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Attenuation of the Ultrasonic Waves in Metals. II
Stainless Steel*

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Synopsis

Ultrasonic attenuation coefficients of stainless steel with various grain sizes were measured by pulse method at the frequencies ranging from 0.5 to 6 Mc/s. The stainless steel used was of austenite structure containing about 19 per cent of chromium and 10 per cent of nickel. It was found that the attenuation coefficient increased remarkably with the frequency, and that the increase was more rapidly with increasing size of crystal grains. The nature of such an attenuation behaviour was explained by assuming that the travelling ultrasonic waves are scattered by the austenite crystal grains in accordance with the Rayleigh's law.

I. Introduction

The ultrasonic attenuation coefficients of plane carbon steel and some alloy steels were measured by several authors.(1) It was then found that the attenuation was greatly influenced by the change in structure due to the heat treatment of the specimen as well as the frequency of the ultrasonic waves propagating through it. The research was also made on the dependence of ultrasonic attenuation on the size of pearlite grains. Further, some conclusive remarks were given by the present authors that such an attenuation would be due mainly to the scattering of ultrasonic waves by crystal grains. Concerning austenite steel, however, there are no reliable data on the ultrasonic attenuation. Hence, the present measurement was carried out with nickel-chromium stainless steels. As the stainless steel has austenite structure, the scatteraing of ultrasonic waves by crystal grains will be expressed in far simple form compared with the case of steel of pearlite structure. Though, the stainless steel is highly corrosion- or heatresisitive and used widely for the structural members, such resistivities are sometimes highly destructed by heat treatment, working or welding. For the purpose of detecting the weak parts of such members, the ultrasonic inspection may be most suitable, and the ultrasonic attenuation measurement in stainless steel relating to grain size will give the fundamental data to the inspection.

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* The 912th report of the Research Institute for Iron, Steel and Other Metals.

(1) F. Firestone and J. Frederick, J. Acoust. Soc. Am., **18** (1947), 200 ; E de Kerversau, Bleton et P. Bastie, Rev. Metall. **46** (1949), 277 ; ibid **47** (1950), 421 ; R. Roderick and R. Truell, J. Appl.Phys., **23** (1952), 267 : K. Kamigaki, Sci. Rep. RITU, A **9** (1957), 48.

II. Specimens and method of measurements

The specimens were nickel-chromium stainless steel,* the compositions of which are shown in Table 1. The ingots were first hot-forged and then cut into cylinders, 5 cm in diameter and 4, 5, 9 and 10 cm in length, respectively. The end surfaces were cut by lathe, finished by hand scraper and lapped into flat plane. The flatness was checked by means of a screw micrometer, and the result was that the deviation from geometrical plane was as small as 1/100 mm. Further, the both end surfaces were made parallel to each other, the deviation being 1/1000 for the length. All the specimens were annealed at 1000°C for a quarter of an hour and then cooled in the way specified as standard annealing, which will be shown below.

Table 1. Composition of the specimen.

C	Si	Mn	P	S	Ni	Cr	Cu
0.11 %	0.64	0.76	0.064	0.012	9.92	19.20	0.72

For the purpose of changing the grain size each specimen was annealed once or twice in vacuum furnace; each annealing complied with the standard of Iron and Steel Institute of Japan, and the program of such an annealing is shown in Fig. 1. The designation of the specimens and the annealings are shown in Table 2.

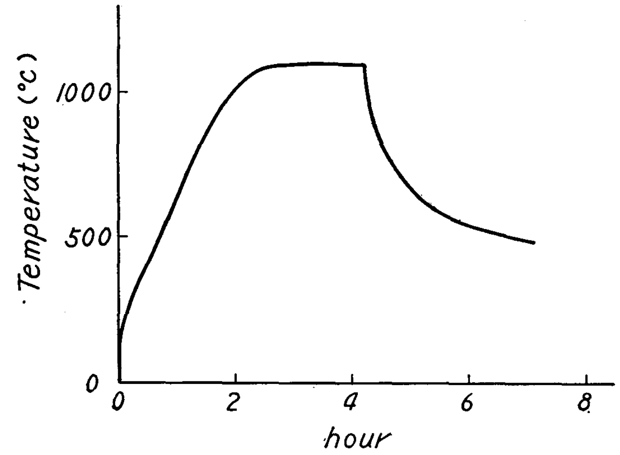

Fig. 1. A program of heat-treatment of the specimen in vacuum furnace.

After each heat treatment the microstructure was observed at the lapped surfaces and the micrographs are shown in Photo 1, the etching reagent being aqua regia of about 20°C. Not all the grains had the same size, and sometimes the twin boundaries were

Table 2. Symbols of the specimens.

