2.7 NEWLY DEVELOPED NON-DESTRUCTIVE TESTING METHOD FOR EVALUATION OF IRRADIATION BRITTLENESS OF STRUCTURAL MATERIALS USING ULTRASONIC

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ABSTRACT

Surveillance testing is important to evaluate neutron irradiation embrittlement of reactor pressure vessel material for long life operation. An alternative test method for evaluating the irradiation embrittlement of the pressure vessel material will have to be proposed to support the limited number of surveillance test specimens in order to manage the plant life to be extended. In this study, ultrasonic testing for irradiated A533B-1 steel and weld metal was applied to examine material degradation nondestructively. With increasing the shift of Charpy 41 J transition temperature, ultrasonic velocity decreased and attenuation coefficient of ultrasonic wave increased. Especially, the difference of ultrasonic velocity for 5 MHz shear wave between as-received and irradiated material is corresponding to the shift of transition temperature showing material degradation.

INTRODUCTION

For the life extension of nuclear power plants, it is very important to detect aged deterioration of the materials used for structures and components such as a reactor pressure vessel (RPV). Since the RPV is exposed to neutron irradiation during the service period, the irradiation damage may occur to the RPV steel. Therefore, surveillance test to evaluate the irradiation embrittlement of the RPV material has been specified to the nuclear power plant. Irradiation capsules filled with the surveillance test specimens to measure the shift of Charpy transition temperature and the fracture toughness deterioration for the material of RPV are installed in the reactor [1]. As the number of those specimens will be insufficient if the plant life is extended, it is anticipated that the useful techniques of destructive or nondestructive test to support the surveillance testing is being required in the irradiation study. The reconstitution technique of Charpy impact specimens to be broken in the surveillance testing is indispensable for the implementation of destructive testing [2]. On the other hand, study on the nondestructive detection of the irradiation damage is also performed by measuring ultrasonic echo [3], positron annihilation [4], magnetic hysteresis [5] and neutron scattering [6] as a substitution for the surveillance testing. Nondestructive testing technique for the irradiation embrittlement is very useful not only for the backup of surveillance testing but also for the reduction of radioactive waste which will be produced by surveillance testing.

The main purpose of this study is to confirm the nondestructive evaluation method by using the ultrasonic wave for characterizing the irradiation embrittlement of the RPV material. As a first step, propagation time and echo amplitude of ultrasonic wave for the A533B-1 steel and weld metal, which were irradiated in the Japan Materials Testing Reactor (JMTR), were measured by remote manipulation in a hot cell of the JMTR Hot Laboratory. The irradiation damage of these materials is nondestructively evaluated on the basis of ultrasonic testing results.

EXPERIMENTAL PROCEDURE

Three kinds of materials whose chemical compositions are shown in Table 1 were used in this study. The commercial A533B-1 (ASTM A533 gr. B cl. 1) steel is a material for the reactor pressure vessel. The Low P A533B-1 steel is melted in the laboratory to reduce the phosphorus content. The weld metal was fabricated by submerged arc welding. The configuration and dimensions of the Charpy impact specimen used in this study are in accordance with JIS Z2202. Test specimens were irradiated in the JMTR (thermal power: 50MW) at about 523 K or 563 K up to a fast neutron fluence of 1 x 10^{24} n/m^2 (E>1 MeV). An annealing heat-treatment at 673 K for 5 min was applied to some of the irradiated specimens in order to prepare the samples with the different embrittlement characteristics. The Charpy impact test of these specimens was performed in the lead cell of the JMTR Hot Laboratory, complying with the specification of ASTM A 370.

Figure 1 shows the schematic diagram of the ultrasonic wave measurement system installed in the lead cell of the JMTR Hot Laboratory to examine the characteristics of the ultrasonic wave for the irradiated Charpy specimens. An ultrasonic probe fixed to the clamping rig was placed on the surface of the specimens by the manipulator to measure the propagation time and the pulse amplitude of the ultrasonic wave. A couplant to be used to propagate the ultrasonic wave from the probe to the specimen smoothly was both machine oil and glycerin. The size of transducer was 6.3 mm in diameter. The test frequencies of the ultrasonic wave are 5 MHz for share wave, and 10 and 15 MHz for longitudinal wave. Propagation time between first and second echo, and amplitude of these echoes were obtained from the pulse echo displayed on a CRT. After the ultrasonic testing, thickness of specimens was measured with accuracy of ± 1 μm. The ultrasonic velocity and attenuation coefficient of materials were calculated by the following equations, respectively [7].

