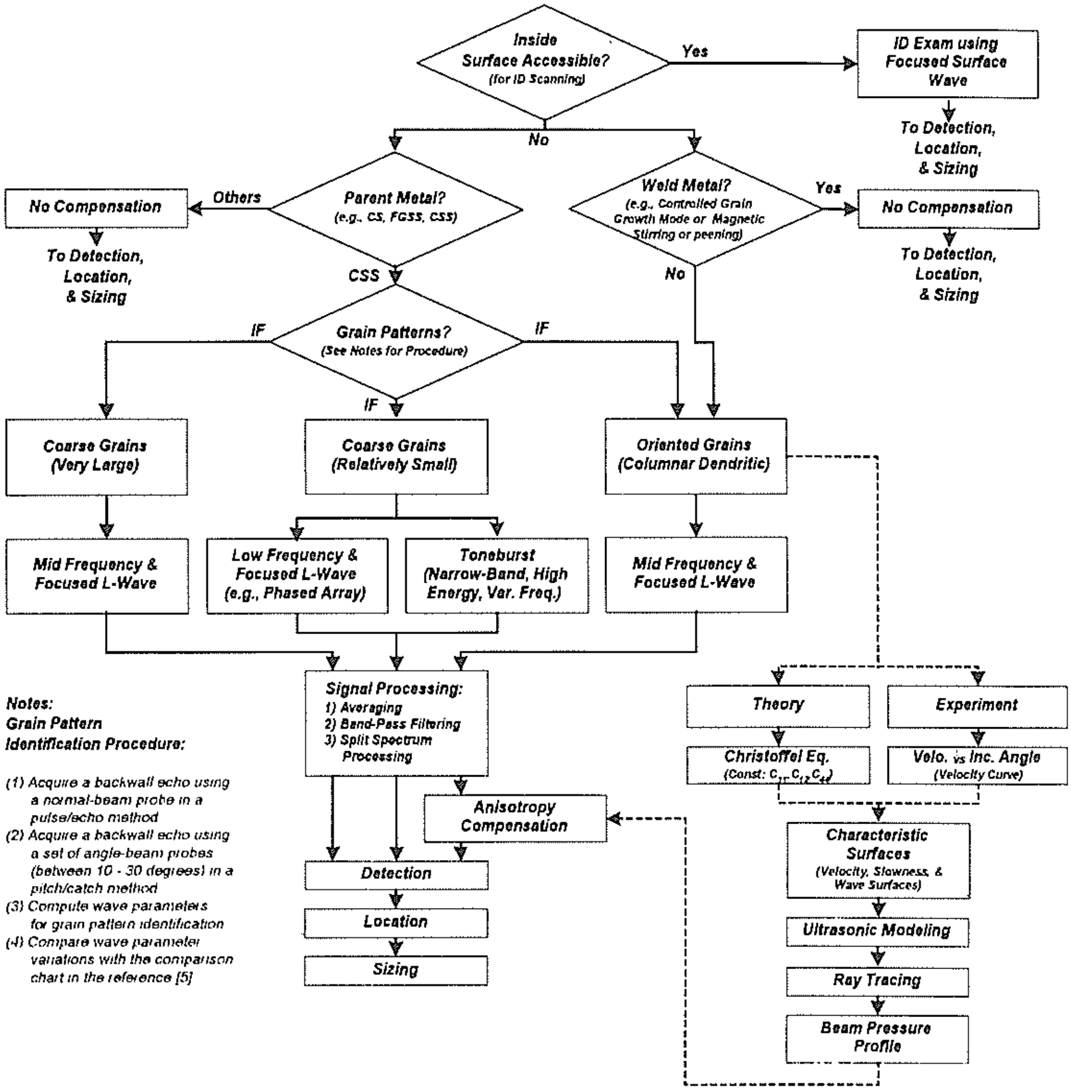


Figure 6: Suggested ultrasonic inspection procedure for CSS component weld.

SUMMARY

Although CSS is known to have improved mechanical properties compared with other critical component materials, plant construction engineers have realized the difficulties of CSS materials examination and initiated the efforts to avoid the use of such coarse grained materials wherever possible. However, a significant number of existing power plants in the world already have various critical components installed with CSS materials. Consequently, the CSS material examination problems still remain. In this study, the experimental and the theoretical work reported in the past were investigated to identify the reasons behind the difficulties of ultrasonic examination of CSS weld. And utilizing the information gathered, an integrated CSS weld examination procedure was suggested for increasing the examination effectiveness.

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