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IMPLICATIONS OF ULTRASONIC ATTENUATION TO NONDESTRUCTIVE TESTING

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METALLURGY DIVISION

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IMPLICATIONS OF ULTRASONIC ATTENUATION TO NONDESTRUCTIVE TESTING

J. K. White, R. W. McClung, and J. W. Allen

ABSTRACT

In order to relate ultrasonic inspection data to actual conditions inside a metal part, it is essential that the inspector have some knowledge of attenuation as it affects ultrasound. This paper briefly reviews the the theory of attenuation of ultrasonic energy. It discusses the first part of a study being conducted for the purpose of understanding and evaluating the large losses encountered in cast and welded steels. The equipment required and techniques employed for measuring attenuation are described. The results of these attenuation measurements are described with special reference to weld inspection.

INTRODUCTION

Ultrasonic testing has become a powerful tool for the detection of internal flaws in metals, but there are certain materials which are not well suited to this type of inspection. Among these are uranium, brass, certain ferrous castings, and austenitic stainless steel welds, in all of which ultrasonic energy suffers high attenuation. High attenuation usually precludes the possibility of the very sensitive inspection considered necessary for reactor components. In order to extend the usefulness of ultrasonic testing to these borderline materials, studies of ultrasonic attenuation in such materials have been initiated and the first phase of the studies is reported here. This first phase consists of the determination of adequate techniques, a general exploration of the attenuation characteristics of the austenitic stainless steels and their welds, and an empirical determination of the form of the frequency-attenuation relationship.

BASIC CONSIDERATIONS

Ultrasonic attenuation is the sum of absorption, scattering, and other losses. The absorption of ultrasound may be explained on the basis of thermoelastic effects, dislocation damping, ferromagnetic effects, relaxation, and the effects of neutrons and electrons upon the sound beam. Scattering effects are usually much greater than these absorption effects in polycrystalline metals. Each time an ultrasonic beam impinges upon a metal interface, there may be specular reflections, mode conversion, and diffuse scattering effects. If the proper conditions are met, Rayleigh scattering occurs and in elastically anisotropic materials a refractive scattering can take place.

Probably the most important factor in ultrasonic attenuation in polycrystalline metals is Rayleigh scattering. The Rayleigh law states that a sound or light beam, traversing a medium which contains scattering centers whose diameter is much smaller than the wave length of the radiation and whose concentration is small enough to obviate interaction, will be attenuated as the fourth power of the frequency of radiation and as the third power of particle diameter. Mason,[1] Huntington,[2] Roth,[3] Elion,[4] and others have extended the Rayleigh law to include scattering in metals, and in this extension, metallic grains are interpreted as being the scattering centers. The Rayleigh law has been applied to any case in which average grain diameter is less than one-third of the wave length. This condition is met in almost all ultrasonic testing of polycrystalline metals.

Another type of scattering occurs in metals whose elastic constants are not the same in all crystallographic directions. The elastic anisotropy factor $\frac{\Delta K}{K}$ is used to describe a metal, and it has been shown[5] that ultrasonic attenuation due to this type of scatter varies as $(\frac{\Delta K}{K})^2$. Probably this accounts for the high ultrasonic attenuation in uranium.

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[1] W. P. Mason and H. J. McSkimmin, "Energy Losses of Sound Waves in Metals Due to Scattering and Diffusion," J. Appl. Phys., 19, 940-946 (1948).

[2] H. B. Huntington, "On Ultrasonic Scattering by Polycrystals," J. Acoust. Soc. Amer., 22, 362-364 (1950).

[3] W. Roth, "Scattering of Ultrasonic Radiation in Polycrystalline Metals," J. Appl. Phys., 19, 901-10 (1948).

[4] Herbert A. Elion, "Metallurgical Structure Analysis by Ultrasonics," Proceedings of the National Electronics Conference, Vol. XIII (October 1957).

[5] R. K. Roney, PhD Thesis, Cal. Tech. (1950).

Additional losses may occur in a thick layer of couplant or in a film of some foreign matter which may act as an acoustic transformer on the surface of the test piece. Energy may also be lost due to divergence of the ultrasonic beam. These miscellaneous losses are considered to be uninformative and must be kept to a minimum.

