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ULTRASONIC TECHNOLOGY FOR MEASURING MOLTEN ALUMINUM QUALITY

T. L. Mansfield
Reynolds Metals Company

Richmond, Virginia

In order to increase our understanding and control of the quality aspects of aluminum in the molten state, we have developed a pulse-echo ultrasonic system to make four ultrasonic measurements, as follows:

1. Discontinuity evaluation
2. Relative changes in attenuation
3. Longitudinal wave velocity
4. Spectrum analysis of reflected pulses

These measurements are made possible through the use of a specially designed probe which is immersed in the molten metal; the metal can be either in a quiescent or a dynamic (flowing) condition. We have applied the system to examine several conditions of molten aluminum quality and have determined that it can detect improvements, as well as deleterious effects.

Introduction

Until the development of the Mansfield Molten Metal Monitor (Reynolds 4-M System^{TM}) there was no method available for continuously or directly determining the nonmetallic content of molten aluminum. This pulse-echo ultrasonic system permits continuous monitoring of the quality of molten metal during casting and the evaluation of molten metal processing and/or cleaning operations such as fluxing practices, holding time and filtering techniques.

The use of ultrasonics to study molten metals has been reported by several authors [Pitcher and Young(1-2)*, and Stremousov and Tekuchev(3)] This work demonstrated that ultrasonic techniques can be employed to determine the presence of nonmetallics, precipitation effects, and the velocity of sound in molten aluminum. The methods and apparatus described in these papers have obvious limitations for practical use.

For example, in the two-probe arrangement used by Pitcher and Young(1-2), critical alignment of both probes is of utmost importance for any degree of success. The very limited convergent point needed for reflection of sound from the larger particles in suspension within the melt severely limits the volume of metal which can be inspected. Also the delay line geometry would result in spurious unwanted side-wall reflections and a separate reflector is needed for attenuation measurements.

Overall, it would seem to be a very awkward system to employ under cast house conditions for continuous inspection purposes. In any arrangement, the high temperature becomes the limiting factor.

Test Setup

For our work a new approach was taken. A titanium probe(4) was designed and constructed which greatly simplifies the procedure required. The 4-M probe is shown in Figure 1.

The probe was designed such that it has a built-in cavity with top and bottom surfaces machined flat and parallel. The bottom surface (reflector) provides a means for continuously monitoring sound in the melt and also provides a reference signal for all measurements. This design allows molten metal to fill and/or flow through the cavity.

The probe can be moved about, held stationary, raised and lowered without occurence of any misalignment. It is a very stable probe -- thermally, ultrasonically and physically.

Four simultaneous ultrasonic measurements can be made without any changes in the probe setup.

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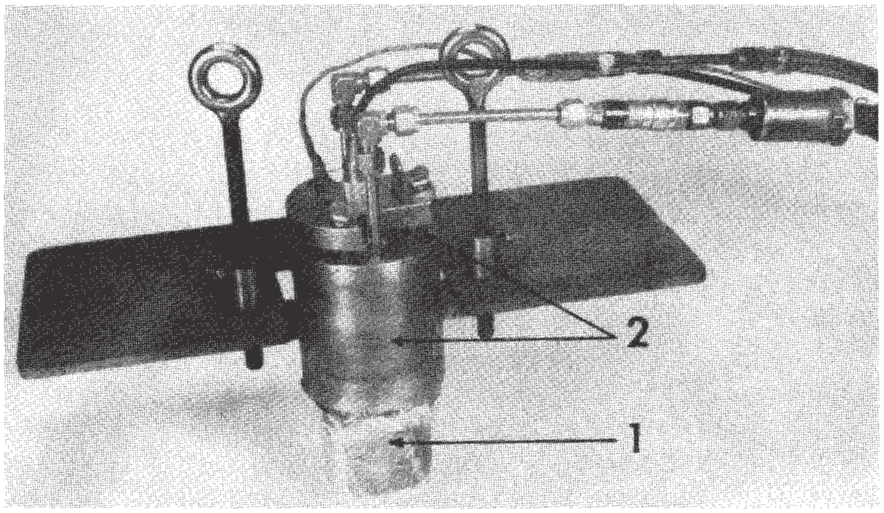
*All references appear at end of paper.



