Attenuation of the Ultrasonic Waves in Metals. I : Aluminium

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journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	7
page range	455-464
year	1955
URL	http://hdl.handle.net/10097/26727

Attenuation of the Ultrasonic Waves in Metals. I
Aluminium*

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(Received June 18, 1955)

Synopsis

Attenuation coefficients of longitudinal ultrasonic waves in aluminium were measured by pulsed ultrasonic waves at the frequencies ranging from 2 to 25 megacycles per second. Specimens were annealed several times successively at the temperatures below its melting point to promote the growth of crystal grain from 0.2 to 2 mm. Some corrections on the measured values of attenuation were carried out to eliminate the errors arising from propagation characteristics of the sound waves in the specimens. General feature of the change of attenuation coefficients with respect to frequency and grain sizes were as follows: (1) when the grain diameter was smaller than wave length of sound, the slope of attenuation versus frequency curve increased with grain size; (2) when grain diameters were greater, the slope became very small; (3) at the intermediate size of grain gradual variation of the slope appeared between lower and higher range of wave length. From these characters of ultrasonic attenuation in polycrystalline metals, several remarks for ultrasonic flaw inspection in metals and alloys were obtained.

I. Introduction

As an important technique of non-destructive testing, the ultrasonic flaw inspection⁽¹⁾ is utilized for various materials in their course of production. This method is very powerful for detecting internal flaws of material, but sometimes it becomes difficult to interprete the pulse figures of ultrasound owing to the propagation characteristics of sound waves in materials tested. It has been pointed out⁽²⁾⁻⁽⁷⁾ that attenuation values of ultrasound in metals and alloys varies widely according as their micrographic structures and heat treatment. It is presumable that there may be certain ranges of testing frequency suitable for the nature of each metal, and sometimes attenuation value itself may be a measure of the quality of metal. Sometimes irregular patterns of oscilloscope figure appear due to random reflection of sound waves in the materials and there may be chances of misunder-

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* The 812th report of the Research Institute for Iron, Steel and Other Metals.
Read at the meetings of the Physical Society of Japan and the Japan Institute of Metals (1952), and published in the J. Japan Inst. Metals, **17** (1953), 412, 456; and this work was partly supported by Grant in Aid for Developmental Scientific Research of the Ministry of Education (1951, 1952).

(1) Symposium on Ultrasonic Testing, ASTM Special Technical Publication, No. 101.
(2) C. de Kerversau, J. Bleton et P. Bastien, Rev. Mêtallurgie, **97** (1950), 421.
(3) H. B. Huntington, Phys. Rev., **72** (1947), 321.
(4) W. P. Mason, H. J. McSkimin, J. A. S. A., **19** (1947), 464; J. Appl. Phys., **19** (1948), 940.
(5) W. Roth, J. Appl. Phys., **19** (1948), 901.
(6) R. K. Roney, Ph. D. thesis, California Inst. Tech., (1950).
(7) R. L. Roderick and R. Truell, J. Appl. Phys., **23** (1952), 267.

standing the distribution of flaws. The relations between the attenuation values of longitudinal ultrasonic waves and micrographic structures of aluminium of high and ordinary purity were studied in the present experiments.

II. Method of measurement

The attenuation measurements of longitudinal ultrasonic waves in the medium were carried out by observing the decay of the amplitudes of isolated wave trains in their course of transmission. For the purpose of emitting pulsed wave trains into the medium and detecting them, an ultrasonic flaw detector was used, the construction of the apparatus being shown in Fig. 1. The output of 600 cps of the sweep oscillator was differentiated and amplified to build an exciting pulse of several microseconds in width, and the high-frequency oscillator was controlled by this pulse so as to build up high frequency wave trains. This high-frequency output was then amplified, put through the matching circuit and applied to an X-cut quartz crystal plate fixed to the surface of the specimen by wax. The wave form of this pulsed signal is illustrated in Fig. 2, which has an envelope similar to sinus curve with a steep initial ascent. The longitudinal ultrasonic waves emitted into the medium were received by another X-cut crystal plate soldered at the opposite plane of the specimen and the resulting electrical signals were fed into an amplifier through the variable attenuator. The attenuator used was of the standard signal generator type and variable from 0 to 100 db at an interval of 1 db. The receiving amplifier was of the super-heterodyne type with a gain of about 100 db, and the amplified high frequency signal was detected and amplified and then fed to a cathoderay oscilloscope. When the tested material is inserted as shown in Fig. 1, a pulse figure appears on the oscilloscope at the interval corresponding to the length of the specimen, and the height of each pulse is determined by the intensity of detected ultrasonic waves, these circumstances being shown in Photo. 1. The highest pulse at the left of this photograph represents the incident sound wave, the next is the direct transmission pulse and the n-th pulse corresponds to the reflected pulse of $(n-2)$th order. If the length