$$\text{Ultrasonic velocity} = \frac{\text{(Specimen's thickness) x 2}}{\text{Propagation time between first and second echo}} \quad \text{-----------} (1)$$

$$\text{Attenuation coefficient} = \frac{\text{(Amplitude of first echo / Amplitude of second echo)}}{\text{(Specimen's thickness) x 2}} \quad \text{-------------} (2)$$

The longitudinal wave velocity, shear wave velocity and attenuation coefficient were obtained from the result of measurement.

RESULTS AND DISCUSSION

Figure 2 shows Charpy impact test results and typical transition curves for the commercial A533B-1 steel irradiated at 563 K. Charpy transition curve for the as-received material was determined by fitting the data to the hyperbolic tangent equation [8]. The transition temperature at 41 Joule of absorbed energy for the as-received materials is 234 K. Assuming that the Charpy transition temperature for irradiated material is obtained by shifting typical curve for the as-received material to the irradiated material, due to the limited number of irradiated specimens. The shift of Charpy 41 J transition temperature (hereafter with transition temperature) for irradiated material will be estimated to be 225 K. The shift for the material annealed after the irradiation is to be 160 K in the same way. It is recognized that the embrittlement of the irradiated material is recovered by annealing at 673 K for 5 min. The transition temperature for the irradiated material may be estimated to be a smaller value against the real transition temperature to be measured because the maximum temperature of Charpy impact testing was also low. The data of transition temperature and its shift, which are estimated for three kinds of materials, are summarized in Table 2.

Figure 3 shows the correlation between the ultrasonic velocity of 5 MHz shear wave and the shift of transition temperature for four kinds of materials. The ultrasonic velocity decreases with increasing the shift of transition temperature. It was found that the ultrasonic velocity of 5 MHz shear wave depends on the degree of embrittlement for the materials used in this study.

The correlation between the ultrasonic velocity of 10 MHz and 15 MHz longitudinal wave and the shift of transition temperature is shown in Fig. 4 and Fig. 5, respectively. The velocity of both longitudinal wave decreases slightly with increasing the shift of transition temperature, but the scattering of data is observed in these figures.

Figure 6 represents the difference of the ultrasonic velocity for 5 MHz shear wave between the as-received material and the irradiated material or annealed material after the irradiation. The value of the ultrasonic velocity difference decreases with increasing the shift of transition temperature. The good relation between the ultrasonic velocity difference and the transition temperature shift was obtained as shown in the solid line.

Figure 7 shows the experimental data in case of 10 and 15 MHz longitudinal wave. The amount of velocity difference is smaller than that of the data for 5 MHz shear wave, and the scattering of data is observed. The solid and dotted lines showing the velocity difference for 10 and 15 MHz represent the good corresponding, respectively.

Figure 8 shows the correlation between the attenuation coefficient of 15 MHz longitudinal wave and the shift of transition temperature. Attenuation coefficient increases with increasing the shift of transition temperature except for the data on the commercial A533B-1 steel irradiated at 523 K.

Figure 9 represents the difference of the attenuation coefficient for 15 MHz longitudinal wave between as-received material and irradiated material or annealed material after the irradiation. The good relationship between the difference of the attenuation coefficient and the shift of transition temperature was obtained as shown in the solid line.

The sound pressure of ultrasonic in the irradiated materials becomes lower compared with the unirradiated materials, which may be related to the factor such as the helium void, vacancy and lattice defects induced by neutron irradiation [7,9].

It was found the NDE method by ultrasonic testing is applicable and indispensable for characterizing the irradiation embrittlement of material such as RPV or its component.

CONCLUSIONS

The following relations between the ultrasonic characteristics and Charpy transition temperature for A533B-1 steel and weld metal were obtained.

(1) Ultrasonic velocity decreased with increasing the shift amount of Charpy transition temperature.

(2) The tendency that the attenuation coefficient of ultrasonic wave increased with increasing the shift of Charpy transition temperature was observed.