MEASURING TECHNIQUES

In general, the technique used for measuring ultrasonic attenuation is that of Truell[6] and involves conversion of an RF pulse into ultrasonic energy by a quartz crystal which is cemented to a sample of the material under test. The ultrasonic pulse echoes from wall to wall of the sample and decays in a logarithmic fashion. As each echo strikes the quartz crystal it is reconverted to an RF signal and is presented on an oscilloscope where an electrically generated and calibrated logarithmic decay curve is matched to the echo decay pattern. A commercial instrument, the Sperry Attenuation Comparator, is being used for this study along with a wide-band amplifier which extends the lower frequency limit of the comparator from 5 Mc/sec to 1 Mc/sec. Data collected at the lower frequencies are not considered to be entirely satisfactory, since beam divergence, which increases at low frequencies, may be great enough to cause a tendency toward high readings below 15 Mc/sec. Similarly, attenuation values greater than 2.5 dB/μsec are subject to more uncertainty than mid-range values because at the higher readings only a few echoes are available for comparison; thus, any interference or diffraction effect in any single echo is more likely to cause an error.

X-cut quartz crystals, cemented with phenyl salicylate (Salol), are used exclusively for this study. A brief trial of an immersed technique was made, but the technique proved to be unacceptable. This was due to the high precision with which the crystal must be held parallel to the surface of the sample. Very small departures from parallelism cause precession of the echoes away from the transducer, and hence result in high attenuation values. The same effect may be caused by any appreciable taper in the sample. Specimens for this work are surface ground parallel within 0.001 in./in. and certain special samples are ground parallel within

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[6] R. L. Roderick and R. Truell, "The Measurement of Ultrasonic Attenuation in Solids by the Pulse Technique and Some Results in Steel," J. Appl. Phys., 23, 267 – 279 (1952).

0.00001 in./in. For thick samples and for high attenuation, the former value suffices. In thin specimens of low attenuation, accurate attenuation measurements are said to require a lapping operation to obtain sufficient parallelism.

Accurate attenuation measurements require a careful bonding of the crystal to the specimen. The crystal must be wrung to the ground surface of the specimen which is moistened with molten Salol. Salol is subject to supercooling and may require seeding to initiate solidification. When the Salol solidifies, the bond is tested at the highest frequency to be used. Any lack of resolution may indicate a poor bond.

Resolution may also be unsatisfactory if the specimen is not as thick as twice the pulse length, and no resolution can be expected if the specimen is less than one pulse length in thickness. The Sperry instrument provides a choice of one-half, one, or two microsecond pulse lengths. Theoretically, the shortest should provide best resolution with thin specimens, but this is not borne out by experimental evidence due, possibly, to the broadened frequency spectrum which is characteristic of very short pulse lengths.

The transmitted pulse of the instrument has proved difficult to tune precisely to crystal resonance. There is often a wide area of uncertainty in tuning within which a subjective decision must be made. Brown University research personnel, who developed the instrument, concluded that the minimum attenuation reading indicates correct tuning, but this does not always occur at crystal resonance. Another factor of uncertainty is the resonant frequency of the crystal itself. The crystal is operated at resonance or at odd harmonics of resonance and a small deviation from the frequency assumed to be resonant can cause a rather large error at high harmonics. Since most errors tend to increase the apparent attenuation, lower values are considered more accurate.

EXPERIMENTAL RESULTS

An example of the comparatively high ultrasonic attenuation exhibited by austenitic stainless steel welds is illustrated in Fig. 1 (ORNL-LR-DWG 32881). As shown here, the attenuation in a stainless steel weld, as expressed in dB/μsec, is usually about ten times greater than the attenuation in the parent wrought metal. A similar relationship is shown in Fig. 2 (ORNL-LR-DWG 32882), and here another fact becomes apparent. Wrought base