1--Flow Through Cavity
2--Cooling and Support Equipment

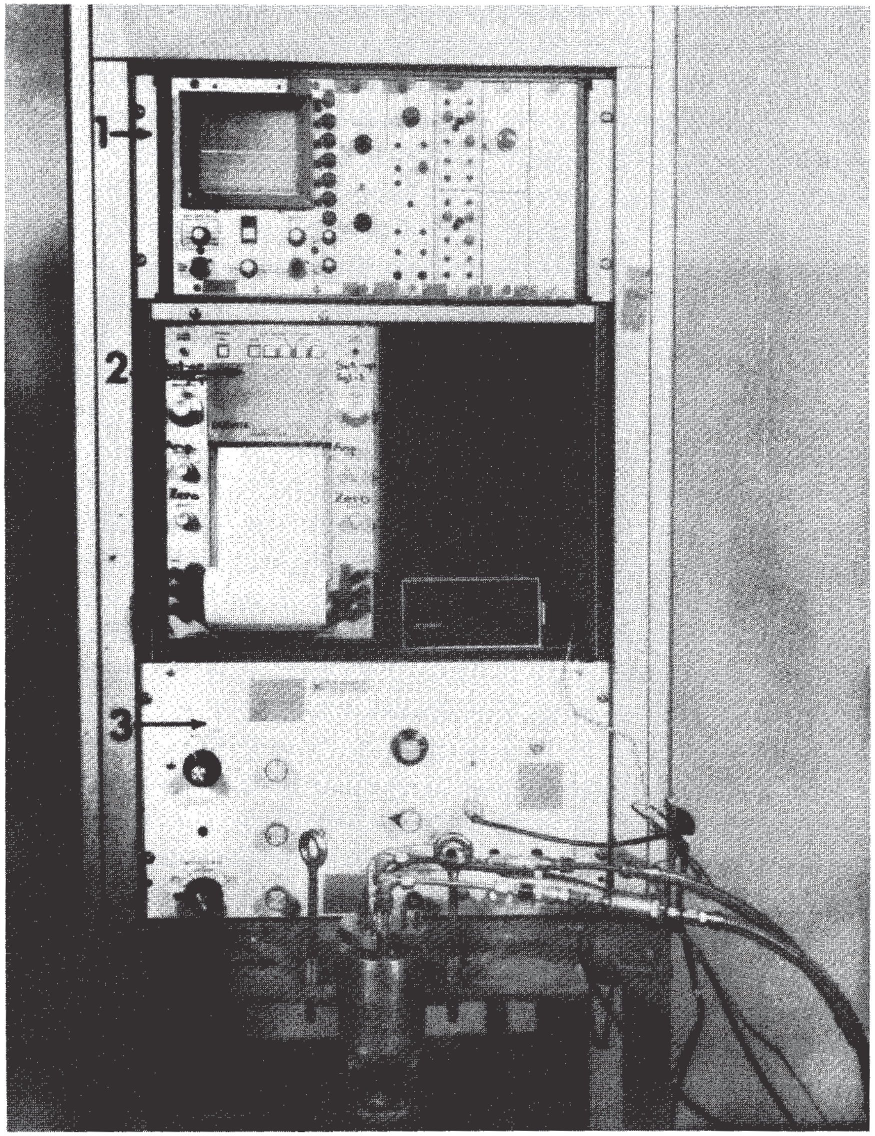
Figure 1
4-M Probe

The measurements which can be made are of interest to us, both for practical as well as research purposes. The measurements are classified as follows:

(1) Relative changes in attenuation
(2) Discontinuity detection capabilities
(3) Longitudinal wave velocity measurements
(4) Spectrum analysis of reflected pulses

The prototype system which makes these measurements is shown in Figure 2. The pulse oscillator(-3-) generates the necessary electrical signals to the ultrasonic transducer which produces the acoustical ultrasonic waves in the 4-M Probe(-4-). These pulse signals are transmitted into the melt and then received again after they have completed their inspection function. The resulting acoustical signals are processed by the pulse oscillator receiver(-3-) and the display(-1-). These signals are then sent to the recorder(-2-) where they are permanently recorded and can be analyzed.

