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DEVIATION OF LONGITUDINAL AND SHEAR WAVES IN AUSTENITIC STAINLESS STEEL WELD METAL

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by

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DEVIATION OF LONGITUDINAL AND SHEAR WAVES IN AUSTENITIC STAINLESS STEEL WELD METAL*

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ABSTRACT

One of the difficulties associated with the ultrasonic inspection of stainless steel weld metal is the deviation of the ultrasonic beams. This can lead to errors in determining both the location and size of reflectors. The present paper compares experimental and theoretical data related to beam steering for longitudinal and shear waves in a sample of 308 SS weld metal. Agreement between predicted and measured beam deviations is generally good. Reasons for discrepancies are discussed.

INTRODUCTION

Slow cooling of austenitic stainless steel weld metal leads to the formation of a coarse-grain structure, in which the grains tend to grow with a <100> orientation and essentially along the lines of heat dissipation. This microstructure results in acoustically anisotropic welds with orthotropic symmetry. Thus, the ultrasonic inspection of austenitic stainless steel weld metal is difficult, and the acoustic properties are not easily understood.

Within the anisotropic weld metal the beams may deviate from the expected propagation directions. The extent of the beam deviation depends on mode (longitudinal or transverse) and propagation direction relative to the columnar grain axis. The beam deviation is most significant in the propagation of longitudinal waves, where it may be the predominant factor in

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the apparent attenuation. The situation for shear waves is more complex; here, Rayleigh scattering, mode conversion, and beam deviations are all factors in the apparent attenuation. The deviation of ultrasonic beams in anisotropic media (including stainless steel) has been studied by many investigators. Musgrave described the propagation of ultrasonic waves in anisotropic media and presented calculations for the deviation of the beam from the wave normal (2). In 1963, Holmes pointed out that in austenitic stainless steel weld metal, the erroneous detection of flaws and the inability to detect known defects were due to the unpredictable propagation of ultrasonic waves (3,4). The high ultrasonic attenuation in the weld metal and the increase in this attenuation with grain size were also noted at that time. Pilseneer and Louis noted variations in sound velocities and problems in locating and sizing defects in stainless steel weld metal because of apparent beam deviations (5).

Yoneyama et al. have studied the causes of false indications sometimes observed in austenitic stainless steel welds and have demonstrated that shear-wave signals can be reflections caused when the acoustic beam deviates from the anticipated path (6). Baikie et al. showed the orientation dependence of longitudinal wave velocity and demonstrated that the apparent attenuation of longitudinal waves at 2 MHz in stainless steel weld metal varied with propagation direction relative to the columnar grain axis (7). The minimum attenuation occurred for waves propagating at about 45° to the columnar grain axis (the direction of maximum wave velocity). More recently, Tomlinson et al. interpreted Baikie's data on the basis of beam deviation, concluding that the variation in apparent attenuation may be primarily due to the variation in beam width (and deviation) with propagation direction, with the smallest beam width observed for directions of maximum velocity (8). References 9-17 describe other work related to inspection of austenitic stainless steel welds.

In this paper we present calculations and experimental data for predicting and measuring beam deviation for longitudinal and shear waves using a cylinder cut from a sample of 308 SS weld metal.

THEORY

The anisotropy of stainless steel weld metal suggests that, in a model which describes the region of the weld where the columnar grains are vertical, one may assume that the grains are long, cylindrical single crystals randomly oriented about the vertical axis in the <100> direction. In other words, the sample has orthotropic symmetry (1). The following discusses the phenomenon of beam steering, which can have a great effect on apparent attenuation of both longitudinal and shear waves. The discussion begins with the simple example of a single crystal of stainless steel and concludes with the model previously described.

Calculations of velocity surfaces and deviations in the 100 and 110 plane for single-crystal Type 304 stainless steel were performed by Musgrave's method, using elastic constants from single-crystal specimens discussed in Ref. 17 (2,18,19). The beam deviation results are plotted in Figs. 1 and 2.