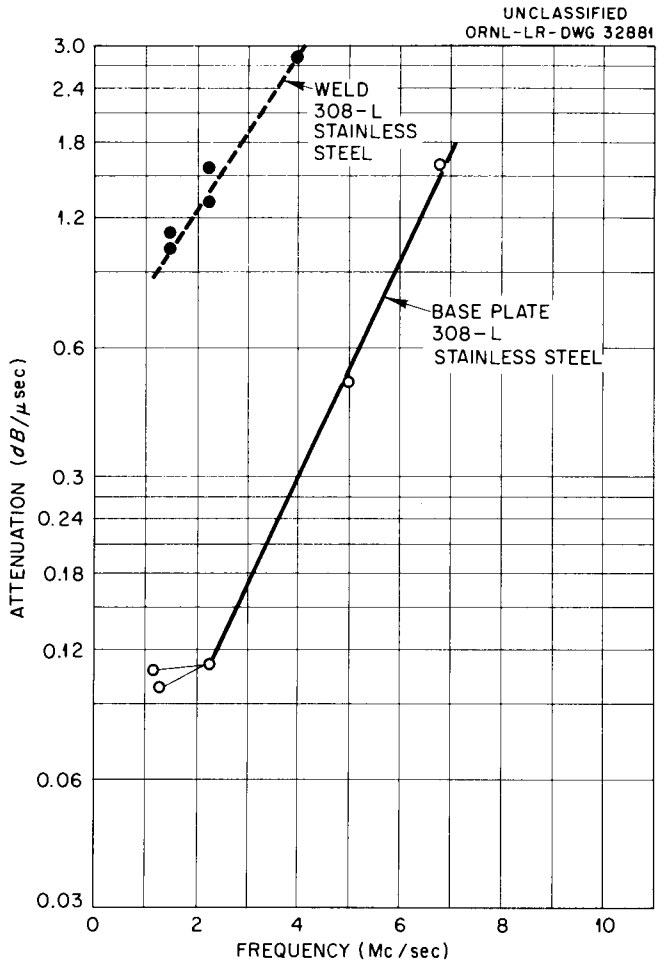

Fig. 1. Ultrasonic Attenuation vs. Frequency in Austenitic Stainless Steel Weld and Plate.

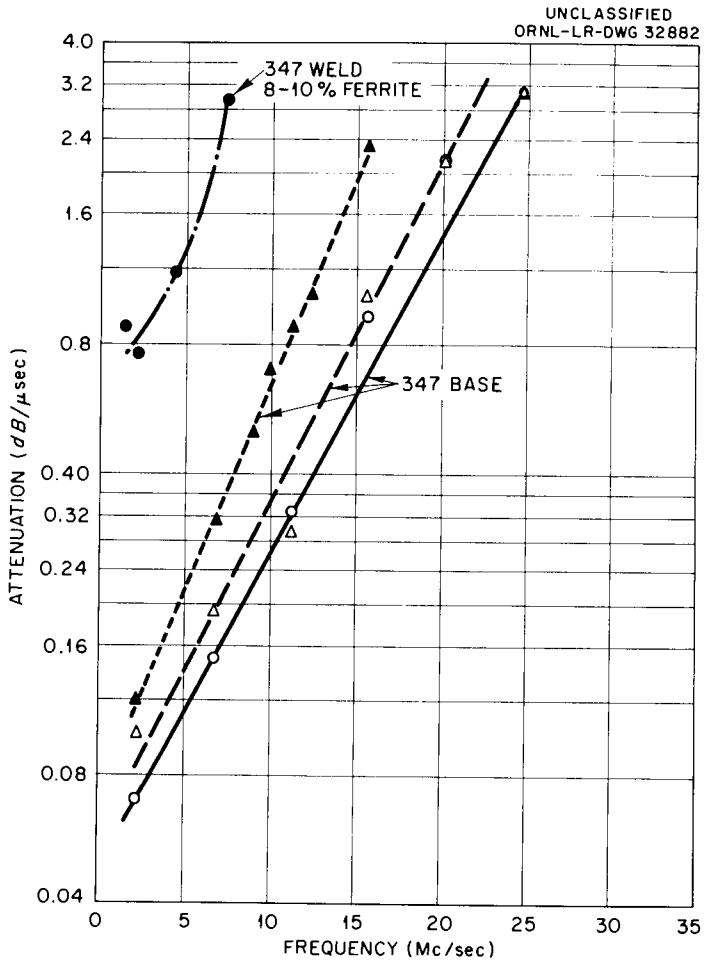

Fig. 2. Ultrasonic Attenuation vs Frequency in Austenitic Stainless Steel Plates and in a Weld of Similar Composition.