More advanced systems are under construction under contract for Reynolds Metals use and will be approximately 1/3 the size of this model. They will also contain a complete data acquisition, control and processing computer to simplify operation and to provide a hard copy analysis of the inspection at the end of the casting operation.



1 -- Display
2 -- Recorder
3.-- Pulse Oscillator
4 -- 4-M Probe Assembly

Figure 2
Prototype Reynolds 4-M System^{TM}

Figure 3 shows the probe being immersed into a flowing stream of molten metal.

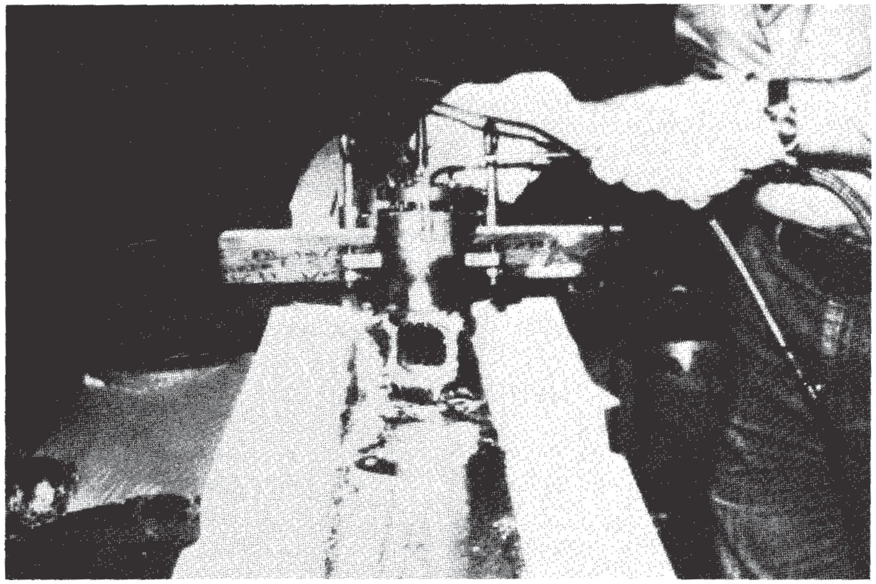


Figure 3. 4-M Probe Assembly Being Immersed Into Flowing Stream of Molten Metal

Description of Measurement Capabilities and Results

1. Attenuation Measurements

Relative changes in attenuation are due primarily to a change in the amount and type of suspended particles within the melt. These particles are of a nature to absorb and/or scatter the ultrasonic energy -- theoretically particles on the order of 1/10 the ultrasound wave length(5).

Thus, as the relative attenuation increases, we may associate this with an increase in the amount of suspended particles within the melt. Attenuation is measured in decibels (dB); a 2:1 change in attenuation is equivalent to 6 dB. That is, we quantitatively characterize molten metal to the degree that it attenuates the sound passing through the metal over the duration of a test. From observations to date, relative changes in attenuation can be related to general metal quality.

2. Discontinuity Detection Capabilities

The probe can also be used to detect discontinuities which are suspended in the melt -- theoretically particles on the order of 1/2 the ultrasound wave length(5).