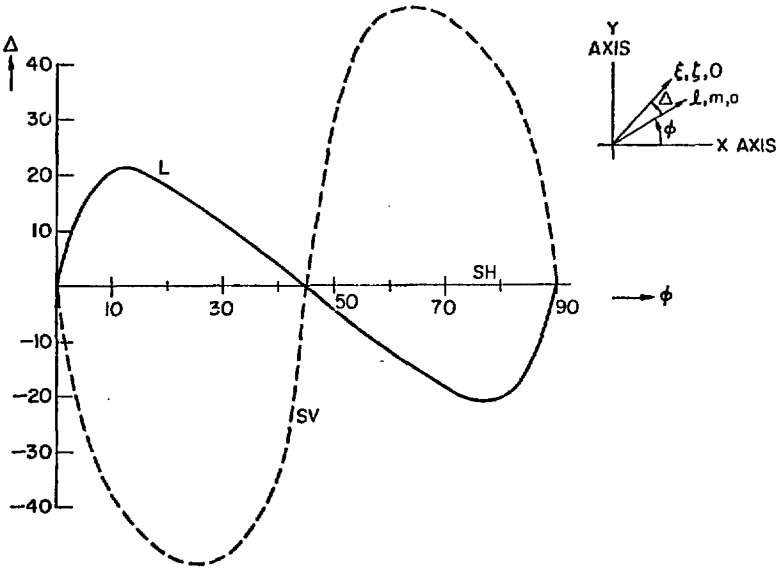

Fig. 1. Deviation in the 001 Plane for Single-crystal Stainless Steel. L = longitudinal waves; SV = vertically polarized shear waves; SH = horizontally polarized shear waves (no deviation).

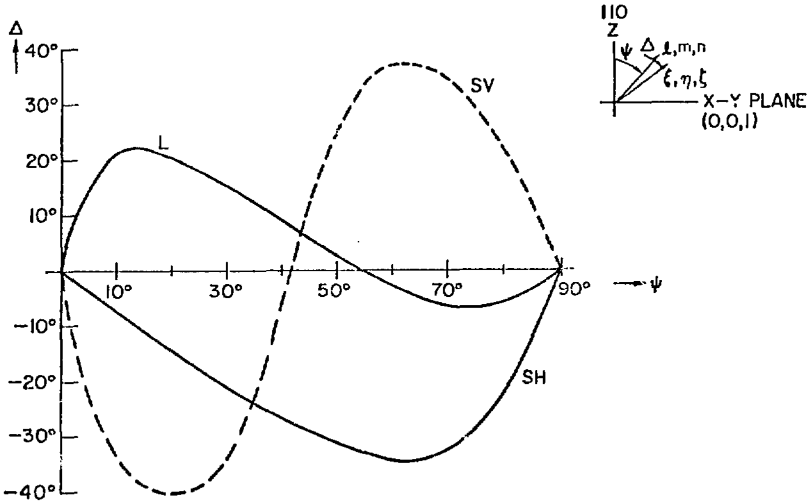

Fig. 2. Deviation in the 110 Plane for Single-crystal Stainless Steel.

The deviation is labeled positive if it is in the same direction as the increment of the angular-velocity direction cosine, and negative if it is in the opposite direction. The results are similar to curves obtained by Musgrave for nickel (2). The data for velocity surfaces show that the quasi-longitudinal velocity can vary from 6.4×10^3 to 5.1×10^3 m/s and the shear-wave velocity from 4.0×10^3 to 2.1×10^3. The angle between velocity vector and energy ray (beam deviation) can amount to 22° for longitudinal waves, 50° for vertically polarized (SV) waves, and 35° for horizontally polarized (SH) shear waves in single crystals of stainless steel.

Columnar grain structures exhibit symmetry around one axis (the z-axis), and there will be five independent elastic constants rather than three for the single-crystal case (20):

$$\overline{C}_{11D} = \overline{C}_{22D} = \overline{C}_{11} + \frac{3\gamma C}{20} \qquad \overline{C}_{33D} = \overline{C}_{11} + \frac{2\gamma C}{5}$$

$$\overline{C}_{44D} = \overline{C}_{55D} = \overline{C}_{44} - \frac{\gamma C}{5} \qquad \overline{C}_{66D} = \overline{C}_{44} + \frac{\gamma C}{20}$$

$$\overline{C}_{13D} = \overline{C}_{23D} = \overline{C}_{12} - \frac{\gamma C}{5} \qquad \overline{C}_{12D} = \overline{C}_{12} + \frac{\gamma C}{20}$$

where $\overline{C}_{ij}$ is the elastic constant for polycrystalline materials (11). The texture anisotropy factor γ, defined in Ref. 20, can be derived from the following considerations:

(a) In the 001 plane (cross section of a grain), the ultrasonic velocity should be independent of direction of incidence.