plate of the same nominal chemistry varies considerably from plate to plate in its ability to transmit ultrasound. Considerably better transmission has been obtained along the grains, as opposed to transmission across the grain in large steel blooms,[7] and in the present work it has been evident that transmission is somewhat better in the direction of rolling of a plate of type 347 stainless steel than in the perpendicular directions. In the type 347 stainless steel plate specimens whose characteristics are plotted in Fig. 2, the hardness and grain size are not significantly different and cannot be correlated with attenuation.

Figure 3 (ORNL-LR-DWG 32883) shows a large improvement in ultrasonic transmission effected by a grain-refining heat treatment. The samples of mild steel illustrated here had a grain size of ASTM 4, as received. After heat treatment, the grain size was slightly larger than ASTM 7. The evident improvement in sound transmission shows the importance of grain size when working with wave lengths much larger than average grain diameter. With the exception of frequency, grain size appears to have the most important effect upon attenuation in polycrystalline metals at frequencies in the low megacycle region.

Figure 4 (ORNL-LR-DWG 32884) shows the effect of a similar heat treatment upon a sample in which the grain size was not appreciably reduced. The mild steel in this case was received with an ASTM grain size of 5. After heat treatment, the grain size was from 5 to 6. The change in attenuation characteristics is barely perceptible.

A sample of type 420 stainless steel bar stock was found to have very low ultrasonic attenuation, and because this allowed measurements over a broad range of frequencies, type 420 stainless steel was used for an experiment to show the effect of several heat treatments upon attenuation.

Figure 5 (ORNL-LR-DWG 32885) shows a series of type 420 stainless steel samples of various heat treatments. One sample was oil quenched from 1900°F and drawn at 400°F, producing a diamond point hardness of 543 (10 kg load). A second sample was oil quenched from 1700°F and drawn at 650°F, producing a DPH of 456 (10 kg). A third sample was annealed by furnace cooling from 1600°F to a DPH of 200 (1 kg). A fourth sample was vacuum cast, resulting in an average hardness of 497 DPH (10 kg). A fifth sample was taken of the bar stock, as received. The hardness of this sample is

[7] J. V. Russell, "Application of Ultrasonic Testing to Steel Plant Metallurgical Control," Nondestructive Testing, 8, 7–11 (Fall, 1949).