(3) The difference of ultrasonic velocity for 5 MHz shear wave between as-received and irradiated material shows a good corresponding to the shift amount of Charpy transition temperature.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Yoneyama and Mr. Yoshida of Ishikawajima-Harima Heavy Industries co., ltd. for their technical supports. In addition, they are grateful to Mr. Baba and Mr. Onizawa for their helpful advice.

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Table 1 -- Chemical composition. [Wt %]

	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
Commercial A533B-1 steel	0.22	0.31	1.36	0.01	0.012	0.58	0.13	0.52	0.14
Low phospholus A533B-1 melted in Labratory	0.21	0.28	1.36	0.003	0.01	0.6	0.11	0.51	0.16
Weld metal	0.076	0.23	1.46	0.016	0.01	0.66	0.037	0.47	0.089

Table 2 -- Charpy transition temperature (and its shift). [K]

	As recieved	Irrad.+Annealed	Irradiated
Commercial A533B-1 steel irrad. at 523K	234	439 (205)	484 (250)
Commercial A533B-1 steel irrad. at 563K	234	394 (160)	459 (225)
Low P A533B-1 steel irrad. at 563K	199	303 (104)	403 (204)
Weld Metal irrad. at 563K	217	357 (140)	477 (260)

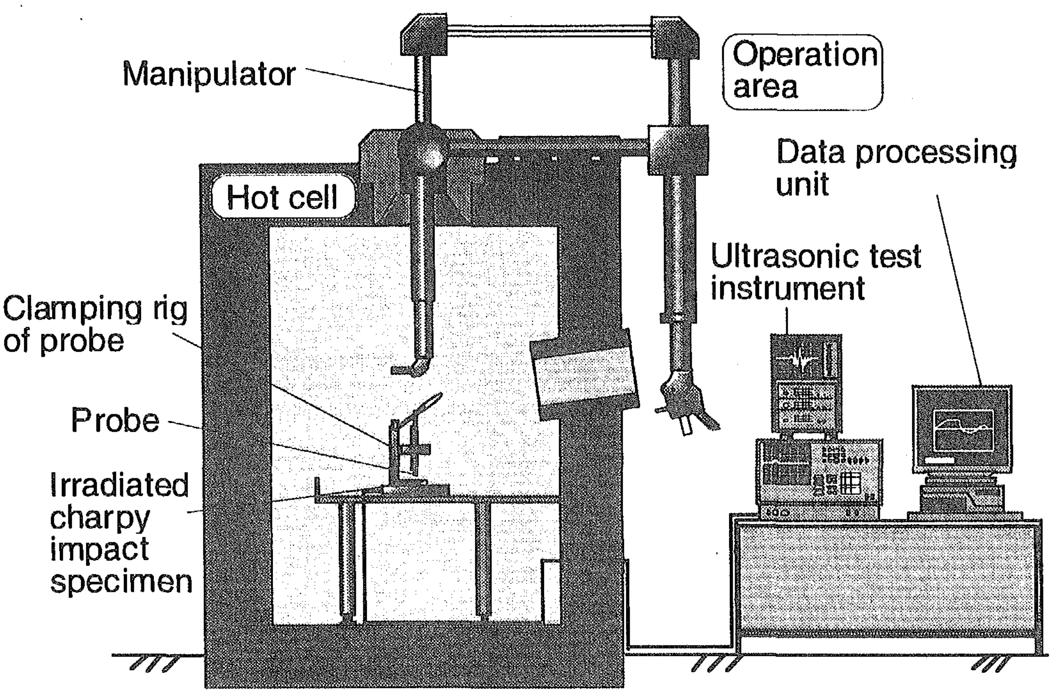

Fig. 1 -- Schematic view of experimental apparatus for nondestructive evaluation of irradiation embrittlement in hot cell.