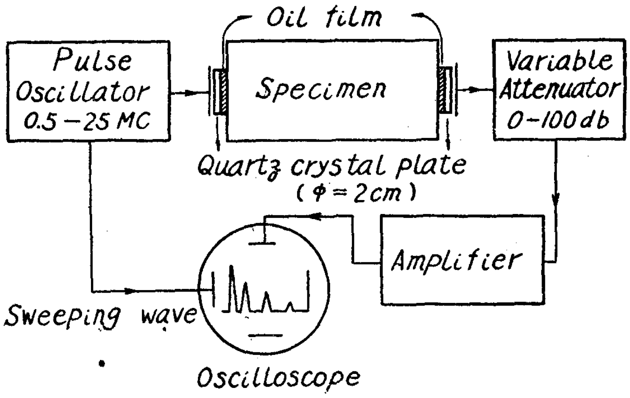

Fig. 1. The apparatus for ultrasonic attenuation measurement.

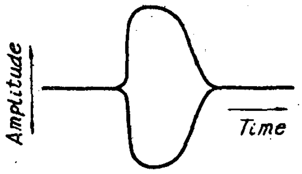

Fig. 2. Figure of emitted pulse.

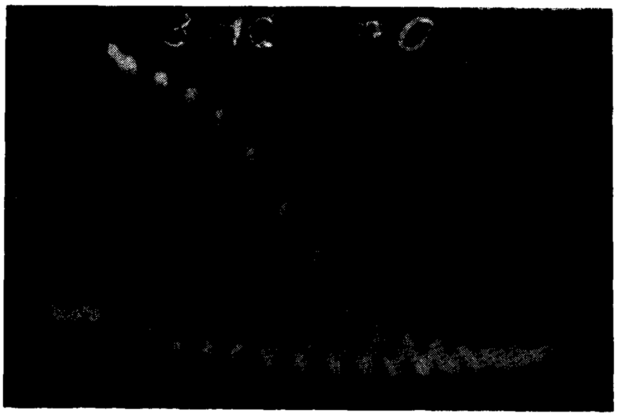

Photo. 1. Reflection pattern of ultrasonic pulses in the never heat treated specimen of 99.4% Al at 3 Mc/s.

of the specimen is l cm, the entire path length of the n-th pulse L_n is expressed by

$$L_n = (2n - 1)\,l\,. \qquad (1)$$

Hence, the path difference of successive pulse is $2l$. Thus, if the amplitude of pulsed ultrasonic waves diminishes from $A(0)$ to $A(x)$ after travelled by x cm through the medium in exponential type as

$$A(x) = A(0)\exp(-\alpha x)\,, \qquad (2)$$

where α is an attenuation coefficient, the height of the succeeding pulses on the oscilloscope decays exponentially with the number of round trips n. So it must be possible to determine this coefficient α from measuring the height of successive pulse. For the measurement of the height of an individual pulse, the attenuator inserted in the receiver side was so adjusted that the height of each pulse coincided with the fixed mark on the cathode ray oscilloscope and then the attenuation value was read from the attenuator in the unit of decibel. The readings of the attenuator and the order or the number of round trips of the pulse travelling through the specimen are plotted in Fig. 3, which take a feature of straight line for various frequencies, as will be seen from the above formula (2), the measured