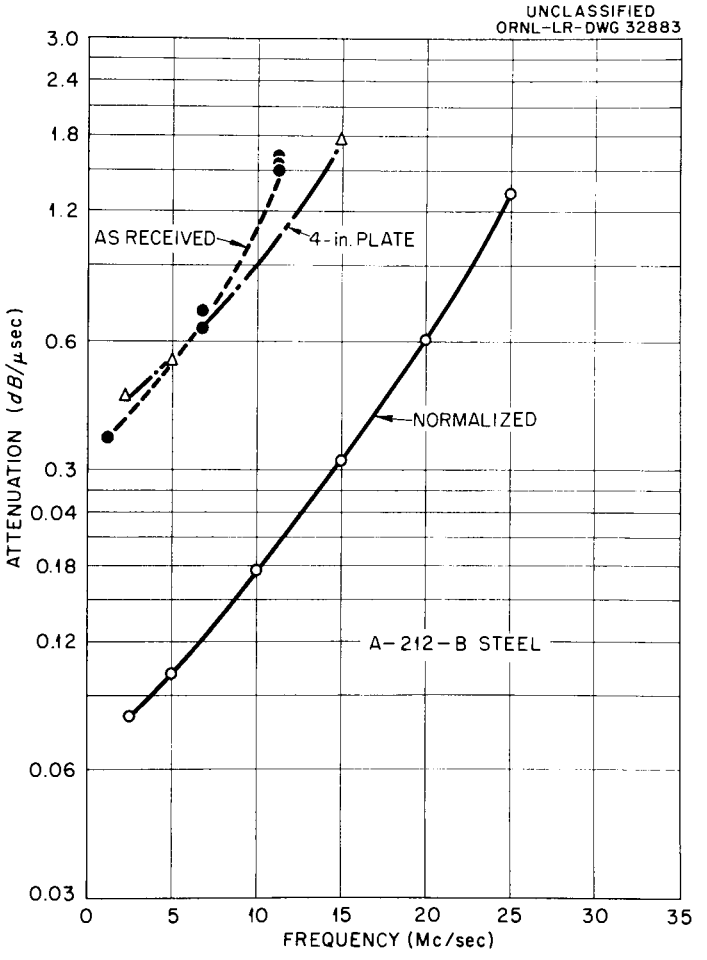

Fig. 3. Ultrasonic Attenuation vs Frequency in a Carbon Steel Before and After Normalization.

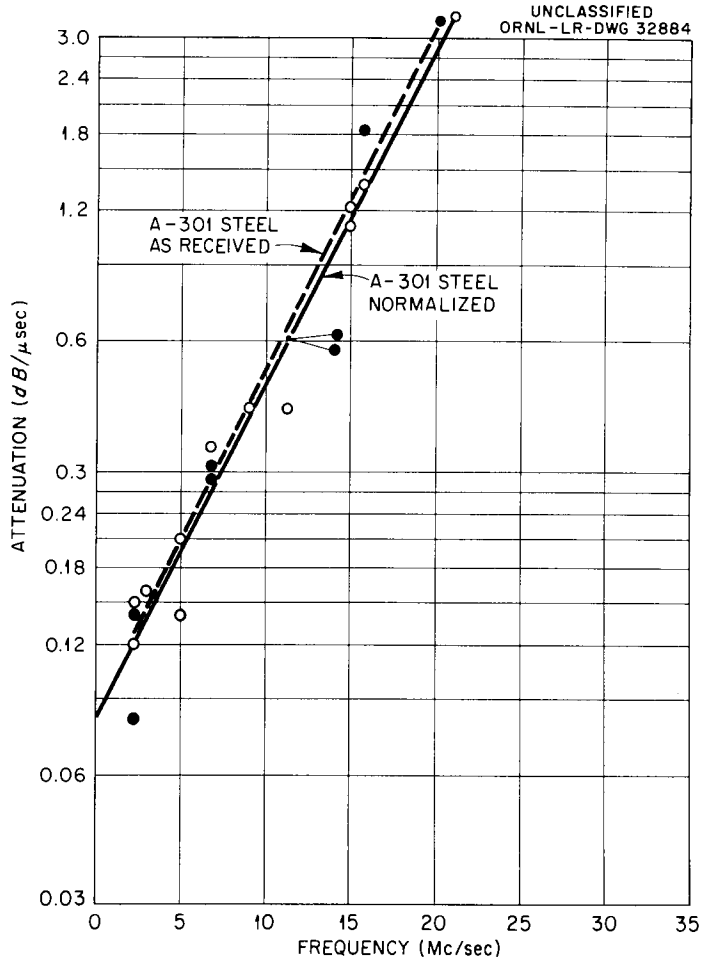

Fig. 4. Ultrasonic Attenuation vs Frequency in a Carbon Steel Before and After Normalization.