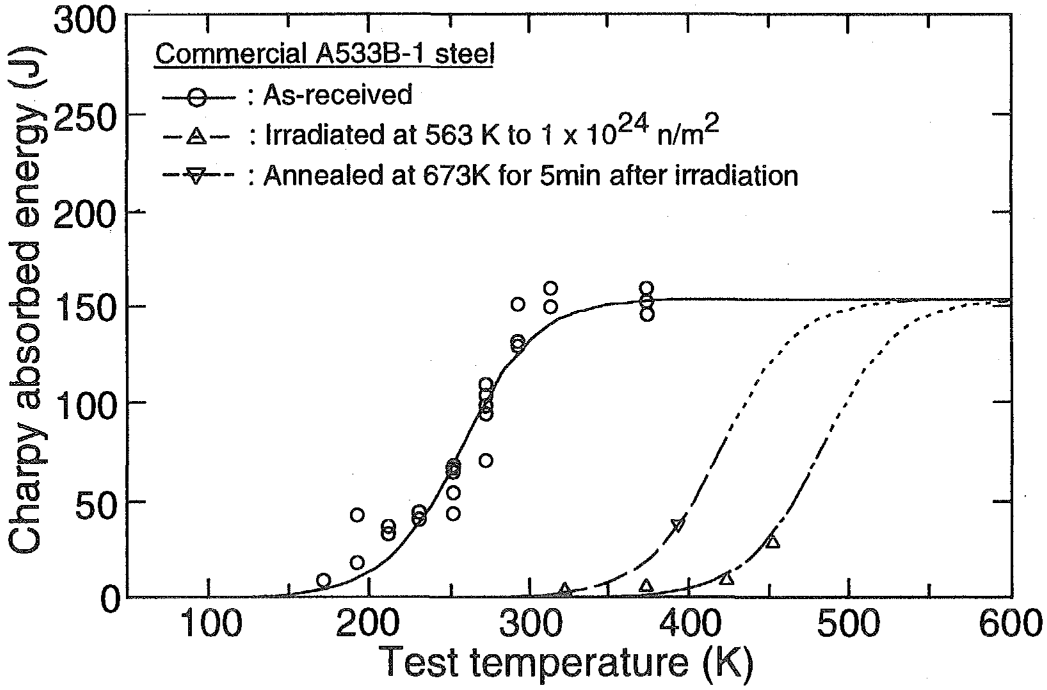

Fig. 2 -- Charpy impact test results for commercial A533B-1 steel.

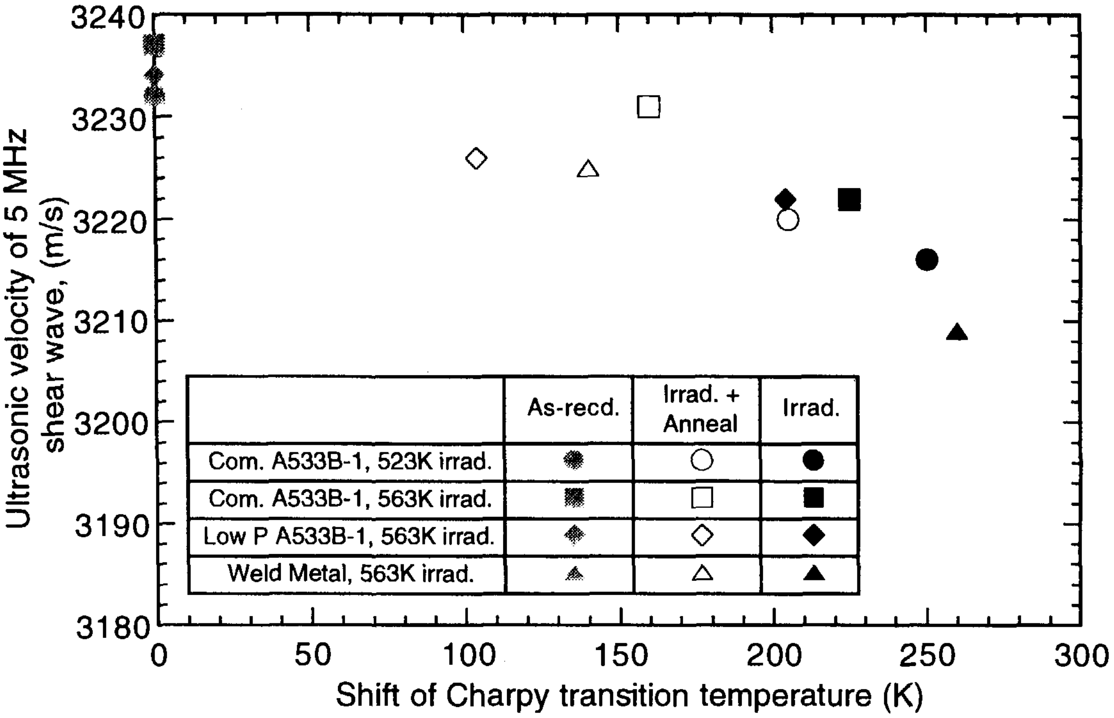

Fig. 3 -- Correlation between ultrasonic velocity of 5 MHz shear wave and shift of Charpy transition temperature.