(b) The velocities parallel to the z-axis (the axis of symmetry) should be the same as given by $\overline{C}_{11}$ and $\overline{C}_{44}$ in a single crystal.

These restrictions establish the value $\gamma = 1$ as described in Ref. 20. Using the relations $\overline{C}_{ijD}$ and the same single-crystal elastic constants used previously, velocity surfaces and deviation were calculated for columnar grain structures of Type 304 stainless steel. The results for beam deviation are plotted for the 110 plane in Fig. 3.

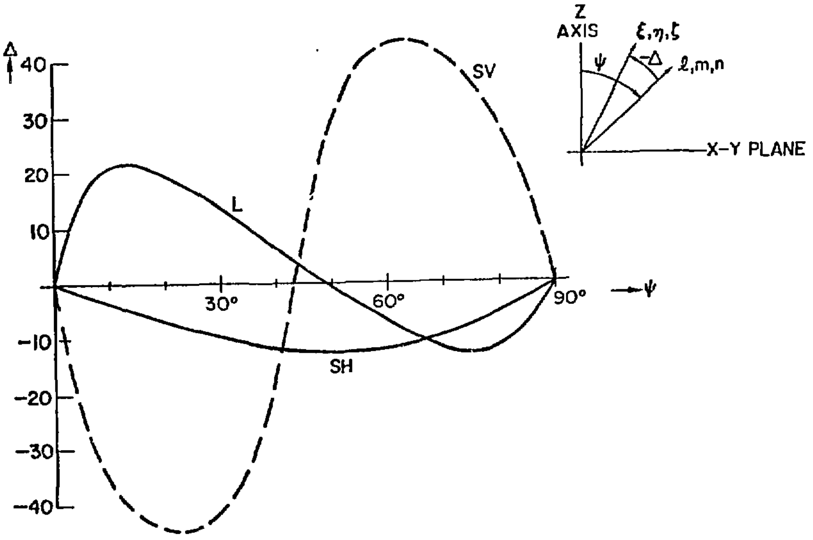

Fig. 3. Deviation in the 110 Plane for Columnar Grain Structure of Stainless Steel.

In the 001 plane the plots of velocity and wave surfaces would be concentric circles and the deviation would be zero. The data from velocity curves indicate that in the 110 plane the quasilongitudinal velocity can vary between 6.2×10^3 and 5.1×10^3 m/s, while the shear-wave velocities can assume values between 4.0×10^3 and 2.4×10^3 m/s (SV) and 4.0×10^3 and 3.2×10^3 m/s (SH). The deviation of longitudinal waves can be as large as 21°, slightly larger than but within the experimental uncertainty of the theoretical maximum of ∿ 18° and the experimental maximum of ∿ 15° (from Ref. 8), while that of shear waves can reach values of 44° (SV) or 13° (SH). Calculated values of velocity in discrete directions were within 10% of values obtained by measurements on a sample of weld metal. This comparison is made in Ref. 17.

The above theoretical considerations can lead to a better understanding of consequences that will be encountered in the practical application of ultrasonic testing of structures with preferred orientations, such as stainless steel welds. The deviation of the beam orientation from the direction of impinging velocity can lead to the wrong flaw location if Snell's law is used. Bending along the axis of symmetry can result in a focussing or defocussing of the beam, making defect sizing very difficult. Comparisons of these theoretical results with experimental data are presented in the next section.

EXPERIMENTAL PROCEDURE

Experimental results were obtained for a multipass shielded-metal arc weld. The original welded plate (300 x 150 x 50 mm) from which specimens were cut was Type 304 stainless steel with Type 308 stainless steel weld metal. The weld was "V"-type with a 77° included angle. This specimen was cut in half along the long dimension. From one half, a 20-mm-dia x 25-mm-long cylinder was removed for ultrasonic examination, as shown in Fig. 4a. Metallographic and x-ray diffraction techniques were used to verify the columnar grain structure shown schematically in Fig. 4b.

