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# Studies on the Correlation between Mechanical Properties and Ultrasonic Parameters of Aging 1Cr-1Mo-0.25V Steel

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Mechanical properties of in-service facilities are required to evaluate the integrity of power plants and chemical plants Non-destructive technique can be used to evaluate the mechanical properties To investigate the mechanical properties using ultrasonic technique, the four classes of thermally aged specimens were prepared using an artificially accelerated aging method Ultrasonic tests, tensile tests, fracture toughness tests, and hardness tests were performed for the specimens Then the mechanical properties were compared with ultrasonic parameters such as attenuation and non-linear parameter From the investigation, we confirm that the ultrasonic parameter can be used to evaluate the mechanical properties

**Key Words :** Mechanical Properties, Ultrasonic Technique, Attenuation, Non-Linear Parameter

## Nomenclature

$A_{1st}$ Amplitude of the fundamental wave
$A_{2nd}$ : Amplitude of the second harmonic wave
$\beta$ Non-linear parameter
$K_{IC}$ : Fracture toughness
$v$ Phase velocity
$\omega_o$ Angular frequency
$z$ Thickness of specimen

## 1. Introduction

The mechanical properties of in-service facilities are decreased by material degradation The degradation of mechanical properties affects the safety of operating facilities So the evaluation of mechanical property or material degradation is important for structural integrity evaluation A non-destructive method is a good technique to monitor the change of mechanical properties of in-service facilities (Yoo, 1994)

Up to now, ultrasonic test, electric resistance test and ball indentation test have been applied to evaluate the mechanical properties Among them, ultrasonic method is a good technique to evaluate them Velocity and attenuation of ultrasonic wave are two important parameters in linear ultrasonic technique The attenuation of ultrasonic wave is sensitive to the grain size of material and its frequency The velocity of ultrasonic wave is a function of its frequency or wavelength, then propagating medium is dispersive (Pollard, 1977 , Ruud and Green, 1984 ; Sachse and Pao, 1978) The methods used for flaw detection in non-linear ultrasonic method are based on observing the waves reflected or scattered by non-linear factors such as porosity, crack and dislocation A harmonic generation of the incident wave is the most typical non-linear response in the material with non-linear factors (Sutin et al , 1992 , Kim et al , 1996 , Breazeale and Ford, 1998) Empirical evidence is presented to show the relation that exists

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between the ultrasonic attenuation properties and fracture toughness properties of polycrystalling metallic materials (Vary, 1978) The relation between frequency and decay constant is suggested to the degree of material degradation (Maeda et al, 1995, Shin et al, 1996; Kwon et al, 2002, Im et al, 2002) Electric resistivity of 1Cr-1Mo-0 25V steel was measured as degradation (Nahm et al, 1996, Seok et al, 2002) and ABI technique is used to determine changes of the mechanical properties of nickel base alloy components due to aging (Matthew et al, 1999)

In this study, we prepared for four different simulated specimens of 1Cr-1Mo-0 25V steel using isothermal aging heat-treatment for each 453, 933, 1820 hour at 630℃ respectively and a reference specimen The effect of aging on the mechanical properties of each specimen has been investigated using tensile test and the fracture toughness test Then the mechanical properties were compared with ultrasonic parameters such as attenuation and non-linear parameter From the investigation, we were able to confirm that the ultrasonic parameter can be used to evaluate the mechanical properties

## 2. Mechanical Properties

### 2.1 Tensile properties

Tensile test was performed using a universal testing machine at the room temperature according to ASTM E 8-95a (Abdel-Latif et al, 1982) Figure 1 shows the dimensions of the specimen for tensile test and the true-stress true-stain curves are shown in Fig 2 From the test results, yield strength, ultimate tensile strength and uniform elongation were determined Table 1 and Table 2 show the chemical composition and experimental test results for 1Cr-1Mo-0 25V steel for each aging time, respectively From the experimental test results, we can observe that the material strength decreased as the aging time increased

### 2.2 Fracture toughness

An universal testing machine was used for fracture toughness testing Fracture toughness was determined on the basis of "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials (ASTM E 399-90)" at room temperature Figure 3 shows the dimensions of the specimen for fracture toughness test and Fig 4 is the test result for variation of fracture toughness,