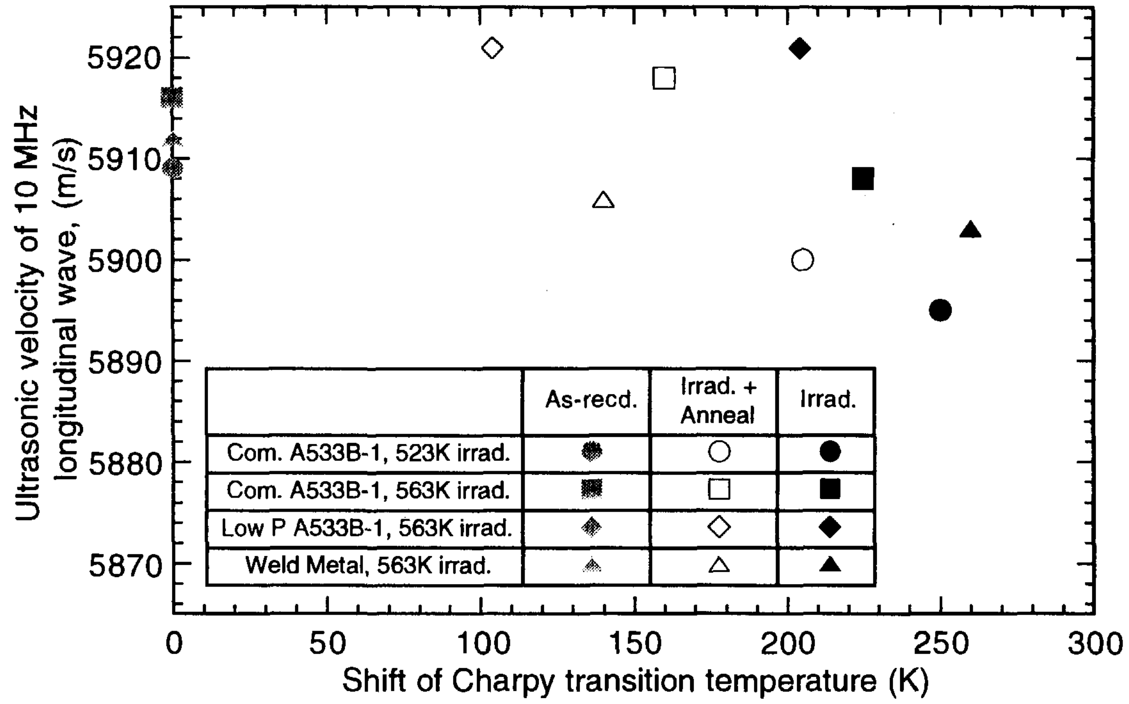

Fig. 4 -- Correlation between ultrasonic velocity of 10 MHz longitudinal wave and shift of Charpy transition temperature.