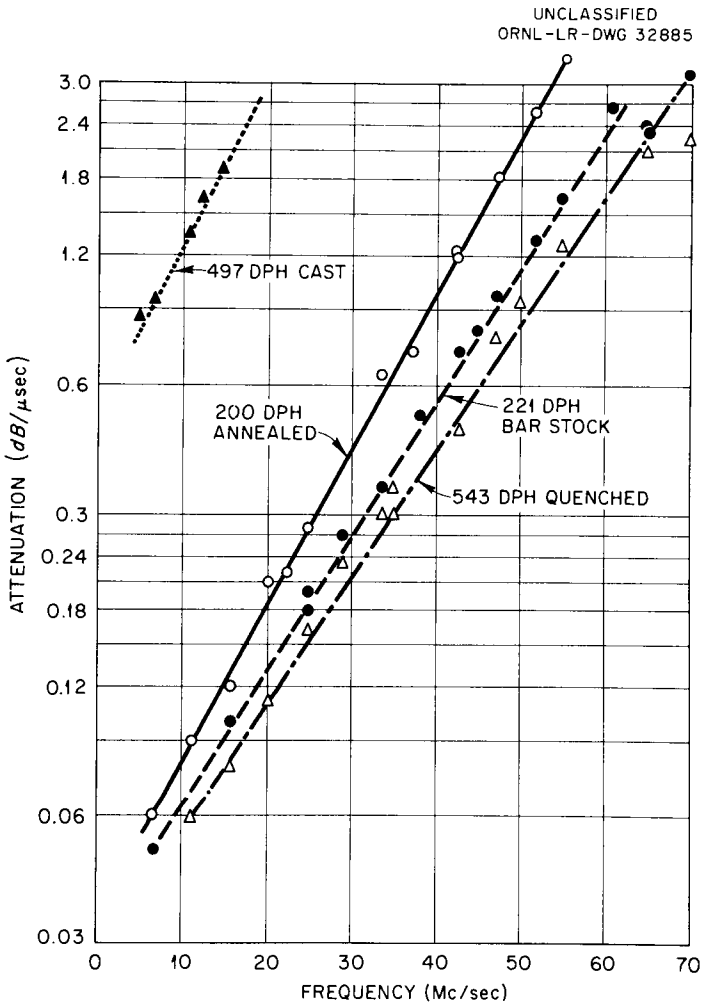

Fig. 5. Ultrasonic Attenuation vs Frequency in Type 420 Stainless Steel of Various Heat Treatments.

221 DPH (1 kg). All of the samples show a fine-grained structure of approximately ASTM 7–8; grain-size differences are within the error in determining them. The one exception to this fine-grained structure is the casting, which has a grain size of greater than ASTM 1. The second sample shows a great deal of spread in its attenuation and its values cannot be accurately plotted against frequency. The other three fine-grained samples show an inverse relationship of hardness to ultrasonic attenuation. A relation of hardness to attenuation has been shown before[8] but apparently this is a secondary effect which has not been adequately explained. It is worthy of note that no large differences of slope of the attenuation-frequency curve are evidenced, although the annealed sample shows a slightly greater slope. Once again, the casting illustrates the overriding effect of the large-grained structure which caused extremely high attenuation.

Most of the steel welds examined in this study are included in Fig. 6 (ORNL-LR-DWG 32886). It can be seen that all of the austenitic stainless steel welds tested exhibit high attenuation. All are much poorer transmitters of ultrasound than the carbon-steel weld sample. Apparently, small changes in composition of the weld metal are not effective in adequately improving the transmission of ultrasound through austenitic stainless steel welds.

The relation of attenuation to frequency was determined empirically in metals which transmit ultrasound over a broad range of frequencies. Zircaloy-2 samples follow the fourth power Rayleigh law quite closely, whereas additional factors influence the steels. Figure 7 (ORNL-LR-DWG 32887), which is a log-log plot, illustrates the fact that type HY-80 steel (a high-strength steel) and type 420 stainless steel show a more rapid increase in losses with increasing frequency than the fourth power curve shown for Zircaloy-2. In Fig. 8 (ORNL-LR-DWG 32888) the semi-log plot reveals a relationship which matches the data for steel more closely than a fourth power curve. This relationship is of the form

$$\alpha = A\epsilon^{\gamma F}$$

in which α is attenuation, F is frequency, and A and γ are constants.

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[8] R. L. Roderick and R. Truell, "The Measurement of Ultrasonic Attenuation in Solids by the Pulse Technique and Some Results of Steel," J. Appl. Phys., 23, 267 – 279 (1952).