Specimen	Number of annealings at 1000°C		
	pre	1	2
0	000	001	002
1	100	101	102
2	200	201	202
3	300	301	302

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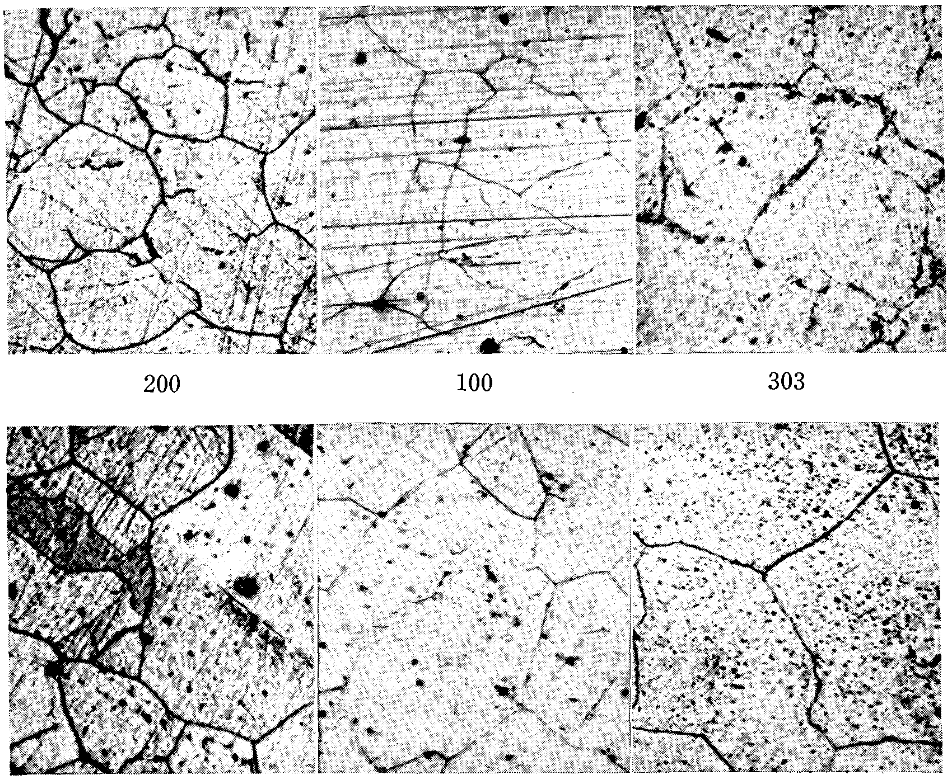
* Supplied by Tôhoku Special Steel Manufacturing Co. Ltd.



200 100 303

202 000 002

Photo. 1. The austenite grains in the stainless steel (×100)

observed, but mean grain sizes were determined by referring to the ASTM Standards, and the values are shown in Table 3. The Vickers hardness were also measured on the end surfaces and the results are shown in Table 3, and all the values fall in the range specified by the standard.

Table 3. Vickers hardness and grain size of the specimens.

Specimen	Vickers hardness	Grain size	Specimen	Vickers hardness	Grain size
000	181	3-4	200	178	4-5
001	142	2-3	201	138	4-5
002	142	2	202	143	3-4
100	157	4-5	300	165	4-5
101	145	3-4	301	142	4
102	148	2-3	302	142	3-4

The apparatus and the method of attenuation measurements were the same as those in the previous study(2); the frequency of ultrasonic waves was set in the region from 0.5 to 25 Mc/s. Two x-cut quartz crystal transducers were affixed to the both end surfaces of the specimen by means of vaselin oil, and the crystals were drived in their fundamental or overtone modes of vibration. The pulsed longitudinal ultrasonic waves were emitted into the specimen from one transducer

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(2) T. Hirone and K. Kamigaki, Sci. Rep. RITU, A **7**(1955), 455.

and received by the other after the round trips through the specimen. The attenuation of the amplitudes of the pulsed waves was observed on the cathode ray oscilloscope. The value of attenuation was obtained from the readings of the variable attenuator, setting the heights of each successive pulse in coincidence with a definite value. Now the amplitude of ultrasound $I(x)$ will be expressed after travelling x cm in the medium by the equation

$$I(x) = I(0)\exp(-\alpha x)\,, \tag{1}$$

where $I(0)$ is the initial amplitude of the wave and α the attenuation coefficient. The readings of the attenuator were plotted in the unit of decibel with the number of round trips of ultrasound in the specimen, and some examples are shown in Fig. 2. As the attenuation changed linearly with the number of round trips, it was confirmed that the attenuation in stainless steel can be expressed actually by the relation (1) of the exponential type. Now it was required to add several corrections to the measured values as in the previous case; the corrections for the reflection losses at the end surfaces were performed by making use of attenuation values for specimens of different lengths. The reflection loss β at the interface of steel and vaselin will be obtained from the measured attenuation values $A(L)$ and $A(2L)$ of specimens of the length L and $2L$, respectively, that is,

$$\beta = 2A(L) - A(2L).$$

The calculation was made with the specimens 100 and 301, as these had similar grain sizes but different lengths. The measured values of $A(L)$ and $A(2L)$ are shown in Fig. 3 for various frequencies; from these values the reflection loss was calculated as 1 db per each reflection, and this will be a reasonable value for the interface of steel and vaselin.