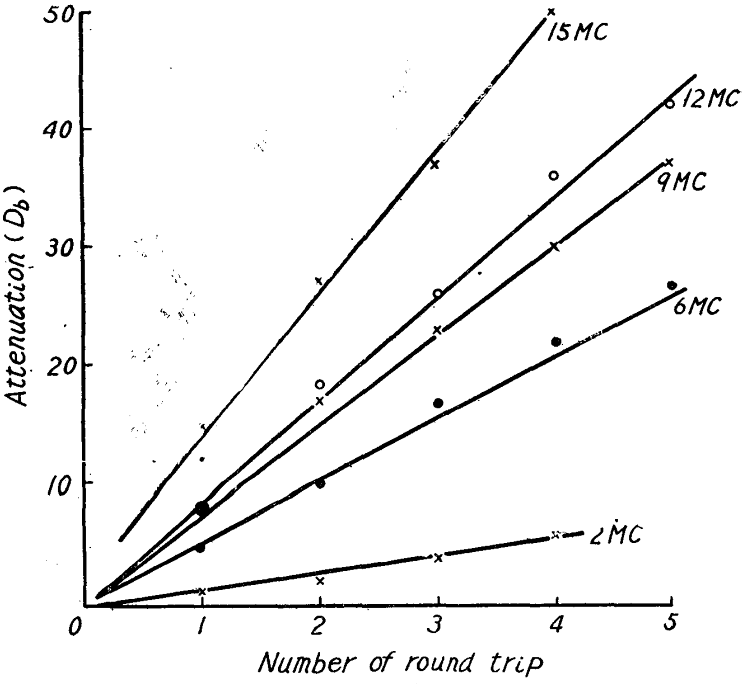

Fig. 3. Linear attenuation of ultrasonic waves as a function of the numbers of round trip.

frequency being marked at each curve. As revealed by this figure the attenuation was proportional to the total path length of the sound pulse or the number of round trips in the medium; the proportional constant corresponds to the attenuation coefficient α, or the attenuation for unit length of transmission. To determine correctly the attenuation coefficient by this method, however, it was necessary to make some corrections basing on the transmission characteristics of sound waves. Many studies have been reported on these complicated characteristics, but it seems to be difficult to carry out perfectly accurate corrections remembering all of the transmission features. So, the present methods were conveniently restricted as follows:

(a) Corrections of reflection loss: As the attenuation is determined by measuring the amplitude of the pulsed ultrasonic waves at the end surfaces in the course of its travelling through the medium, the correction must first be made for the loss of the pulse amplitude due to the reflection and refraction at the interface of specimen and wax. To correct this loss, the results obtained with two pieces of the same material, one 5 cm and the other 10 cm in length, were combined with each other, and the loss due to reflection was eliminated. An example of this loss is shown, together with frency. in Fig. 4.

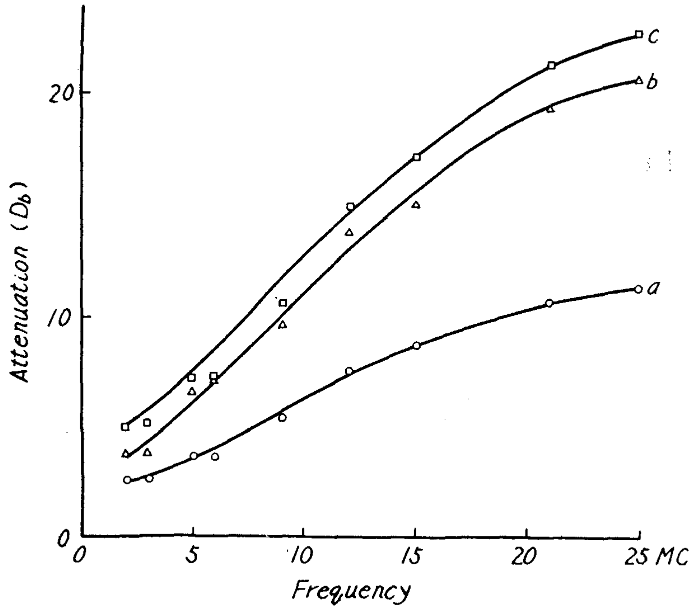

Fig. 4. Measured values of attenuation for specimens 99.99% Al annealed successively up to 470°C; *a*: for the specimen 5 cm in length, *b*: for 10 cm in length, and *c*: for the twice values of curve *a* and the differences between curves *c* and *b* are the reflection loss.

