problems encountered in the extension of the ultrasonic testing to small objects.

The introduction of automatic recording is another step to increase the usefulness of ultrasonic testing. It makes the operation independent of the human variables always present with visual observation of the screen.

In this discussion the application of ultrasonics to product inspection has been stressed. However, it is believed that the greatest usefulness of the equipment described will be as a quality-control tool at the producer's plant tracing defects to the manufacturing step at which they first occur.

Acknowledgments

The authors take pleasure in acknowledging the contributions of Messrs. R. E. Warnow and M. E. Auger, Materials and Processes Laboratory, Large Steam Turbine-Generator Department, General Electric Company, in the construction and testing of the ultrasonic equipment. Special thanks are due to Mr. R. D. Brooks of the Atomic Power Equipment Engineering Section, General Electric Company, who was instrumental in putting the equipment into practice, and also to Messrs. A. L. Williamson and E. Van Zylstra who followed the application.

Addendum

After the manuscript was submitted, the important question was raised[6] whether a pipe or tube with eccentric walls can produce indications similar in appearance to those normally produced by discontinuities.

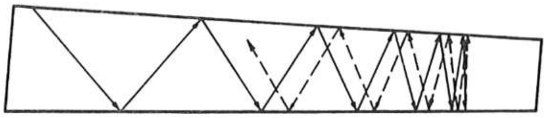

Fig. 11 Formation of a False Echo

The curious though logical answer is yes. Fig. 11 shows a constant slope wedge into which a wave has been introduced at 45 deg. The angle of incidence decreases by a constant value for each reflection; after a few reflections the wave reverses itself and starts traveling back toward the initial point. Thus an echolike indication is formed which is displayed on the face of the cathode-ray tube. However, this false echo is formed only when the wave travels in the direction of decreasing thickness.

In the case of a tube with eccentric walls, the situation is equivalent to two wedges with slopes of opposite signs. When the wave is traveling in the part with decreasing thickness, a false echo may be formed which can easily be mistaken for a defect indication.

However, as can be seen from Fig. 11, it takes several reflections before the direction of the wave is reversed and the false echo is returned. Hence no indication will be present in the initial portion of the sweep.

With the conventional search unit this cannot be observed because the initial pulse and wedge reverberations obscure that initial part of the sweep. However, with the delayed shear wave search unit, the zero point of the sweep (corresponding to the point of incidence of the shear-wave pulse) is perfectly clean and, as a result, that phenomenon can be observed.

While the eccentric tube rotates, the false echoes can be seen traveling across the screen, but contrary to true defect indications they die out before they reach the zero point of the sweep. In this way, a clear distinction between true and false indications is accomplished. Moreover, for automatic recording, gate No. 1 can be set next to the zero point of the sweep and, in that way, made immune to false echoes.

Discussion

J. J. B. Rutherford.[7] Inspection of steel by ultrasonic methods has found widespread prevalence in the past few years, but it has generally been restricted to the inspection of large masses of metal containing machined surfaces. The authors have devised an ingenious method of damping out overtones and thereby making the technique applicable to mill-produced parts.

Since this method of inspection has been developed for application to a specific case of close-tolerance tubing, it would be interesting to know the modifications necessary for variations of this product. For example, what modifications of transducer and wedge are necessary with change of tube diameter—change of wall thickness—change from Type 347 material?

L. N. Wall.[8] The authors are to be congratulated on their clear, concise presentation of this paper free of lengthy description of electronic circuits, which, after all, is not essential to a proper understanding of the operation of their equipment. Their equipment fills a need long felt in industry for a reliable, fast method of nondestructive testing of small-diameter pipe and tubing for internal defects and also provides a convenient permanent record of the test results.

In co-operation with the Knolls Atomic Power Laboratory, we have tested several thousand feet of tubing using the equipment described in this paper. The tubing tested was $1^1/_4$ and $1^1/_2$ in. OD × 0.065 and 0.095 in. minimum wall thickness of both plain carbon and AISI Type 347 steel. A semiautomatic device for holding the searching unit in contact with the tubing and for revolving and advancing the tubing at a predetermined rate past the searching unit was used in all our tests. The fluid couplant was also automatically fed under the searching unit.