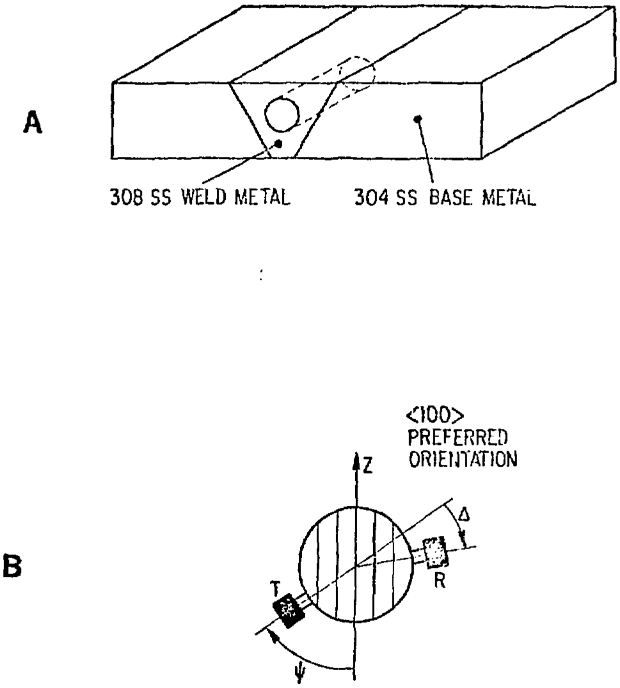

Fig. 4. Schematic Representation of System for Measuring Shear-wave Beam Deviation. (a) The cylinder used (25 mm long x 20 mm dia) was cut from a 308 SS weld. (b) The transmitted pulse (T) is propagated at an angle ψ with respect to the grain axis. The maximum received signal indicates the deviation angle Δ.

Transducers (13 mm dia) were epoxied to the flat side of plexiglass "shoes" (∿ 6 x 6 x 2 mm) curved to fit the cylinder surface. For measurements of longitudinal-wave beam deviations, conventional coupling (glycerol) was employed. For shear waves, since normal-incidence waves were employed, the shoes were epoxied to the cylinder. The shoes could be readily removed, cleaned, and re-epoxied at another location. Although this technique for shear waves is slow, the results obtained were reproducible. Attenuation data obtained from various combinations of ψ and Δ (defined in Fig. 4) will be presented in subsequent sections. When shear waves were generated, polarizations parallel and perpendicular to the plane of Fig. 4 were employed.

An Aerotech UTA-3 pulser-receiver was used for this work, along with Panametrics 2.25-MHz normal-incidence shear and longitudinal-wave transducers. Through-transmission radio-frequency (rf) signals were observed for various ψ-Δ combinations and data were recorded in the form of peak-to-peak rf signal amplitudes versus transducer position.

EXPERIMENTAL RESULTS

The experimental results for longitudinal-wave deviations are presented in Fig. 5 along with the theoretical predictions. The results were readily obtained by fixing the transmitting probe and moving the receiving transducer around the cylinder until the maximum received signal was located. As the columnar grains are ≤ 1 mm in diameter, we can assume the beam crossed a minimum of 25 grains in traversing the specimen. At least three data points were obtained for each transmitter location indicated. The results were generally reproducible; only one discrepancy was found, at $\psi \sim 67°$. As predicted, deviations as large as 22° were observed for wave propagation at $\sim 22°$ and $\sim 67°$ to the grain axis, while only a small deviation was observed for wave propagation at $\sim 45°$ to the grain axis.

The data for shear waves were more difficult to acquire. In addition to the requirement that a solid couplant (epoxy) be used, the deviations were generally smaller than for longitudinal waves and often both SH and SV shear waves were evident in the oscilloscope trace. These modes had to be separated by time-of-flight measurements since, as shown by the wave-velocity curves of Fig. 6, either the SH or SV waves could have the higher velocity depending on the wave propagation direction relative to the columnar grain axis. Ultrasonic through-transmission signal amplitude data showing results for SV waves are indicated in Fig. 7, and the beam-deviation curves for these waves are shown in Fig. 8. The corresponding results for SH waves are shown in Figs. 9 and 10. A comparison of these figures shows that the angle of deviation is better defined, and the results are in closer agreement with the theoretical results, for SV than for SH waves. Deviations from predicted results are probably due to variations from the symmetry assumed in the calculations.