(b) Correction of the spherical wave front(8): The attenuation, as calculated by the formula (2), was determined under the assumption that the ultrasonic waves running through the medium have a form of plane wave. The ultrasonic waves emitted from the crystal plate into the specimen, however, form the so-called short range sound field near the crystal plate owing to the mutual interference of each mode of vibration, and at a sufficiently long distance become spherical form. Now, it was assumed that the short range sound field was of a plane wave type, and the correction at a long distance was required. In this case, the ratio R of the amplitude $A(x_1)$ to $A(x_2)$ after the sound waves are propagated respectively by the distances x_1 and x_2 will be expressed by

$$R = A(x_1)/A(x_2) = x_2/x_1 \cdot \exp(-\alpha(x_1 - x_2)) \qquad (3)$$

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(8) H. Backhaus u. F. Trendlenburg, Z. Tech. Phys., **2** (1926), 630; H. Stenzel, Elektr. Nachr. Techn., **4** (1927), 239; **12** (1935), 16.

Hence, the ratios R_5 and R_{10} of the ampliudes of the sound pulse after the round trips of n, $n+1$ and of n', $n'+1$ in the spesimens of 5 cm and 10 cm in length respectively will be

$$R_5 = \{(2n-1)/(2n+1)\}\exp(-10\alpha),$$
$$R_{10} = \{(2n'-1)/(2n'+1)\}\exp(-20\alpha).$$

Combining above formulas with each other, the attennation coefficient will be obtained from the figures of n-th and n'-th pulses in the form

$$\alpha_{nn'} = \frac{1}{10}\left\{\log\left((2n-1)(2n'+1)\Big/(2n+1)(2n'-1)\right)+\log R_{10}-\log R_5\right\}$$

Since the first logarithmic term in the right side of the above formula changes only its sign when n and n' are interchanged, this term will be eliminated by averaging n and n' of both sides. In this way attenuation coefficient may be expressed as follows:

$$\alpha = \frac{1}{10}\langle\log R_{10} - \log R_5\rangle_{nn'}, \tag{4}$$

where $\langle\ \rangle_{nn'}$ represents the mean value with respect to n and n'. This result shows that the attenuation coefficient may be calculated by taking the mean attenuation values obtained by combining the amplitudes of the pulsed waves of the different orders with one another.

(c) Elimination of the influence of side surface reflections: To eliminate the influence caused by the reflections at side surfaces of the specimen due to the spreading of the sound beams travelling through it, the diameter of the specimen must be taken to be sufficiently large, and the diameter of quartz crystal plate must be determined so as to make the spreading angle of the beam narrow. For the purpose of assuring homogeneity in working and heat-treating, however, the specimen was finisned in 5 cm in diameter, and the quartz plates 2 cm in diameter.

III. Specimen and heat-treatment

To see the various features of ultrasonic attenuation in metals corresponding to the change in the microstructure, polycrystalline aluminium was used. The reasons for this selection of specimen are as follows: (i) in aluminium the transmission loss of sound is considerably small and the attenuation measnrement is comparatively easy; (ii) the size of crystal grains can easily be controlled by heat-treatment; (iii) thus the measurement can be carried out under various conditions. The aluminium specimens were 99.99 per cent pure, containing Si less than 0.009 per cent as impurity. The ingots were first hot-forged and then cold-forged into cylinders, 5 cm in diameter, to assure the degrees of working of some scores of percentage. Then these cylinders were cut into 5 and 10 cm in length and the end surfaces were finished carefully so as to be made parallel within 0.01 mm of deviation. These specimens were successively annealed at various temperatures for the durations shown in Table 1. The grain size was first smaller than 0.2 mm and gradually grew with the repetition of annealing, becoming 2 mm after the final heat-treatment. The micrographs of grains after the heat-treatments c, d, e, g, j, and k are show in Photo. 2.

Table 1. Heat treatment and grain diameters of the specimens.

Heat treatment	a	b	c	d	e	f	g	h	i	j	k
Temperature ℃	150	270	330	360	410	470	520	570	610	620	660
Time hr	1	1	1	1	1	1.5	1.4	1	1	2	8
Grain diameter mm	<0.2	0.21	0.22	0.25	0.26	0.28	0.35	0.42	0.85	1.3	2

Besides, the test-pieces similar to the above were prepared from the ingots of 99.4 per cent aluminium containing 0.24 per cent of Fe, 0.015 per cent of Ti, 0.003 per cent of Cu, 0.333 per cent of Si etc. as impurities. These test-pieces were heat-treated and the ultrasonic attenuation measurements were carried out at each stage of heat-treatment in the way similar to the case of highly pure specimens.