**Table 1** Chemical composition of 1Cr-1Mo-0 25V (Wt %)

| C | Si | Mn | S | P | *Ni* | *Cr* | *Mo* | *V* | *Sn* |
|---|---|---|---|---|---|---|---|---|---|
| 0 29 | 0 01 | 0 74 | 0 004 | 0 007 | 0 06 | 1 29 | 1 24 | 0 25 | 0.0047 |

**Table 2** Tensile and hardness test results

| Aging Time (hour) | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Uniform Elongation (%) | Vickers Hardness |
|---|---|---|---|---|
| 0 | 711 | 844 | 25 3 | 292 |
| 453 | 533 | 676 | 26 8 | 245 |
| 933 | 481 | 615 | 27 8 | 218 |
| 1,820 | 450 | 582 | 30 7 | 196 |

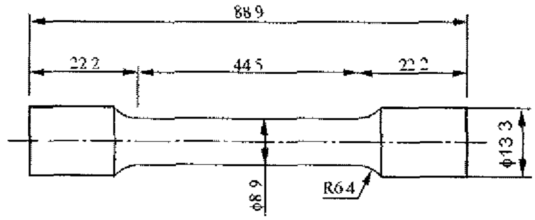



**Fig. 1** Dimensions of the specimen for tensile test (unit mm)

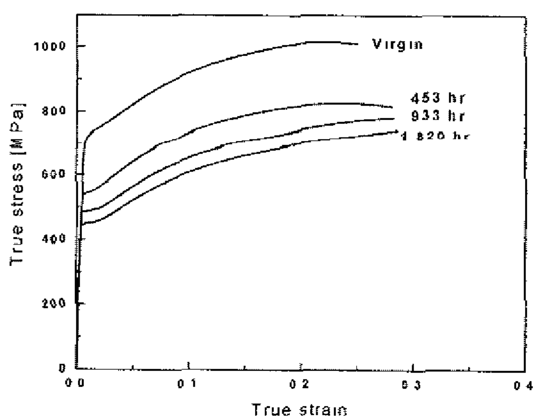



**Fig. 2** Effect of aging time on true stress-true strain curve

$K_Q$, as the aging time is increased The $K_Q$ was decreas ed linearly in comparing the non-linear trend for the curve of tensile test and hardness test

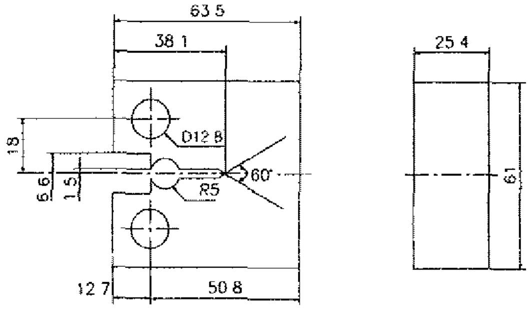



**Fig. 3** Dimensions of the specimen for fracture toughness test (unit mm)

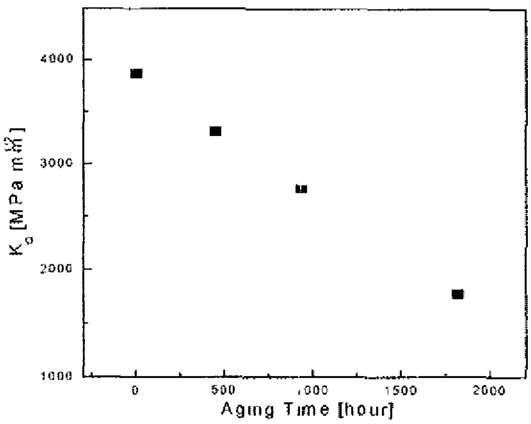



**Fig. 4** Effect of aging time on fracture toughness

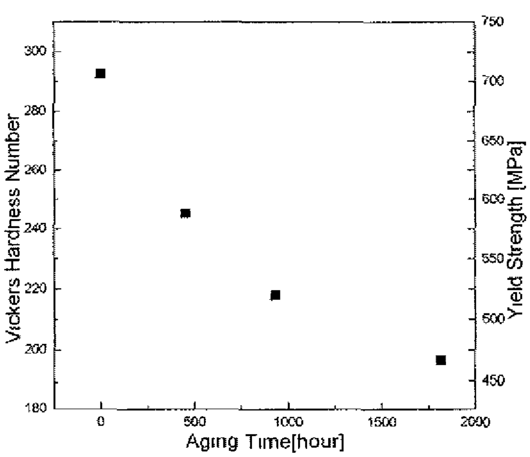



**Fig. 5** Effect of aging time on Vickers hardness and yield strength

results In generally, fracture toughness coincided with the deterioration of mechanical properties during degradation process Especially linear decrease for $K_Q$ can be a good parameter for evaluating material degradation