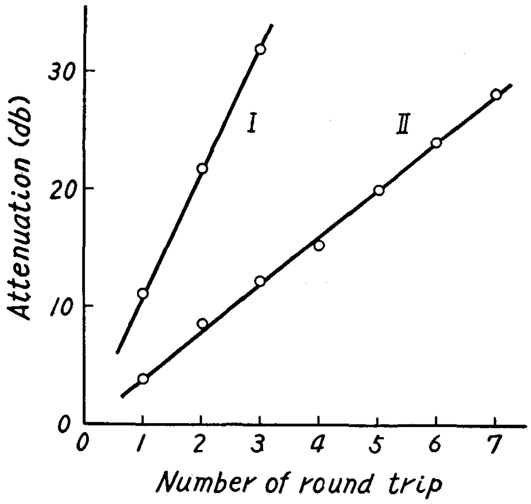

Fig. 2. Attenuation of ultrasonic waves as a function of the numbers of round trips in specimens 202 (curve I) and 301 (curve II).

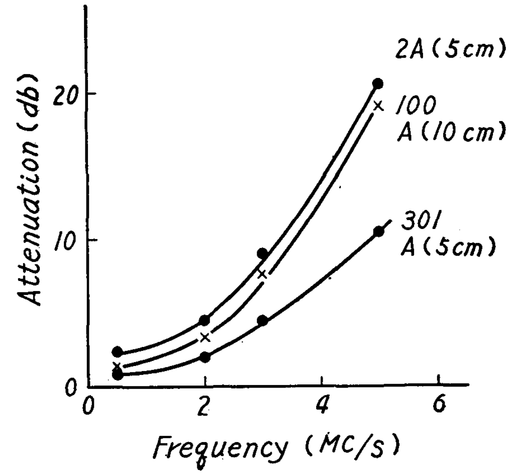

Fig. 3. The attenuation A (5 cm) for the specimen 301 of 5 cm in length and A (10 cm) for 100 of 10 cm, respectively. And also the reflection loss at the interface of steel and vaselin is shown by the dfference between curves 2A(5 cm) and A(10 cm).

III. Results of measurements

In the case of fine grain, the changes in ultrasonic attenuation with the frequency are shown in curves 1 and 2 in

Fig. 4. It was found from the figure that the attenuation value did not vary remarkably at low frequency range from 0.5 to 2 Mc/s, and then increased rapidly with further incresae of frequency. The highest frequency at which the attenuation could be measured was 6 Mc/s in the present case. It was also found that sound waves with high frequency of 10 Mc/s were severely attenuated, and that the detection of propagated waves was difficult.

The results of measurements in the case of coarse-grained specimens are shown in curves 3 and 4 in Fig. 4. The general feature of these curves is similar to that of curves 1 and 2, but the rate of increase in attenuation with frequency is more rapid. The attenuation values became also unmeasurable at 6 Mc/s due to high energy loss of sound waves during the propagation. Such tendency of increase in attenuation became remarkable in the specimens of the largest grain sizes in this measurement, as will be shown in curve 5 in Fig. 4. In this case the transmitting sound waves could hardly be detected even at lower frequencies as 3 Mc/s.

It was found in these measurements that the ultrasonic attenuation coefficients depended remarkably both on the austenite grain size and on the frequency. The present measurements were carried out with different specimens and in the stages of different annealings, but the results were quite reproducible under the same frequency and the same grain size.