IV. Results of measurement

The attenuation measurements of longitudinal ultrasonic waves were carried out in the frequencies ranging from 2 to 25 Mc/sec after various heat treatments shown in Table 1. The results are summarized in Fig. 5.

At the earlier stages of the heat treatment, crystal grains were considerably small, being about 0.2 mm in diameter, and the attenuation coefficient increased approximately linearly with the frequency. The slopes of curves in the specimens a and b were almost equal to each other, being about

$$0.19 \times 10^{-8} \text{ neper cm}^{-1} \text{ cycle}^{-1}$$

With the advance of heat treatment crystal grains grew and the attenuation value increased strongly with the frequency and the attenuation curves became upward concave. After the grain reached a certain size the attenuation value lost the tendency of increasing and tended to show a saturation. The frequency at which such an apparent saturation began decreased with grain size and the attenuation values at the frequency above this diminished at the same time. In the specimens subjected to the heat treatment k, when the crystal grains attained to the maximum size of 2 mm in mean diameter, the attenuation of ultrasound of higher than 6 Mc/s became nearly constant in the ratio of

$$0.052 \times 10^{-8} \text{ neper cm}^{-1} \text{ cycle}^{-1}$$

At high frequencies, the attenuation decreased with increasing grain size, while in low frequencies the attenuation increased with the grain size, and the critical frequency decreased. Looking through the results by different frequencies, the dependence of attenuation on grain size reversed its tendency.

In the specimens of 99.4 per cent aluminium, general features of ultrasonic attenuation were almost the same as in the case of high purity. At the initial heat treatment, crystal grain was about 0.29 mm in diameter and the attenuation

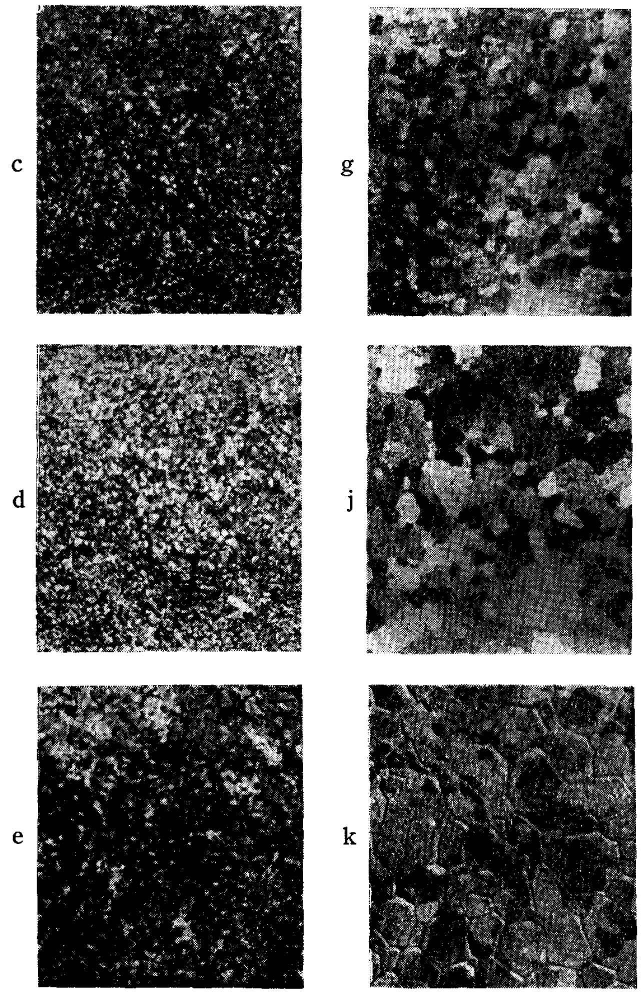

Photo. 2. Micrographs of grain sizes for each stage of annealing.