### 2.3 Hardness

Micro Vickers hardness tester (MVK-H2, Akashi) was used for hardness test To eliminate the effect of surface roughness, powdered alumina treatment was used. Indentation points were kept sufficient distances at an interval of 10 times of the ball diameter. Vickers hardness tests were performed using a self-adjusting tester 10 N force was loaded on the surface of the specimen 10 times for each aged specimen Figure 5 shows the effect of aging time on Vickers hardness From Fig 5, we can see that Vickers hardness numbers decreased as the aging time increased The tendency is similar to that of the yield strength

## 3. Microstructure

To examine the average diameter of grain size, a microscope was used with a magnification of 300 Table 3 and Photo 1 show changes of the average diameter of grain size and microstructure of 1Cr-1Mo-0 25V as degradation, respectively For the convenient, the outlines of some grains indicate to emphasize the grain growth following aging in Photo 1

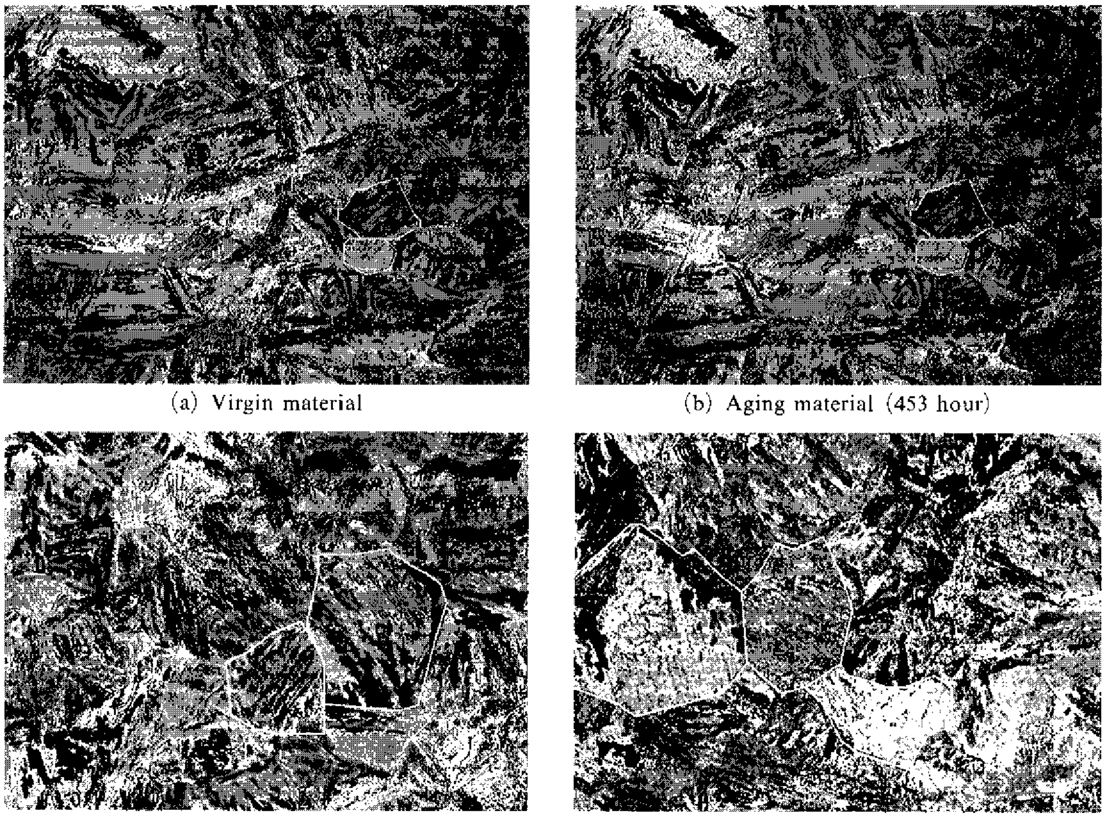
**Table 3** Average diameter of grain size of 1Cr-1Mo-0 25V as degradation

| Aging Time (hour) | 0 | 453 | 933 | 1,820 |
|---|---|---|---|---|
| Aver Diameter of Grain Size ($\mu$m) | 10 12 | 12 88 | 15 74 | 20 24 |