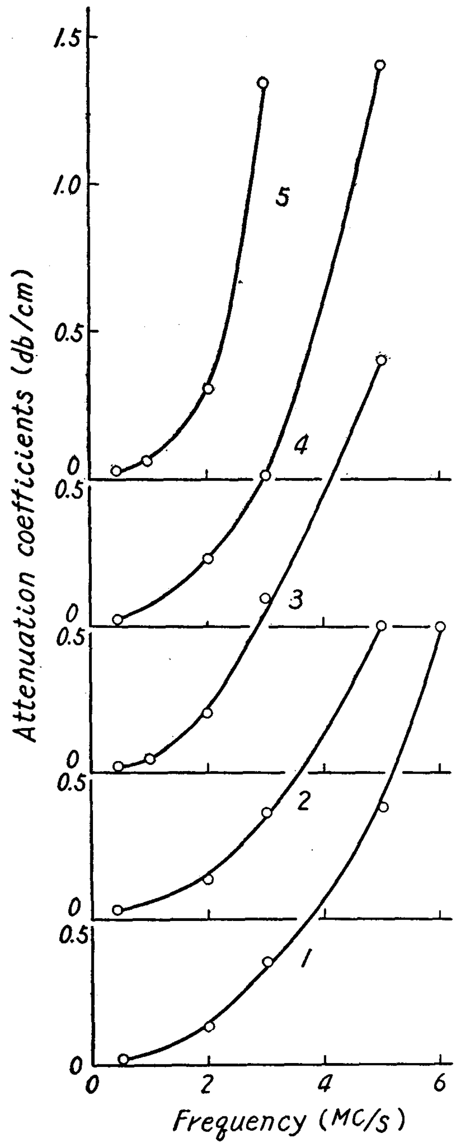

Fig. 4. Ultrasonic attenuation cofficients for specimens 201(curve 1), 301(2), 102(3), 000(4) and 002(5), respectively.

IV. Discussions of the results

It is noted that the dependence of ultrasonic attenuation on the grain size and on the frequency in the present case was similar to that in the previous case of carbon steel. Accordingly, the general aspect of attenuation in this case will be discussed similarly as before.

Now the grain size of austenite structure was about 1/100 mm and the ultrasonic wavelength was about 1 mm. Thus the grain dimension is less than the wavelengths of sound waves and so the ultrasonic waves will be scattered by grains in accordance with the Rayleigh scattering mechanism⁽³⁾ during the propagation through specimen and vibrational energy of sound waves will be dissipated. On the other hand, it has been found that at lower frequencies the vibrational energy is also dissipated by the elastic hysteresis of the medium, and that this mechanism also forms an origin of internal friction. Then the ultrasonic attenuation coefficient α in the present case is made up of the energy loss due to these two mechanisms, and will be expressed for the frequency f of sound waves by the equation of the following type:

$$\alpha = B_1 f + B_2 f^4. \tag{2}$$

The first term in the right side of this equation expresses the hysteresis term mentioned above, which is linearly proportional to the frequency. The constant factor B_1 corresponds to the internal friction as will be measured at lower frequencies. The second term arises from the Rayleigh scattering of sound waves by grains and it is in proportion to the fourth power of frequency. It was shown by Mason⁽⁴⁾ that the coefficient B_2 was expressed by

$$B_2 \propto KV. \tag{3}$$

In this expression K corresponds to the elastic anisotropy of austenite grains and V is the mean volume of grains. If the results of the measurements given in Figs. 4～8 are expressed by the relation (2), the coefficients B_1 and B_2 can be shown to have values in Table 4. Now, it can immediately be seen from the table that the magnitude of B_1 remains almost unchanged, though the grain size changes, while B_2 takes different values with different specimens. If, however, the ratio B_2/V is taken, the value will become almost constant for the specimens of different grain sizes with the value of B_2. This ratio is in proportion to the elastic anisotropy K of austenite grains. Here, V is determined conventionally by the grains corresponding to intermediate region of ASTM number, say, 3 and 4, taking 3.5 on an average; the precise mean volume will be of some different value, but this estima-

Table 4. The values of B_1, B_2 and B_2/V in equations (2) and (3)

Specimen	B_1 db/cm·1/(Mc/s)	B_2 db/cm·1/(Mc/s)^4	Grain size number	V mm^3	B_2/V db/cm·1/(Mc/s)^4·1/mm^3
000	0.09	23.6×10^{-4}	3-4	18.6×10^{-4}	1.27
001	0.2	51	2-3	52.7	0.97
002	0.03	157	2	83.7	1.88
100	0.11	6.5	4-5	6.6	0.99
101	0.05	21	3-4	18.6	1.13
102	0.05	62	2-3	52.7	1.13
200	0.08	3.1	4-5	6.6	0.47
201	0.09	6.6	4-5	6.6	1.00
202	0.07	20	3-4	18.6	1.08
301	0.08	9.6	4	10.3	0.93
302	0.08	11.3	3-4	18.6	0.61

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(3) Rayleigh, *Theory of Sound*, Vol. 2, P. 152.

(4) W. P. Mason, H. J. McSkimin, J. Appl. Phys. **19**(1948), 940.

tion contains no serious inconsistency. The values of B_1 and B_2 are consistent with those obtained previously for steel and cast iron.

From these results, it will be seen that in stainless steel with fine grains the ultrasonic attenuation is considerably small, and that the flaw detection can be carried out by means of ultrasound with comparatively short wavelength. On the contrary, in coarse-grained structure the testing can only be carried out by the aid of the ultrasound with long wavelength. Therefore, the qualification of the grain size in austenite steel will be possible by measuring the ultrasonic attenuation. The results obtained here will give the foundations of ultrasonic testing, and some of the difficulties in the practical procedures will clearly be resolved.