The discontinuity detection capabilities of the probe include the ability to monitor the metal "noise level" (i.e. signals from very small reflecting surfaces within the melt). With electronic gates, each event of a change in relative attenuation and/or a discontinuity passing through the cavity can be detected and recorded automatically. As an example of this capability, for a plant transfer system where metal is flowing through the probe cavity, gates could be used to automatically alarm on a predetermined size discontinuity and provide the necessary input signal to record the relative size, number and time of the discontinuities. These "time events" could then be correlated to the "time in a drop" to determine, for example, the relative position of the discontinuities in the ingot.

The following Figures 4, 5, 6, and 7 illustrate both the attenuation and/or discontinuity information recorded from different experiments carried out under actual cast house conditions.

Figure 4 shows three effects with a filter which we will designate Type 'A'. In the upper recording with the probe upstream of the filter, we see several large and small discontinuities. The vertical scale measures relative amplitude of discontinuities, while the horizontal scale is related to time into the drop. In the lower recording, the probe has been moved downstream of the filter. On the left we see a general improvement in melt quality with the obvious absence of the very numerous discontinuities we had in the upper presentation. However, at about the half-way "time" position, we see a return to a very numerous and large discontinuity condition. This was a direct result of the operator disturbing the filter. When this happens, we believe that material filtered from the melt is admitted back into the melt, but now it is downstream of the filter. The Monitor easily picks up this condition.

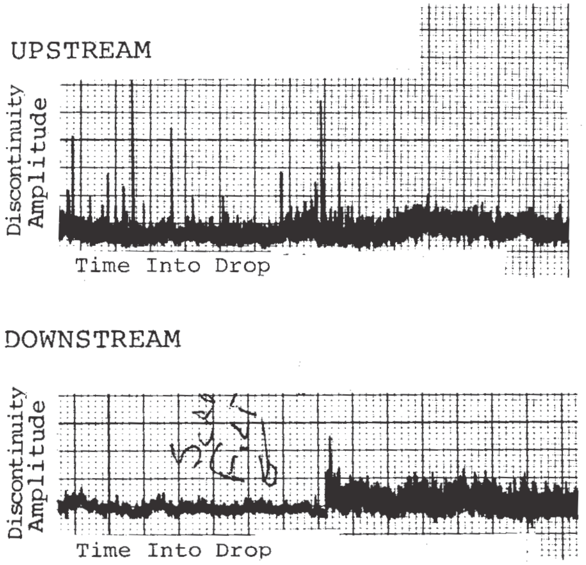


Figure 4

Effect of Disturbing a Type 'A' Filter

Figure 5 shows the effect when an alloy is processed through a Type 'B' filter. The top display shows the melt containing several discontinuities. When the probe is moved downstream, as shown in the lower display, we see the obvious removal of discontinuities which were present in the upstream metal.

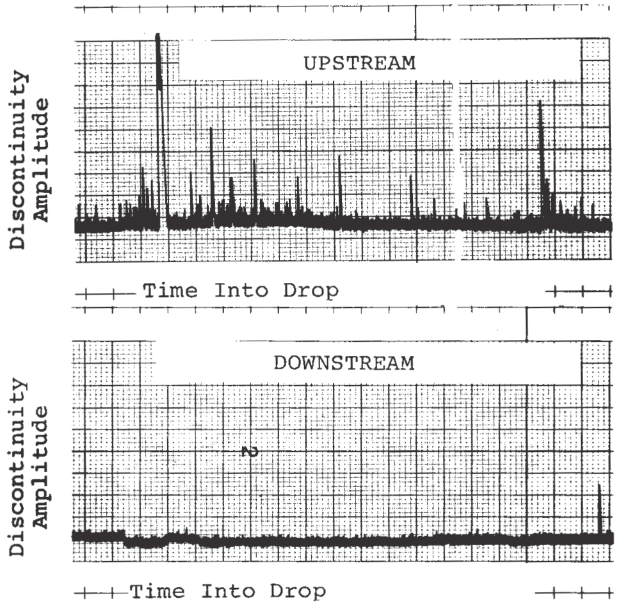


Figure 5

Operation of a Type 'B' Filter

Figure 6 shows the effect of holding or settling time. In the top display, the probe is placed upstream of a filter. There are no detectable discontinuities. This represents a drop of metal which had in excess of three hours holding time. The lower trace shows, with the probe again upstream of the filter, the next drop of the same alloy. This drop had no holding time. The difference between the two drops is evident.