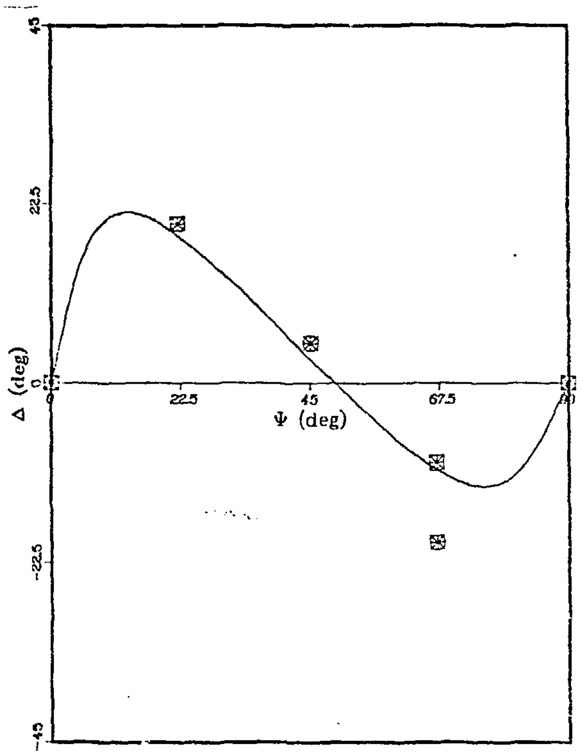

Fig. 5. Beam Deviation (Δ) vs Propagation Angle Relative to Columnar Grain Axis (ψ) for Longitudinal Waves. Experimental data points and calculated curve are shown.

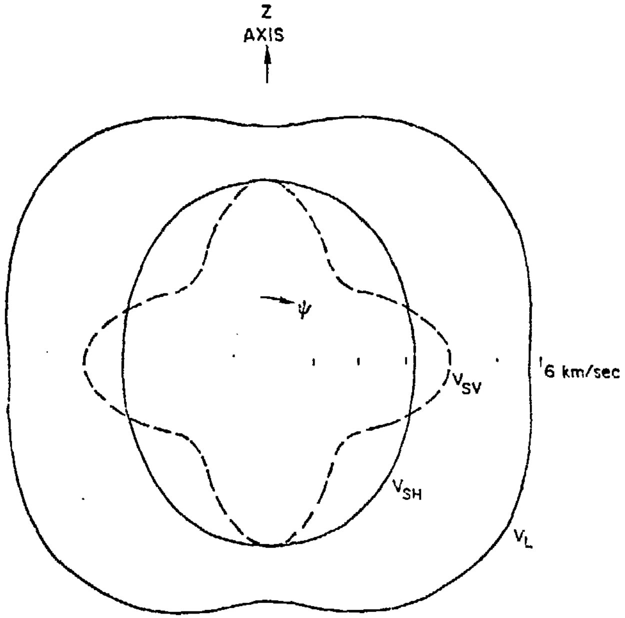

Fig. 6. Velocity-surface Intersection with the 110 Plane for Columnar Grain Structure of Stainless Steel.