## 4. Ultrasonic Properties

### 4.1 Attenuation coefficient

To measure the attenuation coefficient of the material, immersion ultrasonic method was used The specimen was smooth, flat and parallel A pulse-echo configuration was used in this work



(a) Virgin material (b) Aging material (453 hour)

(c) Aging material (933hour) (d) Aging material (1,820 hour)

**Photo. 1** Microstructure of 1Cr-1Mo-0.25V as degradation (magnification to the size of 300)

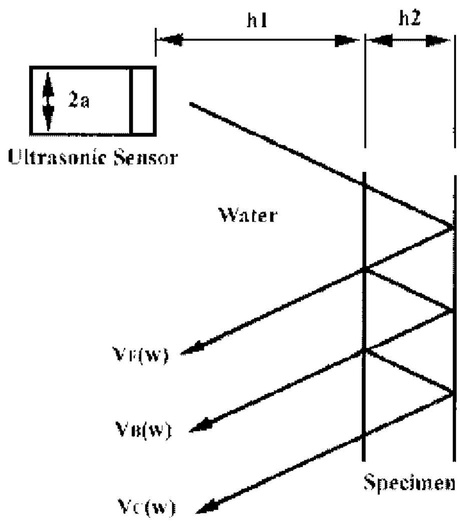



**Fig. 6** Wave propagation paths

with non-focused and immersion transducer and all signals were taken at normal incidence on the interface of water and specimen. Previously the amplitude of the front surface waveform of time domain signal was observed and then the ultrasonic transducer was fixed at maximum amplitude and the experiment was performed.

Figure 6 shows wave propagation paths. The center frequency was 16.7MHz and the -3dB bandwidth of the received pulse was 12.8 MHz~21.7 MHz. The distance between the surface of the specimen and the transducer was 20.8 mm, the thickness of the specimen was 10.2 mm, and the diameter of the transducer was 12.25 mm. The frequency domain signal was used to calculate the attenuation coefficient (Lester et al., 1992). Sampling rate was 100 MS/s.

Figure 7 shows the effect of frequency on attenuation coefficient for each aged specimens. As the aging time increased, the attenuation coefficients increased. Measurement deviation of the attenuation coefficient was $\pm 0.001$ N/mm. Figure 8

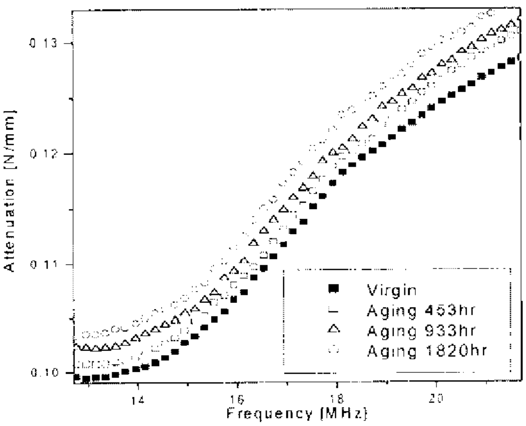



**Fig. 7** Effect of frequency on attenuation coefficient

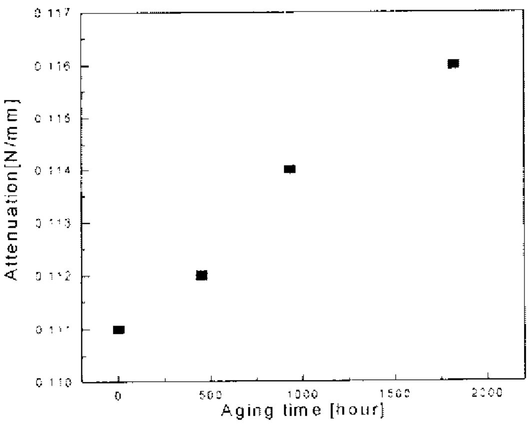



**Fig. 8** Effect of aging time on attenuation coefficient at center frequency

shows the effect of aging time on attenuation coefficient at center frequency.

### 4.2 Non-linear response

Figure 9 is a block diagram of the non-linear ultrasonic instruments used in this study. The size of specimens for non-linear response was 20×30×50(mm). Both PZT transducers, whose resonance frequencies were 1 MHz and 500 kHz, respectively, were attached at the end of the specimen using glue.