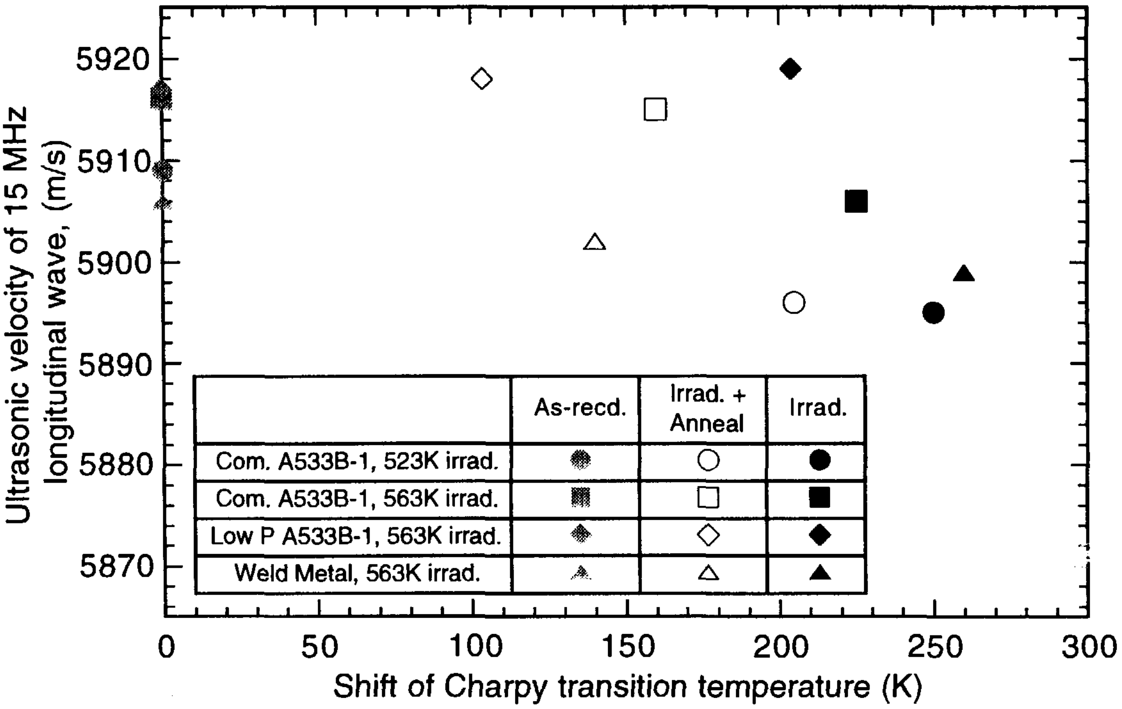

Fig. 5 -- Correlation between ultrasonic velocity of 15 MHz longitudinal wave and shift of Charpy transition temperature.

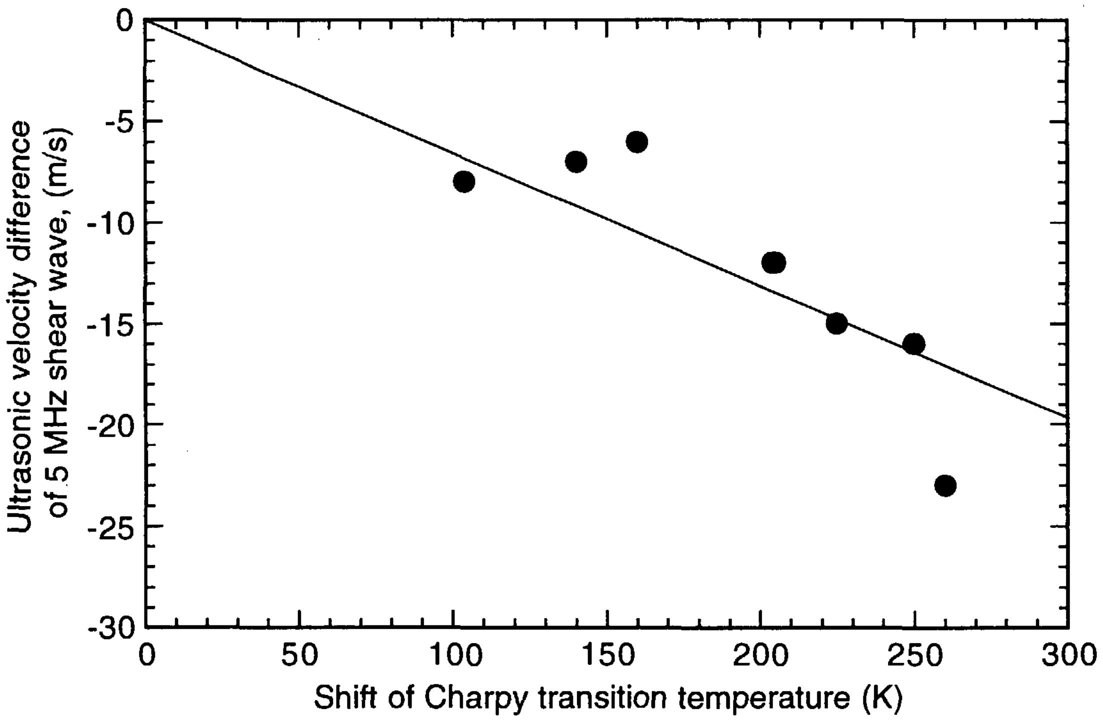

Fig. 6 -- Correlation between ultrasonic velocity difference of 5 MHz shear wave and shift of Charpy transition temperature.