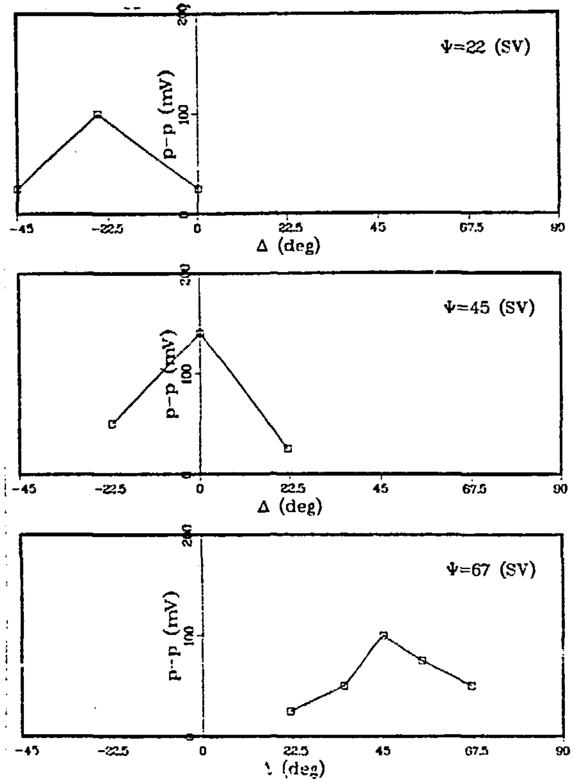

Fig. 7. Ultrasonic Signal Amplitude Data vs Deviation for SV Shear Waves at Various Incident Angles ψ.

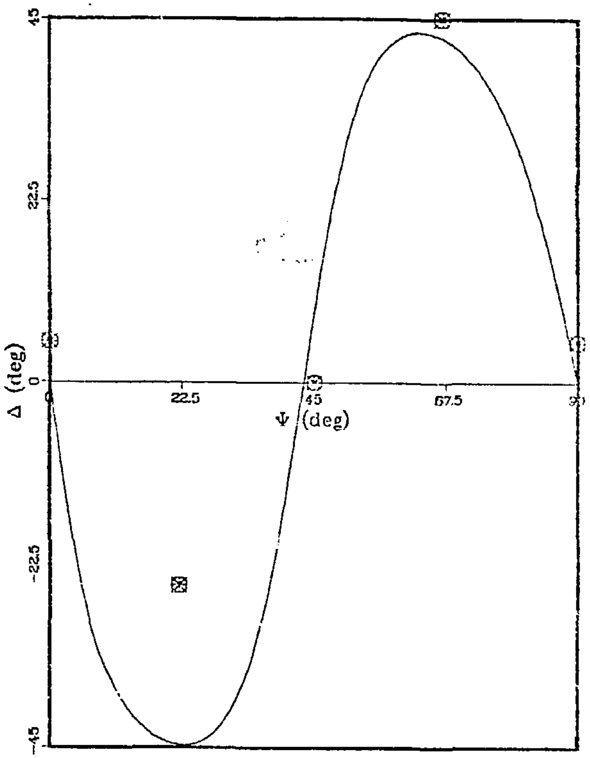

Fig. 8. Beam Deviation (Δ) vs Propagation Angle Relative to Columnar Grain Axis (ψ) for SV Waves. Experimental points as well as calculated curve are shown.

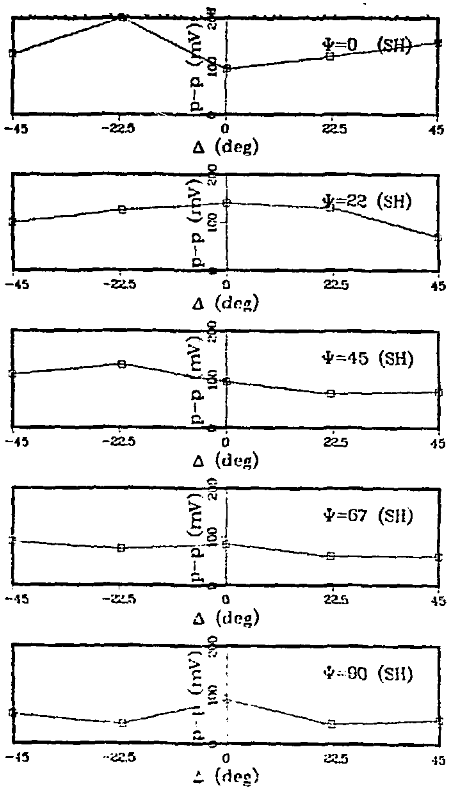

Fig. 9. Ultrasonic Signal Amplitude Data vs Deviation for SH Shear Waves at Various Incident Angles ψ.