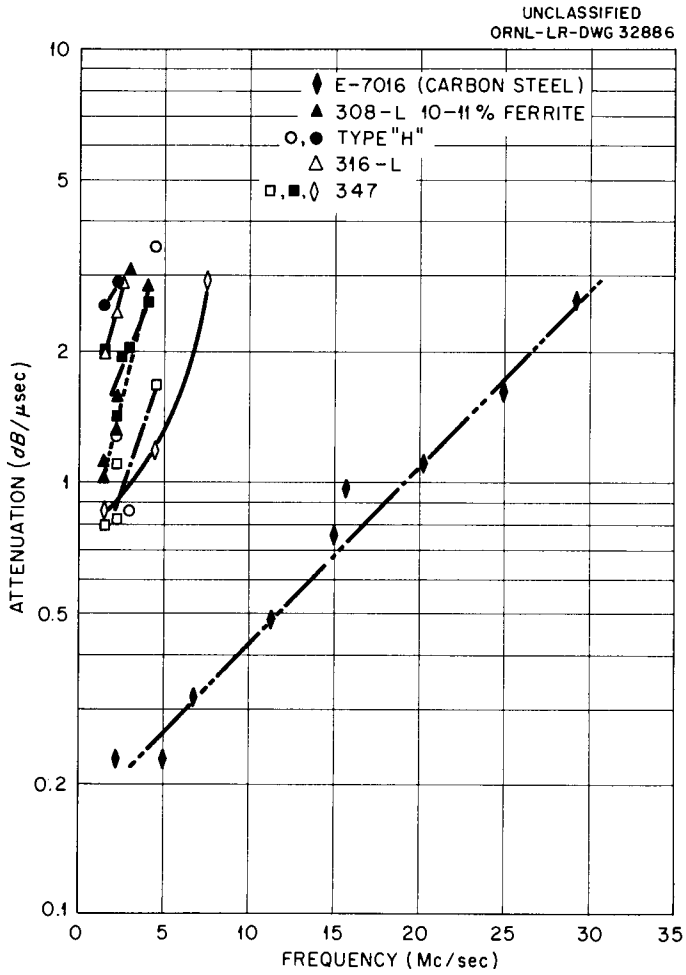

Fig. 6. Ultrasonic Attenuation vs Frequency in Several Welds.

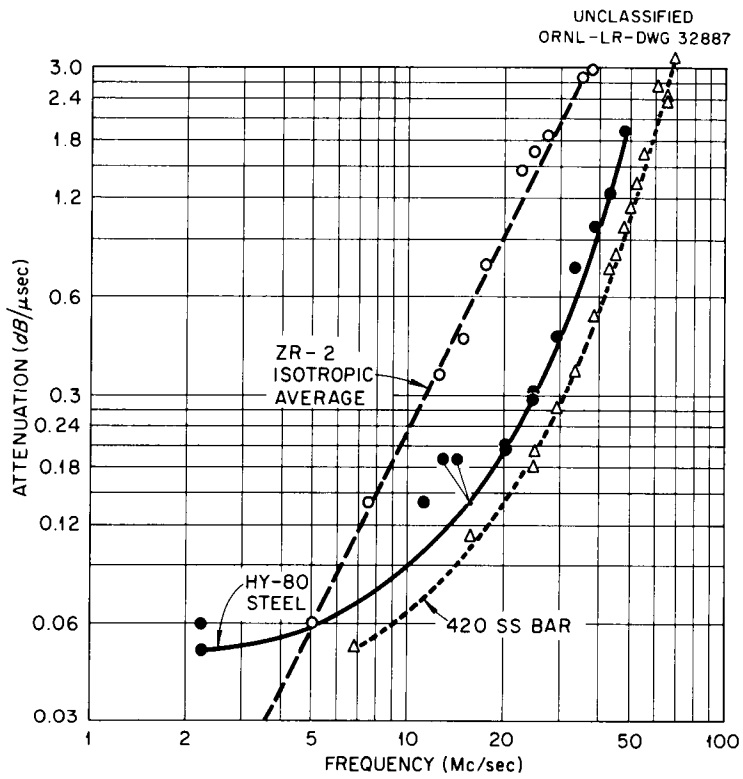

Fig. 7. Ultrasonic Attenuation vs Frequency in a Carbon Steel, a Stainless Steel and Zircaloy II.