As a standard defect, we used a milled longitudinal notch on the inside surface of a piece of tubing of the same material and size as the tubing to be tested. Although in theory, the angle the side walls of the notch make with the incident sound beam should affect the magnitude of the back reflection from the notch, we found no measurable difference in the strength of the back reflection from a vee and a square notch. For that reason we standardized on a straight side-wall notch.

Using as a basis for rejection any defect which gave an indication larger than that from a milled notch whose depth was equal to 3 per cent of the wall thickness of the tubing, we found as high as 30 per cent of some lots of tubing rejectable. The majority of these defects were found to be mandrel marks at the inside surface. The remainder were laps or seams also at the inside surface. In the early stages of this test program, all tubes which gave an indication of a defect 3 per cent of the wall thickness were sectioned at the apparently defective area. In every case, actual defects exceeding 3 per cent were found by visual examination in the sections. However, it was found that the defect indications were not necessarily proportional to the actual size of the defect. This is to be expected since the orientation and surface condition of the defect, as well as size, will affect the ultrasonic indications.

It is hoped that as further experience is obtained in industry with the ultrasonic testing it will be possible to correlate more closely the signal indication with the size and shape of the defect.

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[6] Mr. Frank Lambert, Oak Ridge National Laboratory, private Communication.

[7] Metallurgist, Tubular Products Division, The Babcock & Wilcox Company, Beaver Falls, Pa. Mem. ASME.

[8] Metallurgical Division, Combustion Engineering, Inc., Chattanooga, Tenn.

However, for the present where it is imperative that internal defects in tubular materials must be detected, this equipment provides the only method of detection for long lengths of magnetic and nonmagnetic tubular materials and should find a wide use.

AUTHORS' CLOSURE

We thank both discussers for their pertinent remarks. We feel encouraged by the progress which has been made and to which Babcock & Wilcox and Combustion Engineering, Inc., have contributed.

In regard to Mr. Rutherford's questions concerning variations of the search unit due to changes in material and size of tubing, the following comments are in order:

(*a*) *Material.* The area of contact, as shown in Fig. 12 of this closure, must be carefully chosen in order to avoid transmission of longitudinal waves and formation of strong surface waves.

The first condition is met by making the minimum angle of incidence α_1, larger than the first critical angle α_{c1}

$$\alpha_1 > \alpha_{c1} = \sin^{-1}\frac{V_{L1}}{V_{L2}}$$

in which V_{L1} and V_{L2} are the velocities of longitudinal waves in the search-unit wedge and in the tubing.

The second condition (no strong surface waves) is met by making the maximum angle of incidence α_2, smaller than the second critical angle α_{c2}

$$\alpha_2 < \alpha_{c2} = \sin^{-1}\frac{V_{L1}}{V_{S2}}$$

in which V_{S2} is the velocity of shear waves in the tubing.

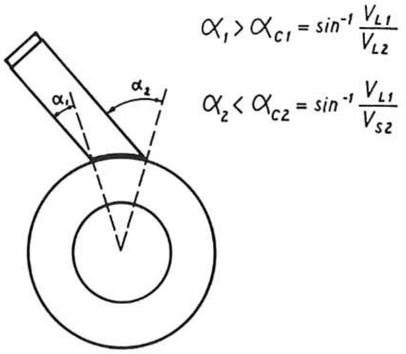

FIG. 12 DETERMINATION OF ANGLES OF INCIDENCE OF SEARCH UNIT

It is apparent from the foregoing formulas that materials with different sound velocities require different angles of incidence.

(*b*) *Outside Diameter.* A variation in outside diameter requires a corresponding variation in the curvature of the area of contact for proper transfer of energy; at the same time, in order to keep α_1 and α_2 constant, the length of the arc of contact must vary in direct proportion to the diameter.

(*c*) *Wall Thickness.* The considerations under (*a*) and (*b*) apply to the case in which the wall thickness is large in relation to the wave length. If this is not the case, Lamb waves will be formed and the optimum angle of incidence must be determined experimentally.

(*d*) *Actual Practice.* Tubing made of ferrous steel, stainless steel, aluminum, and monel, with diameters varying from $1^1/_2$ to $^1/_4$ in. and wall thicknesses from 0.150 to 0.025 in. has been tested successfully using the equipment described in this paper.