value inceased linearly with the rise of frequency, the proportional constant being

$$0.86 \times 10^{-8} \text{ neper cm}^{-1} \text{ cycle}^{-1}$$

This value was considerably larger than that of high purity aluminium specimens. When, however, the specimens of low purity were annealed at high temperatures, certain changes in oscilloscope figure were observed. In Photo. 3(a) the pulse figure of sound wave of 5 Mc/sec passing through the specimen annealed at 600°C for 15 hours are shown. In this figure, the pulses are clearly visible down to the fourth passage, their heights decreasing with the order and revealing the attenuation feature of an ordinary exponential type. Following the fourth pulse, however, some irregularly confused pulses appeared and this sequence of

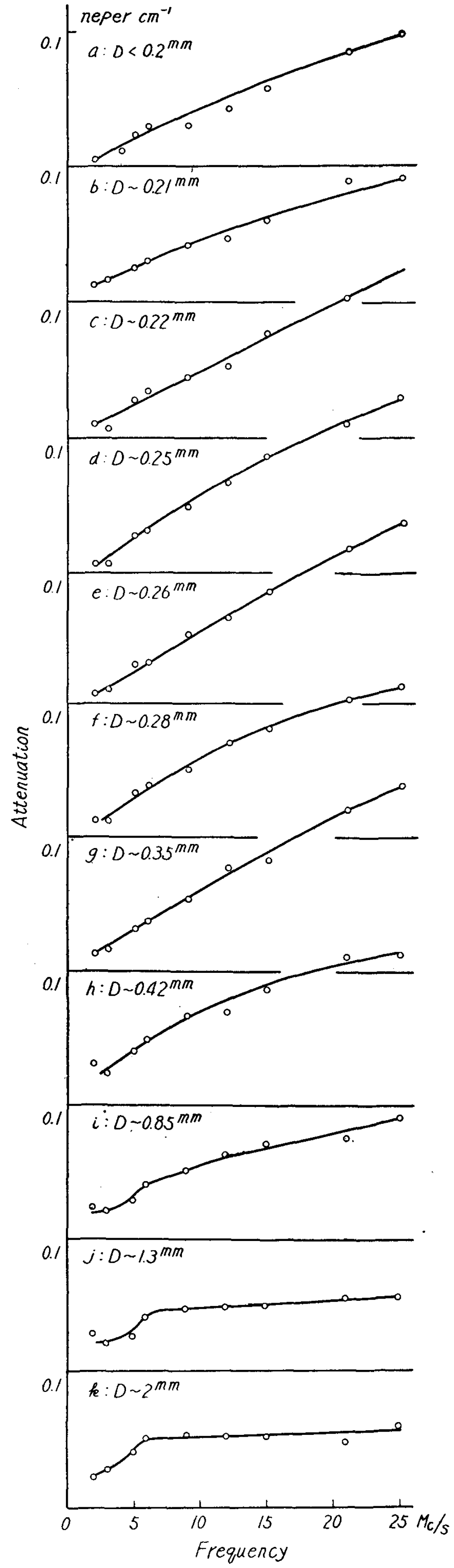

Fig. 5. Attenuation of ultrasonic waves versus frequency, in 99.99% Al specimens having various grain sizes.

pulses could not be called monotonously diminishing. With further heat-treatment such an irregularity became more apparent, and after annealed for 30 hours in total at 600°C pulse figures of the ultrasound of 3 Mc/s became as shown in Photo. 3(b). In this case sound pulses of exponential type and irregular pulses were overlapped and the exact discrimination between them was impossible.