The sinusoidal continuous wave was driven into the specimen with a function generator via a power amplifier. The transmitted ultrasonic wave was detected on the other side of the specimen.

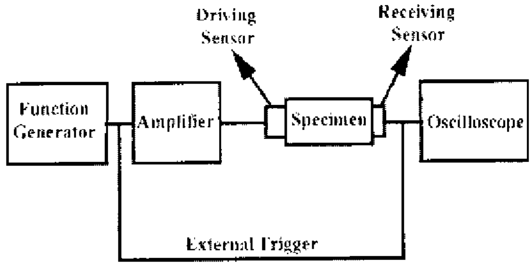



**Fig. 9** Block diagram of apparatus for non-linear ultrasonic test

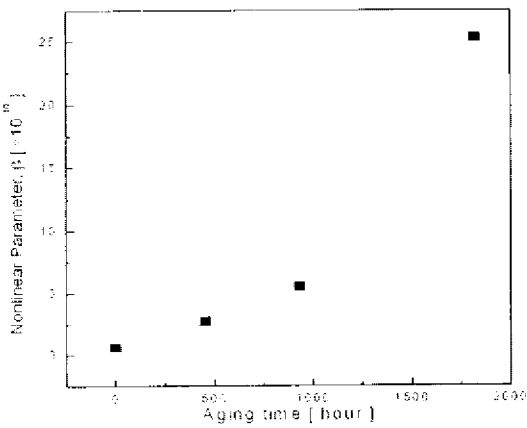



**Fig. 10** Effect of aging time on non-linear parameter ($\beta$)

The signal from the receiver transducer was displayed on the digital oscilloscope. In order to obtain the amplitude of the second harmonic wave, the low-frequency continuous wave was driven into the specimen and the second harmonic level of the transmitted wave was observed through the high-frequency transducer.

At first, operation of the system was checked by varying the gain of amplifier to avoid non-linearity of system with the un-aging specimen and got the proper gain (40dB). Then, the efficiency of harmonic generation was estimated for each of aged specimens.

The amplitudes of the second harmonic wave increased as the aging time increased. The second harmonic of transmitted wave in 1,820 hour aged specimen was observed to exceed 20dB more than that in the un-aged specimen.

If the fundamental and second harmonic amplitudes are given, the magnitude of the non-linear parameter can be determined through the following relationship (Hurley et al., 1998)

$$\beta=\frac{8v^2A_{2nd}}{\omega_o^2 z A_{1st}^2} \quad (1)$$

where $A_{1st}$ and $A_{2nd}$ are the amplitudes of the fundamental and second harmonic waves. And, $z$, $\omega_o$ and $v$ are the thickness of specimen, angular frequency of fundamental wave and the phase velocity. For each aged specimen, several amplitude pairs were obtained using an oscilloscope for fixing the input gain to 40dB. Figure 10 shows the variation of non-linear parameter for different aging specimens.

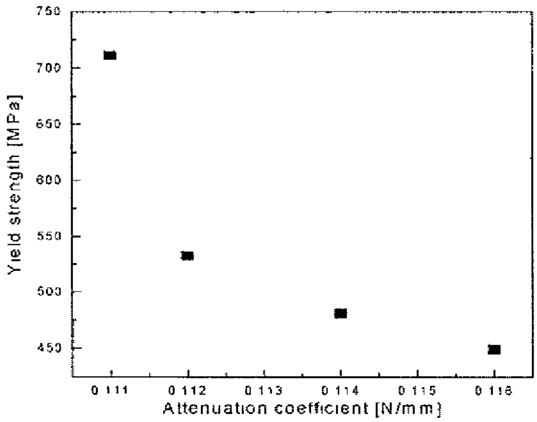



**Fig. 11** Relation between yield strength and attenuation coefficient

## 5. Discussion

### 5.1 Mechanical properties and microstructure

From the experimental results, the degradation of material caused the increase of uniform elongation and decrease of the tensile strength, yield strength and fracture toughness.

Especially, the strength of material was observed to decrease steeply at the early stage of degradation and after that time the decreasing trend of strength are slowed. To confirm the reason for decrease of the strength and the fracture toughness, it's observed micro-structure of degradation materials using a microscope and EDAX (Philips CM2000, energy dispersive analysis X-ray). The grain size was grown as degradation and the degradation precipitated the specific substances such as Cr, S at the grain boundaries.