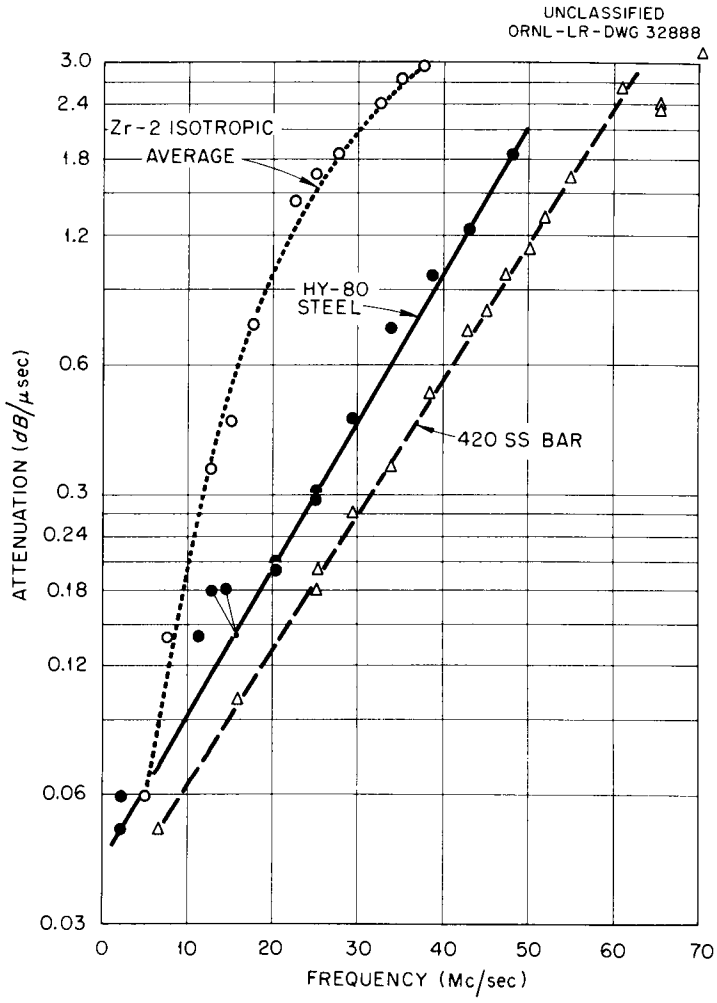

Fig. 8. Ultrasonic Attenuation vs Frequency in Stainless Steel, Carbon Steel, and Zircaloy-2.

For HY-80 steel,

$$\alpha = 0.04\epsilon^{0.08F};$$

for E-7016 carbon steel weld metal,

$$\alpha = 0.16\epsilon^{0.095F}; \text{ and}$$

for 347 austenitic stainless steel,

$$\alpha = 0.04\epsilon^{0.19F}.$$

These relationships are empirical and undoubtedly include experimental error in their constants. The shape and, in general, the slope are remarkably similar and may be common to all steels.

CONCLUSION

The value of ultrasonic attenuation data to the profession of nondestructive testing may be measured by its direct applicability to testing problems. The variation of losses from one metal to another has been shown repeatedly; therefore, the use of test blocks made of one metal to estimate the size of defects in another metal is fallacious unless adequate compensation is effected. It has been demonstrated that in metals whose structure is highly directional due to operations of fabrication or to directional grain formation, cross-grain attenuation of ultrasound may be greater than attenuation along the grains. This implies that, although ultrasonic penetration of a metal may be satisfactory in one direction, it may be inadequate in another direction. The problem of defect evaluation is complicated by directional properties and any preferential attenuation must be taken into account in estimating flaw size.

There is clear evidence that a grain-refining heat treatment improves the ultrasonic transmission characteristics of coarse-grained carbon steels. In cases in which the cost is warranted, it may be possible to perform such a heat treatment prior to ultrasonic inspection. Certainly, if there is a choice as to whether ultrasonic inspection should precede or follow grain refinement, the latter course would be preferred.

Through-transmission techniques require a thorough knowledge of attenuation because, in essence, the technique consists of a measurement of attenuation. Thus some auxiliary nondestructive method must be available to distinguish whether a loss of transmission is due to a harmless change in metallurgy of the part being inspected or whether a flaw is indicated.

Attenuation research has an immediate and direct effect upon nondestructive testing techniques, and more information of this sort must become available before the profession can achieve accurate flaw evaluation ultrasonically.

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