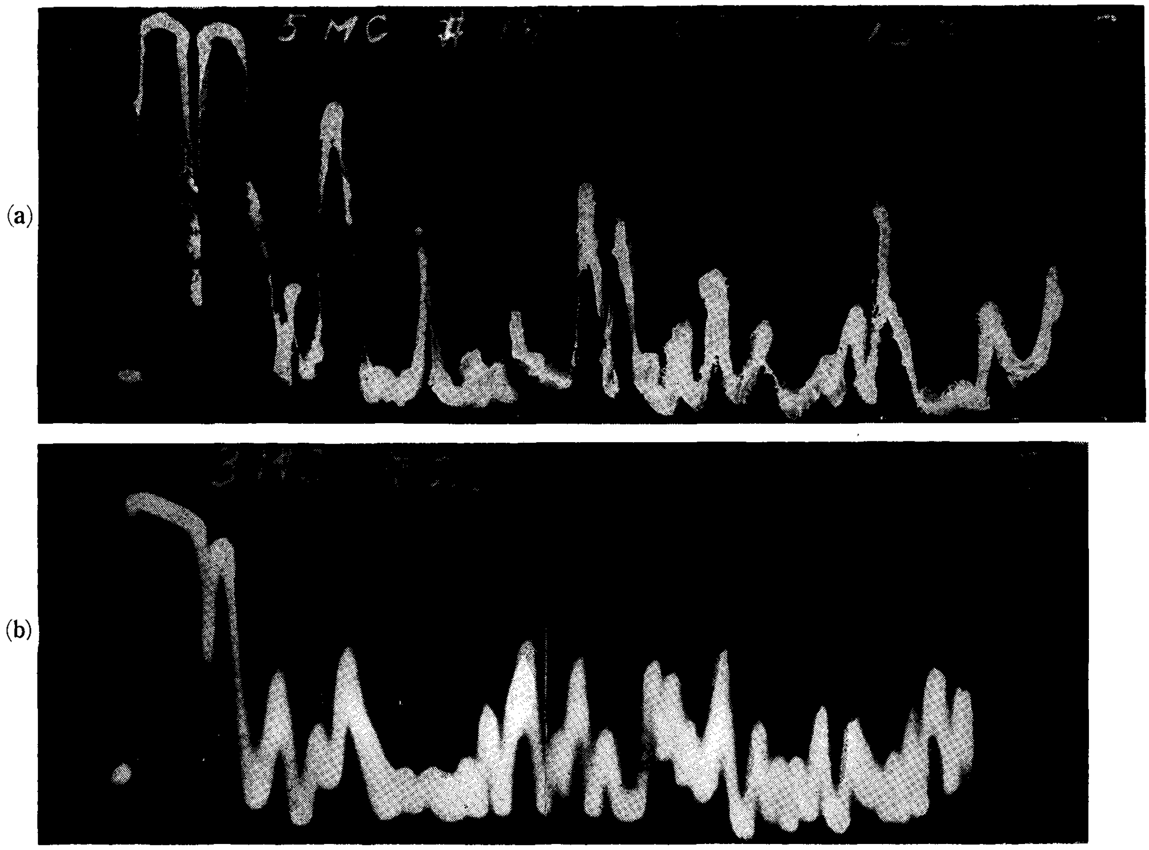

Photo. 3. Random reflection patterns of ultrasonic waves in the specimen 99.4% Al annealed at 600°C for (a) 15 hrs at 5 Mc/s.
(b) 30 hrs at 3 Mc/s.

These prominence of irregular pulses is probably originated from the fact that, with the progress of annealing, the impurity atoms may be forced to diffuse toward grain boundaries, resulting in the enhancement of the reflection at the boundaries with increasing divergence before reaching the receiver.

V. Discussion of the results

When the velocity of a longitudinal sound waves in aluminium is taken to be 6000 m/s, the wave-length λ of the ultrasonic waves is 3 mm at the frequency of 2 Mc/s and 0.24 mm at 25 Mc/s. As mentioned above, the average diameter D of the crystal grains was in the range of 0.2 to 2 mm, and accordingly, λ and D are nearly of the same order in magnitude. Thus, in interpreting the results obtained in the present experiments, three cases $\lambda > D$, $\lambda = D$, and $\lambda < D$ should be distinguished.

In the case in which the wave length λ of sound is larger than grain diameter D, the ultrasonic waves are scattered by each grain and lose their energy gradually because of the different orientations of the elastic axes in the adjacent grains. When a scattering center of radius D with slightly different elasticity is present in a homogeneous medium, the attenuation coefficient is denoted by

$$\alpha \propto D^3 f^4$$

where f is the frequency of ultrasonic waves. But owing to the random and various distributions of grains, the exact expression of α can hardly be obtained in this case. It would be reasonable to assume that, generally speaking, the attenuation grows remarkably with the rise of the frequency and that the growth of attenuation is emphasized by the growth of size of the crystal grains. This feature will roughly be formulated by above relation.