In Figure 7, both the discontinuity and attenuation detection capabilities are displayed to show how one melt condition affects both ultrasonce responses. The top display shows the attenuation data. The vertical scale is in decibels (dB), the horizontal scale displays time into the drop. The bottom display gives discontinuity amplitude on the vertical scale. Time is displayed on the horizontal scale. For this particular drop of metal, we see that the attenuation is constant at about 2.5 dB for the first third of the time (reading from left to right). For this particular drop, a Type 'C' filter was used. During the drop, this filter was disturbed. With the probe downstream from the filter, we see the melt quality downgraded substantially with the attenuation factor reaching infinity, (∞), due directly to this undesirable action. (Infinite attenuation means that all sound was scattered, reflected or adsorbed in the melt.) At this same time, the lower trace displays the very large number of small discontinuities as they were introduced into the melt.

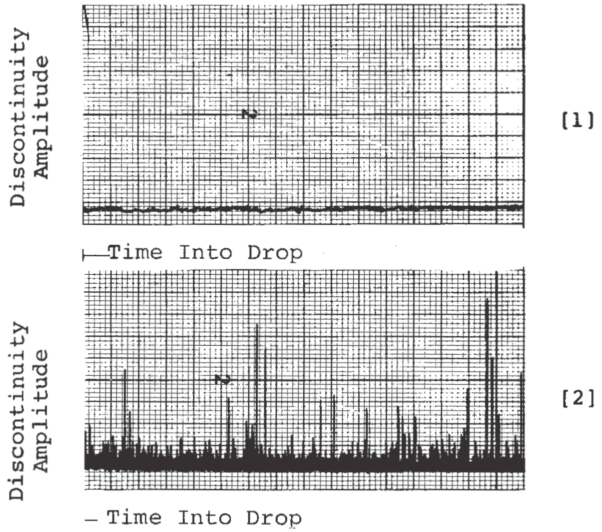


Figure 6. Effect of Holding Time

1. First Drop - > 3 Hours Holding Time 2. Second Drop - No Holding Time

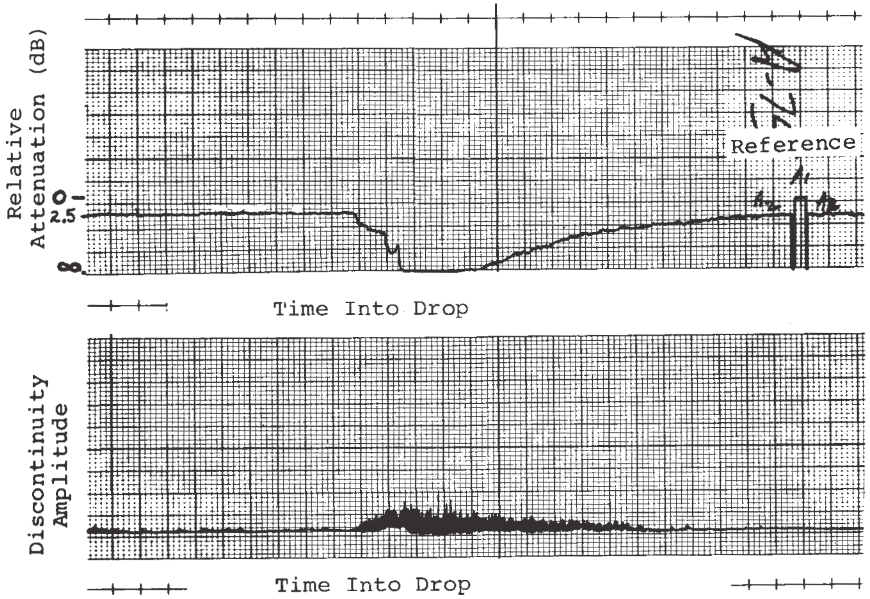


Figure 7. Affect on Discontinuity (Bottom Trace) and Attenuation (Top Trace) Data When a Type 'C' Filter is Disturbed