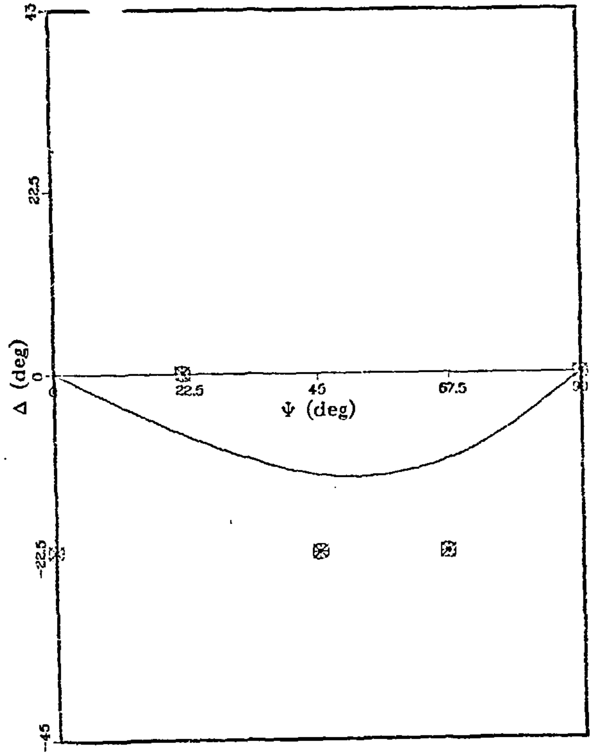

Fig. 10. Beam Deviation (Δ) vs Propagation Angle Relative to Columnar Grain Axis (ψ) for SH Waves. Experimental points as well as calculated curves are shown.

CONCLUSIONS

These results suggest that the phenomenon of beam deviation must be carefully considered in planning an ultrasonic examination of stainless steel weld metal and in the interpretation of the data. The results also suggest that ultrasonic beams will focus or defocus depending on mode (longitudinal or shear) and, in the case of shear waves, on polarization (vertical or horizontal). Divergence occurs when the slope of ψ vs Δ is positive, convergence when the slope is negative. The implication for conventional ultrasonic testing is demonstrated in Fig. 11. For wave propagation at ∿45° to the columnar grain axis, longitudinal or SH waves are most effective; for propagation parallel or perpendicular to the columnar grain axis, SH or SV waves are best.

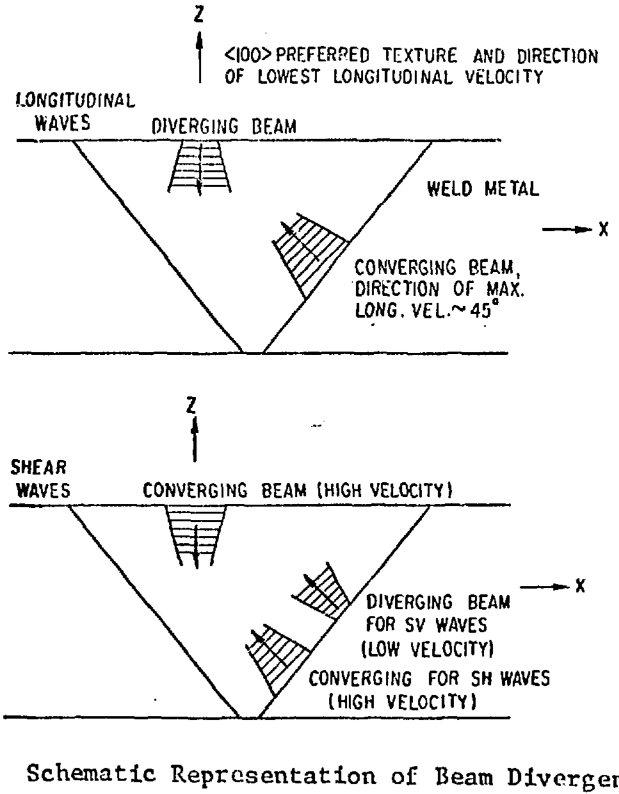

Fig. 11. Schematic Representation of Beam Divergence and Convergence for Longitudinal and Shear Waves with Propagation Directions Indicated by Arrows.

SUMMARY

Beam deviations for longitudinal and shear waves propagating in stainless steel weld metal have been measured experimentally and compared with calculations that assume an orthotropic symmetry. Beam deviations as large as ∿ 22° for longitudinal, ∿ 45° for vertically polarized shear, and ∿ 22° for horizontally polarized shear waves have been observed. Most experimental data are in good agreement with calculated results.

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