When $\lambda < D$, the sound waves′ propagate through the medium with repeated reflections and refractions at grain boundaries. According to Mason and McSkimin(4), the attenuation takes, in this case, a constant value independent of the frequency of the wave, and this value changes proportionally with the frequency of reflection in unit length or inversely proportional to the grain size, namely,

$$\alpha \propto D^{-1}.$$

When λ and D are approximately equal to each other in magnitude, the above relations do not hold. In this case(11), the phase differences of the ultrasonic waves undergo gadual changes during transmission through the grains, and at last suffer remarkable attenuation, which is determined by grain diameter and frequency with the relation

$$\alpha \propto D f^2.$$

Basing on these deductions on ultrasonioc attenuation the relations between attenuation coefficients and frequencies of ultasanic waves in polycrystalline specimens can be realized, which is shown in Fig. 6. The numbers in this figure are the grain size arranged in the order from the small to the large. General feature of the curves is in good agreement with that of the observed results of Fig. 5.

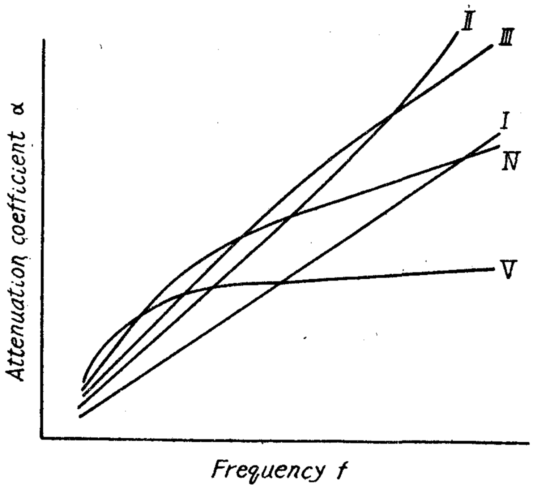

Fig. 6. Schematic figure of ultrasonic attenuation versus frequency for 99.99% Al specimens of various grain sizes, grain size developes from I to V.

Next, these results will be compared with those of previous measurements. With respect to light metals, Mason and MaSkimin(4) reported attenuation measurements on 17 ST (Al, 95%; Cu, 4%; Mn, 0.5%; Mg, 0.5%) and aluminium, and Roth(5) on magnesium. According to the former authors, the attenuation of sound waves with wave-lengths of about three times the diameter of the crystal grains

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(11) Pekeris, Phys. Rev., **71** (1947), 268; H.B. Huntington, J. A. S. A., **22** (1950), 362.

or larger is given by $B_1f + B_2f^4$, where f is the frequency and B_1 ane B_2 are constant. Their attenuation values are greater than the present values, which will be due to the difference in the purities of specimens. On the otherhand, Roth measured the ultrasonic attenuation in the case in which the wave length was much smaller than the grain diameter, with the result that the attenuation and the frequency were in a linear relation, the proportional constants between them diminishing with the rise of D. These results may be regarded to be a portion of the results of the present measurements in longer or shorter range of wave length than gain diameter, and in good agreement with the conclusion illustated in Fig. 6.

Conclusion

Considering the results of the attenuation measurement of longitudinal ultrasonic waves in polycrystalline aluminium, some remarks will be given for practical execution of flow inspections of metals and alloys as follows:

(1) To raise the accuracy of flaw detection, high-frequency ultrasonic waves may be preferred, but such waves are highly attenuated generally in their passage through the materials. But this high resistivity to the transmission of high-frequency waves will vary widely with the fine structure or quality of the material. Some criterions may be offered from above results for determining the convinient frequencies in material testing.

(2) Owing to the finite sensitivities of the apparatus the smallest resolvable signals are determined, and size of tested materials is limited inevitably, so the testing frequency will be decided from the attenuation characteristics.

(3) If the irregular reflection patterns stated above appear, it will be required to take particular care of interpreting the internal flaw distributed within the tested material.

(4) In special circumstances it will be convinient to take ultrasonic attenuation value as a measure of the soundness of the material, and it should be taken into account that the value varies widely with the fine structure of the metal.

Acknowledgement

The authors express their thanks to Prof. Y. Kikuti of Tohoku University, Prof. O. Nomoto of Kobayashi Institute of Physical Research and Mr. R. Utida of Japan Radio Co. Ltd. for their valuable suggestions.