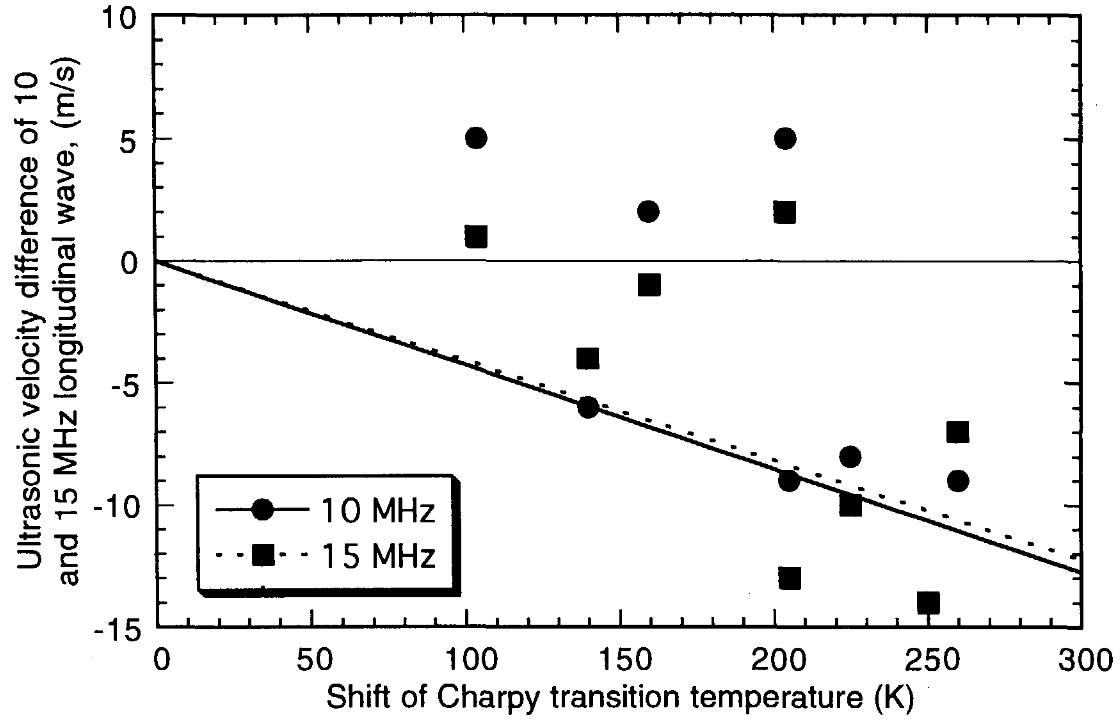

Fig. 7 -- Correlation between ultrasonic velocity difference of 15 MHz longitudinal wave and shift of Charpy transition temperature.