The monitor can be moved very easily and very quickly among locations in the molten metal stream. The response time in any new location is less than one minute. Test periods as short as two minutes have been used. Alternately, the probe can be left at one position for many hours. In any situation, both discontinuity content and relative changes in attenuation are measured and recorded simultaneously. Two of our research units have been equipped with data acquisition systems, microprocessor and printer-plotters. Table I is a record of examples of short and long period use. Note the varying time periods in the different locations for each example. Note also the discontinuity count and that the average attenuations and their standard deviations have been calculated for each data period.

If multiple units are to be used in one location or are distributed among several plants all units will produce the same numerical data. This is accomplished through internal calibrating circuits.

3. Velocity Measurements

The velocity characteritistics of molten metals have been studied by several authors (3,6,7) to determine compressibility. This information can lead to the construction of simple models of the liquid structure. Velocity measurements can also be used to determine material properties and/or composition variations as suggested by other authors (6-7). Determinations of velocity as a function of temperature have been made with the 4-M probe.

4. Spectrum Analysis

The frequency of transmitted and reflected pulses of ultrasonic energy can be obtained with the same probe setup. In solid state measurements, several authors (8-10) used this type of information to describe the nature of a detected discontinuity, namely size and orientation.

For molten metal inspection research, spectrum analysis measurements can be used to determine attenuation as related to frequency and provide another definitive description of molten metal characteristics. For example, Table II shows a study of frequency characteristics after the sound waves have traversed the molten aluminum path.

From work conducted by Serabian (11-12) on solid materials, frequency attenuation was shown to be related to material characteristics. He also points out the fact that for material with frequency attenuation, the defect detection capabilities of the inspection system may become severely limited. For example, the equipment will not detect a small discontinuity at a long metal distance as well as it would at a short metal distance, based on the $\lambda/2$ theory.

General Remarks

The measurement capabilities of the Reynolds 4-M System^{tm} will enable a better understanding of aluminum in the molten state just as similar ultrasonic measurements have helped in solid state measurements.

The development of this technology will open a whole new field for applying ultrasonics to the study of molten metals. It gives the metallurgist in the research laboratory and his colleague in the cast house a powerful tool for studying, understanding, and controlling the processing of molten aluminum.

Table 1. Examples of Short and Long Period Use

Example	Clock Time	Measuring Period	Location	Discontinuity Count	Attenuation (dB) Average	
						σ
A	3:11 p.m.-3:13 p.m.	2 minutes	Downstream of Filter 1	0	1.0	0.1
	3:14 p.m.-3:17 p.m.	3 minutes	Upstream of Filter 1	0	1.7	0.4
	3:18 p.m.-3:20 p.m.	2 minutes	Upstream of Filter 1	5	2.6	0.6
	3:21 p.m.-3:28 p.m.	7 minutes	Downstream of Filter 1	0	0.7	0.1
	3:32 p.m.-3:36 p.m.	4 minutes	Upstream of Filter 1	4	1.7	0.5
B	1:57 p.m.-2:03 p.m.	6 minutes	Upstream of Filter 2	0	12.1	1.5
	2:10 p.m.-3:37 p.m.	87 minutes	Downstream of Filter 2	0	9.1	0.9
	3:40 p.m.-3:53 p.m.	13 minutes	Upstream of Filter 2	1	8.6	0.3

Table II. Spectrum Analysis Measurements Using the 4M System^{tm}

Applied Frequency $\mathrm{MH_z}$	Returned Frequency $\mathrm{MH_z}$
6.43	6.43
8.38	8.38
9.46	9.0

Acknowledgements

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