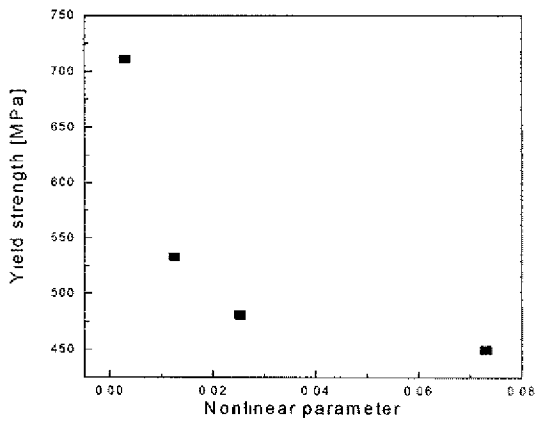



**Fig. 12** Relation between yield strength and non-linear parameter

### 5.2 Yield strength and ultrasonic characteristics

The relation between yield strength and ultrasonic parameter is shown in Figs. 11 and 12. It is known that the attenuation coefficients increased as degradation occurs with decreasing the yield strength of material. The increase of attenuation coefficient is dependent on the scattering components such as grain size and precipitates at grain boundaries. The weakness of material causes the decrease of the yield strength. Decrease of the yield strength can be interpreted as the appearance of the specific substances and the intergranular brittleness due to the formation of the chemical compound at grain boundaries.

Especially, the yield strength of the 453-hour aging material steeply decreased compared to those of the rest. The cause can be explained as the general relation between the yield strength and the grain size. The yield strength is proportional to the inverse root square of the grain diameter, which are determined at the beginning of degradation concerning the Hall-Petch's relation (Dieter, 1986). After forming the critical grain size, the specific elements are diffused to the grain boundaries. So the variation of the yield strength of the material shows a smooth slope.

### 5.3 Uniform elongation and ultrasonic characteristics

Figures 13 and 14 show the relation between uniform elongation and ultrasonic parameter From the result of experiments, attenuation coefficient, non-linear parameter and elongation are increased as the aging time increased The increase of ductility of the material, activated by the movement of dislocation due to the increase of grain size, causes the increase of elongation as the aging time increased

### 5.4 Fracture toughness and ultrasonic characteristics

The relation between fracture toughness and ultrasonic parameter is shown in Figs 15 and 16 The fracture toughness is in inverse proportion to ultrasonic parameters The decrease of the fracture toughness can be interpreted as the weakness of material due to inter-granular brittleness as the aging time increased, namely increase of precipitates at grain boundaries Figure 16 shows that there is a co-relation between non-linear parameter and fracture toughness

### 5.5 Hardness and ultrasonic characteristics

The relation between ultrasonic parameters and Vickers hardness is shown in Figs 17 and 18 The reason for the decrease of material hardness can also be interpreted as intergranular brittleness contrary to the increase of ultrasonic parameters