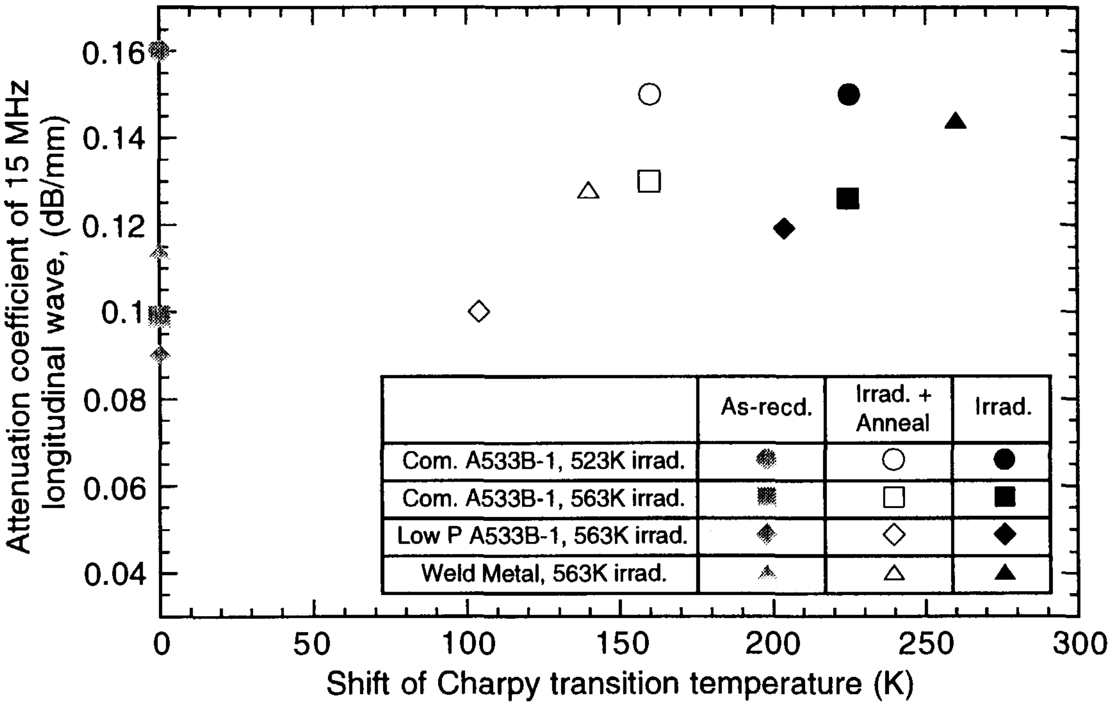

Fig. 8 -- Correlation between attenuation coefficient of 15 MHz longitudinal wave and shift of Charpy transition temperature.

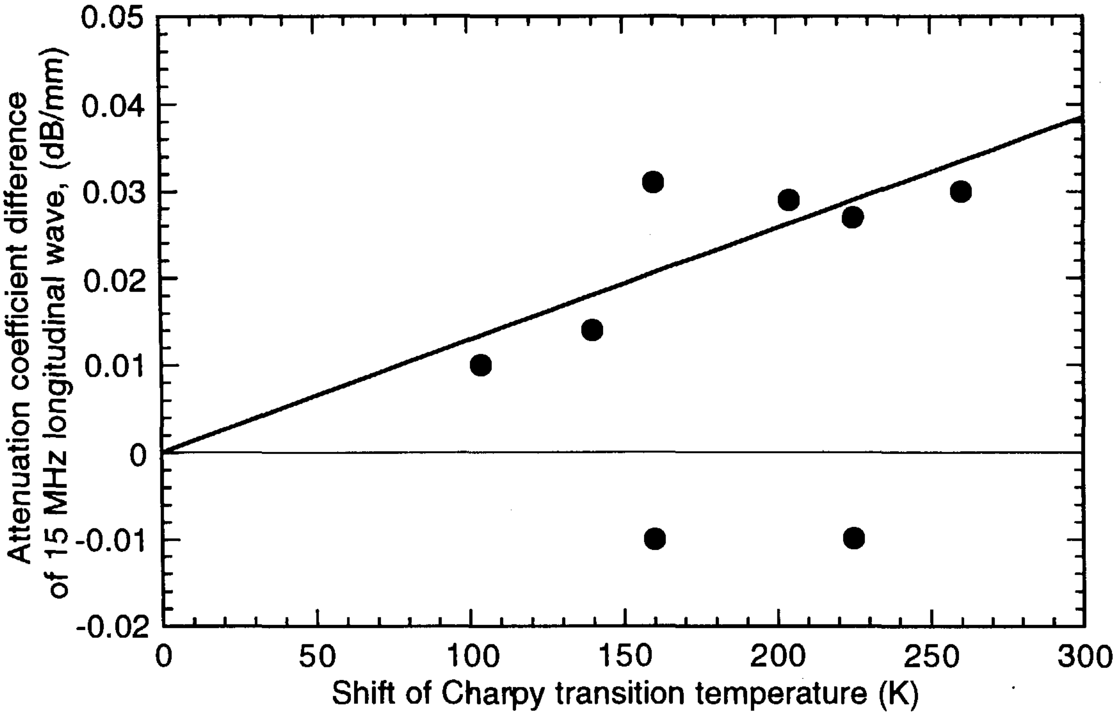

Fig. 9 -- Correlation between attenuation coefficient difference of 15 MHz longitudinal wave and shift of Charpy transition temperature.