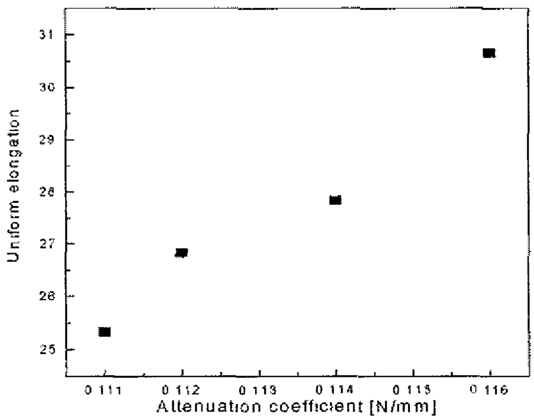



**Fig. 13** The relation between uniform elongation and attenuation coefficient

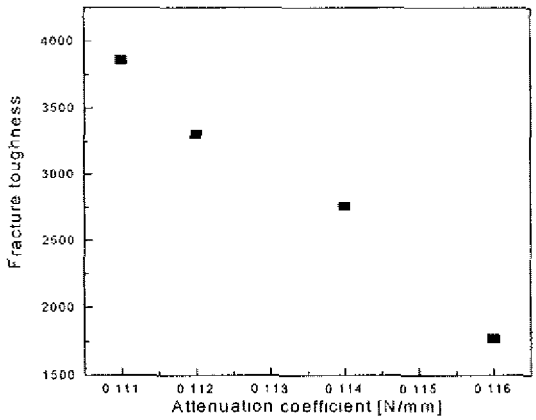



**Fig. 15** Relation between fracture toughness and attenuation coefficient

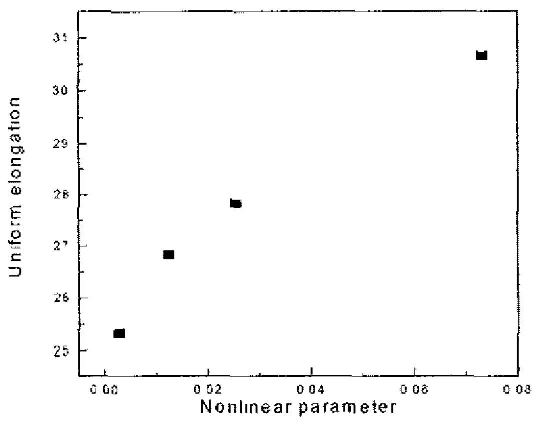



**Fig. 14** Relation between uniform elongation and non-linear parameter

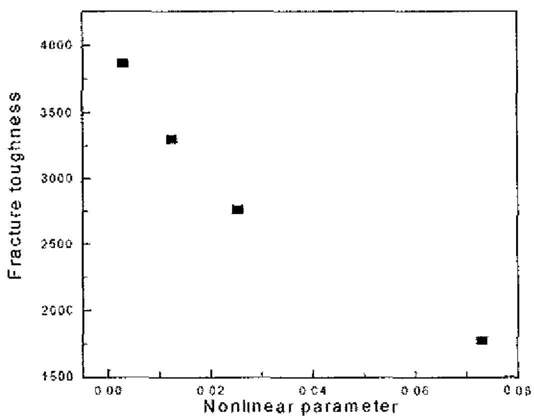



**Fig. 16** Relation between fracture toughness and non-linear parameter

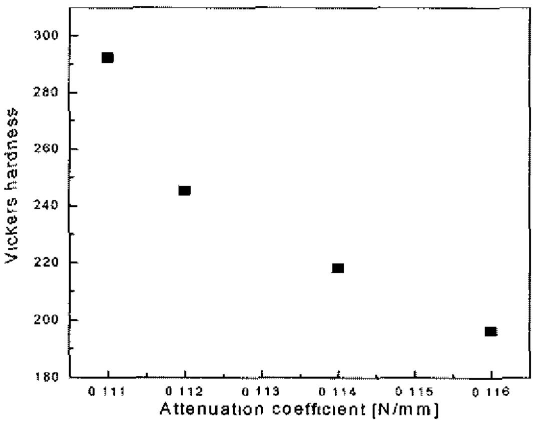



**Fig. 17** Relation between attenuation coefficient and Vickers hardness

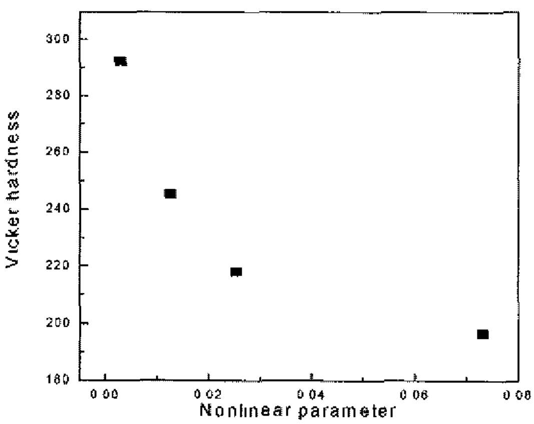



**Fig. 18** Relation between non-linear parameter and Vickers hardness

## 6. Conclusions

To investigate the mechanical properties using ultrasonic technique, we prepared for four different simulated specimens of 1Cr-1Mo-0 25V steel by isothermal aging heat-treatment By comparing various mechanical properties obtained from tensile and fracture test with ultrasonic parameters of these specimens such as attenuation and non-linear parameter, the following conclusions were obtained

(1) The yield strength, the Vickers hardness and the fracture toughness decreased and the elongation of the material increased as the aging time increased

(2) Attenuation coefficients and the harmonic generation level of an ultrasonic signal increased as the aging time increased

(3) The attenuation and non-linear parameters of ultrasonic test are sensitive and will be a good parameter to evaluate the mechanical properties such as yield strength, hardness and fracture toughness

(4) The relation curve between ultrasonic parameters and mechanical properties was obtained So it is possible to evaluate the mechanical properties using the relation.

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